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Research Article

Thermophysical characterization of concrete reinforced with baobab trunk fibers (Adansonia digitata L.) for thermal insulation of buildings

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ABSTRACT

This work deals with characterizing concrete based on baobab trunk fibers for thermal insulation in buildings. The aim is to study the effect of the fiber content and the type of fiber treatment on the hygroscopic and thermo-physical properties of the concrete. Therefore, two types of treatment were carried out: an alkaline treatment and a thermo-alkaline treatment. Hygroscopic test results (34.25% to 54.92% for fiber content ranging from 14% to 28%) show that adding fibers to concrete makes them more sensitive to water. However, thermochemical treatment of the fibers reduces this water sensitivity. The thermal conductivities of concrete range from 0.202 to 0.086 W/m.K for the same fiber content. These results show that these biomaterials can be used in construction to improve building insulation.

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1. INTRODUCTION

The residential building sector consumes large quantities of energy for heating in cooler periods and air conditioning or ventilation in hot periods. In Senegal, the energy consumption of buildings is estimated at 49% of final national consumption [1]. This is explained by the fact that in Senegal, concrete (a conductive material) is the primary building material. With this material, air conditioning and artificial ventilation are always used to achieve minimum thermal comfort. In addition, manufacturing and recycling this material requires large amounts of energy and poses a real problem of environmental pollution and greenhouse gas emissions.

Faced with this problem, developing new alternative materials to concrete is becoming necessary. One of the solutions proposed to mitigate the environmental impact of concrete is the incorporation of vegetable fibers in the manufacture of construction materials. Vegetable fibers are local, available materials with low thermal conductivity. Thus, their use in building materials can be an alternative to reduce heat transfer.

Several researchers have been interested in determining bio-composite materials physical and thermal properties based on cement and plant fibers.

Benmansour et al. [2] studied the effect of fiber content on the water absorption, density, and thermal conductivity of a date palm fibers reinforced mortar. They noted a decrease in density, thermal conductivity, and an increase in water absorption as the amount of fibers in the mortar increased. Abdullah et al. [3] studied the physical and hygroscopic behavior of a cement mortar reinforced with coconut fibers. The authors concluded that the concretes' moisture content and water absorption increase as the fiber content

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increases. However, the density of the concrete decreases. Potiron et al. [4] worked on determining the thermal conductivity and density of concrete based on sugarcane bagasse. The fibers were treated with boiling and alkaline solution. The authors concluded that thermal conductivity and density decreased with increasing fiber content in the composite concrete. Taoukil et al. [5] studied the influence of water content on the thermal properties of a cement-sand composite reinforced with wood chips. The results showed that as the percentage of wood chips increased, the concrete's thermal conductivity and thermal diffusivity decreased. However, these values increase as the moisture content of the concrete increases. Chakraborty et al. [6] worked on the effect of adding jute fibers treated with an alkaline solution and another solution of Sika latex polymer (carboxylated Styrene Butadiene) on the density of cement mortar. The results show that treating the fibers with 5% Sika latex polymer increases the density of the composite concrete. Panesar et al. [7] studied the influence of cork waste fiber content on a cement mortar's density and thermal conductivity. They found that the density and thermal conductivity of the mortar decreased with increasing fiber content.

Osseni et al. [8] worked on the influence of the percentage of coir fibers on the thermal properties of a mortar. The results show that the thermal effusivity and thermal conductivity decrease by about 10% as the amount of coir fibers increases. Ashraf et al. [9] determined concrete's thermal conductivity and density containing date palm fibers. The authors noted a decrease in the thermal conductivity and density of the concrete as the fiber content increased. Similarly, Diaw et al. [10] manufactured and determined the thermo-physical properties of concrete incorporating typha australis aggregates. The authors concluded that these materials can be used in buildings to improve energy efficiency.

Al-Mohamadawi et al. [11] investigated the influence of increasing flax shives treated with paraffin wax on cement concrete's thermal conductivity and density. The results showed that adding raw or treated fibers decreases cement concrete's density and thermal conductivity (<0.3 W/mK). However, the density and thermal conductivity of the treated fibers concrete increased compared to that of the raw fibers concrete. Khazma et al. [12] worked on determining the thermal conductivity and density of concrete reinforced with flax shives treated by coating with a pectin + polyethylene (pp) mixture. The authors noted increased treated concrete's density and thermal conductivity compared to raw concrete. Abderraouf [13] studied the influence of the percentage of Diss and Doum fibers treated with a sodium hydroxide solution on the thermal conductivity of cement concretes. The results show that, for fiber content of 4% by mass, the thermal conductivity of Diss and Doum treated fibers mortars decreases by 40% and 33%, respectively, compared to the control mortar. Becchio et al. [14] studied the influence of the percentage of wood aggregates on the thermal conductivity of cement concrete. Their results showed a decrease in the thermal conductivity of composite concrete compared to control concrete.

This literature review shows that many vegetable fibers manufacture thermal insulation or filling materials in housing construction. No studies have been conducted to determine the hygroscopic and thermo-physical properties of concrete made from baobab (Adansonia digitata L.) trunk fibers. The baobab is a gigantic tree of the Bombacaceae family that grows in the southern, western, and southeastern regions of Senegal [15]. This tree has long been exploited for food (leaves and fruits) and traditional medicine (leaves and bark). Baobab trunk and branches are very fibrous and are used for rope making and mat weaving. Extracting fibers from these parts does not affect the tree's health, as these parts regenerate every six months after exploitation [16].

This work aims to develop and determine cement concrete's hygroscopic and thermo-physical properties based on baobab trunk fibers. The properties studied are water absorption, moisture content, density, and thermal conductivity. Compared to the work mentioned above, the originality of this work is the use of baobab trunk fibers in producing bio-sourced concrete to manufacture insulating cementitious concrete with low environmental impact.

2. MATERIALS AND CHARACTERIZATION METHODS

2.1. Baobab Trunk Fibers

In this study, the fibers used were extracted from the trunk of a local tree, the Baobab (Adansonia digitata L.). The baobab is a gigantic tree generally found in Africa's south-eastern and south-western regions, i.e., in the Sahelian and Sudano-Sahelian zones. In Senegal, the baobab is widespread in areas such as Thiès, Kaolack, Tambacounda, and in the southern regions, the Casamance. After extraction, the fibers were cleanly washed and air-dried for a week before being cut by hand into 1 cm lengths. [16, 17].

Two treatments were applied to the fibers:

- The alkaline treatment consisted of immersing the fibers for 4 hours in a sodium hydroxide (NaOH) solution of 5% concentration by mass at room temperature. They were washed thoroughly with distilled water and soaked again in a 1% sulphuric acid solution for 2 hours. Finally, the fibers were washed clean with distilled water and dried at room temperature for 72h. This fiber is noted as F.T.NaOH.
- Thermochemical treatment involves boiling the fibers for at least four hours and rinsing them thoroughly with distilled water to remove organic substances (waxes, peptides, impurities). The exact process then treats the boiled fibers with the same sodium hydroxide solution. This fibThis fiber F.B.T.

Several studies on the characterization of bio-based composites have already shown that heat treatment and alkali treatment of plant fibers can reduce large quantities of lignin, hemicellulose, and water-soluble substances. These compounds are the primary agents responsible for the delayed setting of the cementitious matrix and poor adhesion at the fiber/cement interface [4, 18].

Table 1. The fibers hygroscopic, physical, and thermal properties [17]

Types de fibres	ω (%)	ρ (kg.m^{-1})	λ (Wm^{-1}.K^{-1})
F.T.N$_a$OH	230.62	225	0.041
F.B.T.	226.08	220	0.043

Table 2. Composition chimique du ciment CEM II/ B-M 32.5 R

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Cl-
Weight (%)	55.8	19.7	6.2	3.9	2.2	0.33	0.70	2.6	0.07

Table 3. Mass percentages of cement and fibers

Components	CFTNaOH/C.F.B.T.					
Fibers content (%)	14	16	20	22	26	28
Cement content (%)	86	84	80	78	74	72

2.2. Sample preparation

This work uses both treated fibers (F.T.NaOH) and (F.B.T.). Their properties are listed in Table 1.

The chemical composition of the fibers was not given because no laboratory was available to carry out the chemical characterization.

The chemical composition of the cement used in this study is given in Table 2.

The concretes manufactured are composed of Portland cement CEMII/B-M 32.5 R supplied by the cement company Sococim Industries of Senegal and fibers from the baobab's trunk (Adansonia digitata L.). The ratio of water mass to cement mass is taken as 0.3. Table 3 shows each composite type's mass percentages of fibers and cement.

The fibers and cement were manually mixed in a 5 L capacity beater to achieve a homogeneous distribution of the fibers, and then the beater was inserted into an E095-type mixer. Mixing was maintained for 5 minutes, gradually adding the water necessary to hydrate the cement. The homogenized paste is then poured into 10 cm x 10 cm x 2 cm heat test molds. A Time-Tronic shaking machine was used to compact a total of 60 shakes. After 24 hours, the samples were removed from the molds, placed in plastic bags to even out the distribution of water, and kept under laboratory conditions for 28 days. Before conducting the thermo-physical measurements, the samples were dried in an oven at 105 °C for 24 hours.

An example of the concrete used for hygroscopic, physical and thermal characterization is presented in Figure 1.

Figure 1. Baobab trunk fibers concretes.

2.3. Characterization Methods

2.3.1. Water Absorption

First, the concretes were dried in an oven for 24 hours, and then their masses were weighed. Then, they were introduced into distilled water at room temperature.

By carrying out successive weighings, It is noted that, after 24 hours of immersion, the concretes reached their water saturation point (Δm≤0.01g). Finally, the masses at saturation were weighed.

The expression of the water absorption is:

$$\omega = \frac{m_h - m_o}{m_o} \, x \, 100 \quad (1)$$

m_h: Mass of concrete saturated with water.
m_o: Mass of concrete in a dry state.

2.3.2. Moisture Content

The concretes were kept in the atmospheric conductions of the laboratory for 24 h before being weighed (m_a) and placed in an oven at a temperature of 105 °C. 24 hours later, the drying was stopped when the last two measurements were very similar (Δm≤0.01g). The expression calculates the moisture content=$\frac{m_a - m_s}{m_a} \times 100$ (2)

m_s: Mass of concrete in a dry state.
m_a: Mass of the concrete in the ambient state.

2.3.3. Apparent Density and Porosity

- The bulk density is the ratio of the mass (m_o) to the bulk volume of the sample. The mass of the sample was weighed with a 0.01 g precision balance. The dimensions of the sample were measured with a caliper to calculate the apparent volume. The equation obtains the bulk density:

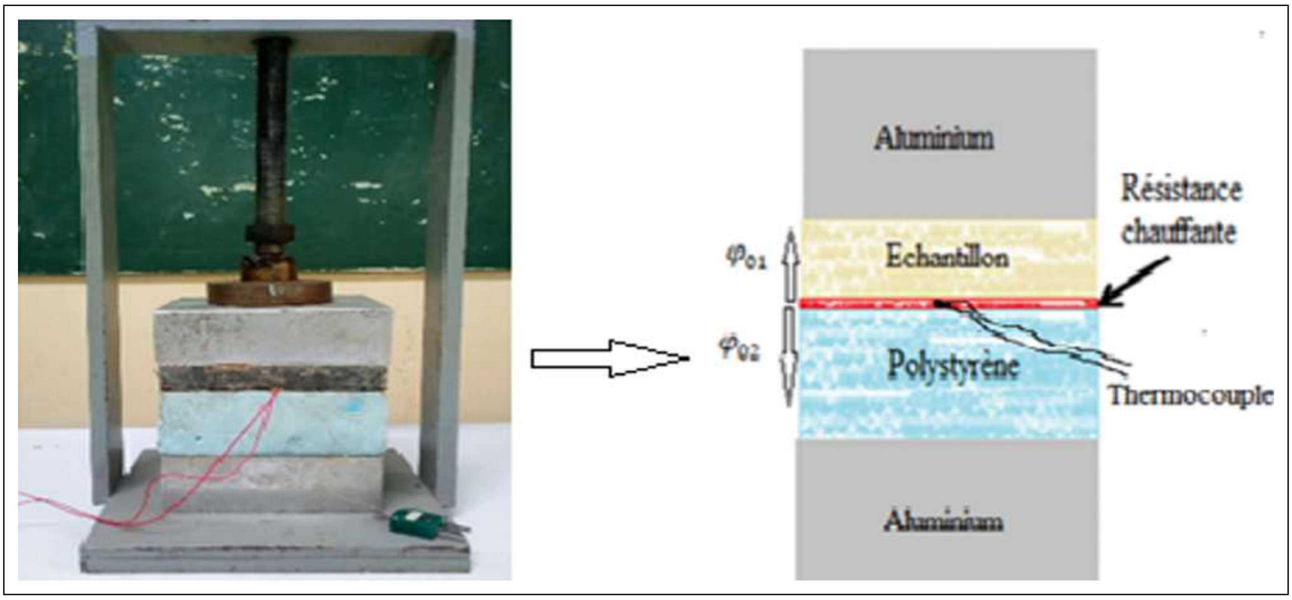

Figure 2. Asymmetrical hot-plane device.

Table 4. Thermal properties of polystyrene

e (m)	λ (Wm^{-1}.K^{-1})	E (J.K^{-1} .m^{-1} .s$^{-1/2}$)
0,015	0,035	43,226

$$\rho = \frac{m_0}{V} \quad (3)$$

- The water-accessible porosity is the ratio of the pore volume to the volume of the concrete. The pore volume is the difference between the mass of the water-saturated concrete (m_h) and the concrete in the dry state (m_o). The equation gives the porosity:

$$\eta = \frac{m_h - m_0}{\rho_e V} x100 \quad (4)$$

η: concrete porosity
V: Volume of the sample
ρ_e: Water density

2.3.4. Thermal Characterization

The thermal characterization consisted of the simultaneous determination of thermal conductivity and thermal effusivity using the asymmetric hot plane method at a constant sample backside temperature (Fig. 2).

The principle of this method and the modeling have been described in detail by Diéye et al. [19]. System modeling is based on two hypotheses: the heat transfer at the center of the sample is unidirectional (1D), and the temperature at the back of the sample is maintained constant. During measurement, the heating element applies a constant heat flow to one side of the 10 cm x 10 cm x 2 cm sample. A thermocouple placed in the center of the heating element records the evolution of the temperature Ts(t). The principle is to determine the values of the sample's thermal conductivity and thermal effusivity that minimize the squared deviation between the experimental and theoretical curves. The expression for the square deviation is:

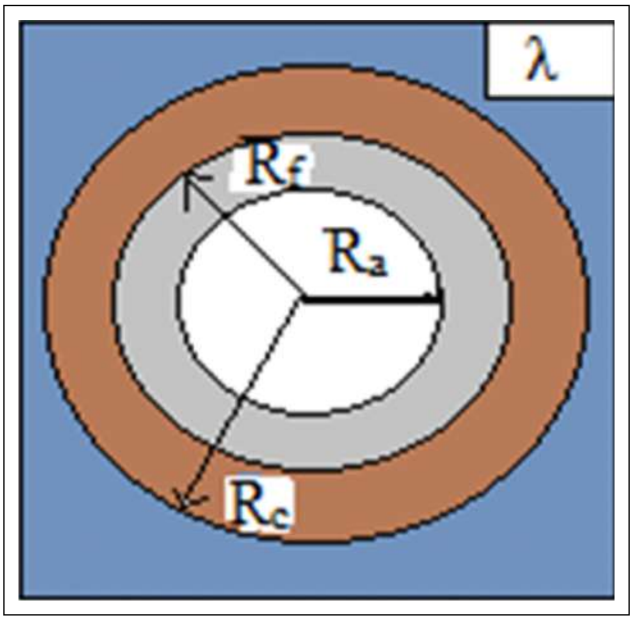

Figure 3. Three-phase homogenized medium.

$$\psi = \sum_i^n [T_{exp}(t_i) - T_{mod}(t_i)]^2$$

With:
ψ: The quadratic error between the experimental and theoretical values.
T_{exp}: Experimental temperature.
T_{mod}: Theoretical model temperature.

To test the validity of this method, an extruded polystyrene sample of known dimensions and thermal parameters was tested, and the results are presented in Table 4.

2.4. Thermal Conductivity Estimation by the Self-Consistent Method

This work used the three-phase model [20, 21] to determine the homogeneous medium's equivalent thermal con-

Table 5. Water absorption of composites

Fibers content (%)	14	16	20	22	26	28
Water absorption-CFBT (%)	34,25	35,56	35,82	36,57	43,84	50,79
Water absorption-CFTNaOH (%)	37,46	37,63	39,44	41,73	51,84	54,92

Table 6. Moisture content of concretes

Fibers content (%)	14	16	20	22	26	28
Moisture content - C.F.B.T. (%)	4,04	4,21	4,33	4,58	4,67	4,9
Moisture content - CFTNaOH (%)	4,28	4,37	4,48	4,66	4,7	4,95

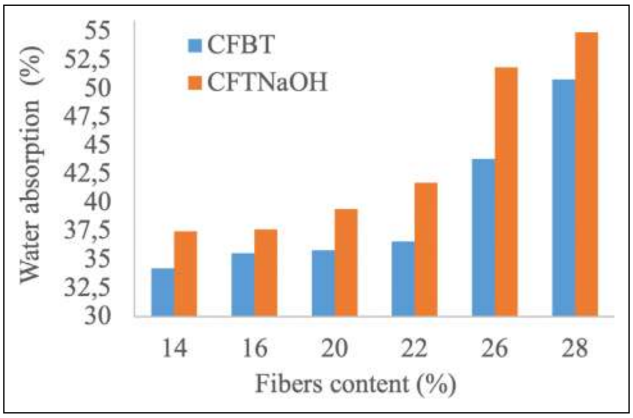

Figure 4. Water absorption as a function of fiber content.

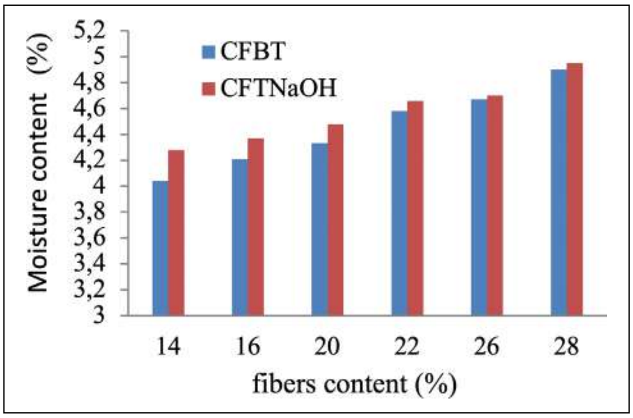

Figure 5. Moisture content as a function of fibers content.

ductivity (λ). The principle of the method is to assimilate a heterogeneous material to a homogeneous medium whose equivalent thermal conductivity is determined. The sample has assimilated an assembly of centrally located spherical air bubbles (Ra, λa), covered by a concentric spherical layer of fibers particles (Rf, λf), and the whole is covered by a cementitious matrix (Rc, λc) as illustrated in Figure 3.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Hygroscopic Characterization

3.1.1. Influence of Fibers Content and Treatment on Water Absorption

The results of water absorption at saturation of the concretes are given in Table 5.

Figure 4 shows the evolution of water absorption as a function of fiber content and type of treatment. It shows that the water absorption of concrete increases as the amount of fibers increases. Baobab trunk fibers have a high water absorption coefficient [17]. Incorporating these fibers in the cementitious matrix explains the increase in water absorption of concretes when the fiber content increases. A similar behavior was observed by Xie et al. [22] on concretes based on rice straw and bamboo fibers and Benmansour et al. [2] on date palm fiber concretes. It can also be seen that the type of treatment affects the water absorption. The water absorption of C.F.B.T. concretes is slightly higher than that of CFTNaOH concretes.

Indeed, it has been shown that the thermochemical treatment of fibers contributes better to reducing the water-soluble components responsible for the hydrophilic character of fibers [17]. This reduces the water absorption capacity of the fibers. This same behavior was observed by Abderraouf [4].

3.1.2. Influence of Fibers Content and Treatment on Moisture Content

The moisture content values of C.F.B.T. and CFTNaOH concretes are shown in Table 6.

Figure 5 shows that the concretes' moisture content increases when the fibers' mass fraction increases. This is because fibers comprise molecules with large amounts of free hydroxyl groups (-O.H.) and can bind water vapor [23]. It can be seen that the type of treatment also influences the moisture content. We noted that the C.F.B.T. concretes showed lower moisture contents than the CFTNaOH concretes (Fig. 5). This phenomenon can be explained by the fact that the thermochemical treatment leads better to the dissolution of lignin and hemicellulose. This makes the fibers less hydrophilic. This same behavior was also found by Sawsen et al. [24].

Although the water absorption and moisture content of the fibers have been reduced, it has to be recognized that the concretes studied are still highly sensitive to water. Therefore, for their use in buildings, they are either used for internal insulation in the form of panels or by applying a layer of waterproof plaster to the outside face when the concretes are used to fill the walls.

Table 7. Apparent densities and water-accessible porosity of concretes

Fibers content (%)	14	16	20	22	26	28
C.F.B.T.						
ρ (kg.m-3)	1122,50	1118,15	1107,40	1018,55	945,05	861,10
Porosity (%)	38,11	38,85	39,20	39,72	41,53	45,69
CFTNaOH						
ρ (kg.m-3)	1111,07	1090,50	1084,25	1027,95	920,00	859,50
Porosity (%)	39,69	40,00	41,53	42,32	46,40	47,79

Table 8. Thermal conductivity of C.F.B.T. concretes

Fibers content (%)	0	14	16	20	22	26	28
Thermal conductivity - C.F.B.T. (W/mK)	0,691	0,202	0,117	0.104	0,096	0,089	0,086
Thermal conductivity - CFTNaOH (W/mK)	0,691	0,188	0,112	0,105	0,091	0,085	0,083

3.2. Thermo-Physical Characterization

3.2.1. Influence of the Fiber Content on the Density

The values of the apparent densities and water-accessible porosity of the concrete (C.F.B.T. and CFTNaOH) are given in Table 7.

Figure 6 shows the density variation as a function of fiber content and type of fiber treatment. It is noted that the bulk density decreases as the fiber content increases. Adding plant fibers in a cementitious matrix increases the porosity of the fiber-reinforced concrete (Table 7). However, as the porosity of the concrete increases, the density decreases. This justifies the decrease in the density of concrete fibers. Potiron et al. [4] also observed the same behavior.

Figure 6 also shows that the treatment influences the bulk density of the concrete. It can be seen that the densities of C.F.B.T. concretes are slightly higher than those of CFTNaOH concretes. Some authors have shown that the treatment increases the density of the fibers Ghabo et al. [17], Asasutjarit et al. [25]. This justifies the importance of the density of C.F.B.T. concretes compared to CFTNaOH concretes.

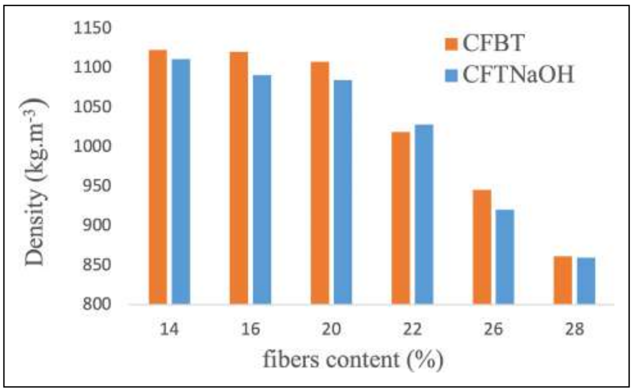

Figure 6. Density of concrete as a function of fiber content.

3.2.2. Influence of Fiber Content and Treatment on Thermal Conductivity

The values of the thermal conductivities of the studied concrete are given in Table 8.

The variation in thermal conductivity as a function of fiber content and type of treatment is shown in Figure 7.

Firstly, It can be noted that the thermal conductivity of the concrete decreases as the fiber content increases. Indeed, adding fibers to a cement matrix increases the porosity of the concrete. This contributes to the decrease of the thermal conductivity of the concrete when the fiber content increases. Other authors have observed similar behavior, Osseni et al. [8] and Benmansour et al. [2].

Secondly, it can be seen that the thermal conductivities of C.F.B.T. concretes are slightly higher than those of CFTNaOH concretes. The thermochemical treatment decreased the porosity of the fibers more than the chemical treatment Ghabo, et al. [17]. Thus, the incorporation of chemically treated fibers reduces the thermal conductivity of the concrete more. This justifies the superior thermal conductivity of C.F.B.T. concretes. Potiron et al. [4] have observed similar behavior in concretes based on sugarcane bagasse fibers.

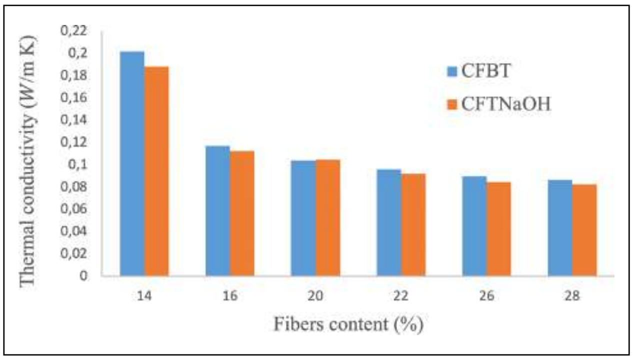

Figure 7. Thermal conductivity of C.F.B.T. and CFTNaOH as a function of fibers content type of treatment.

3.2.4. Influence of Bulk Density on Thermal Conductivity

Figure 8 and 9 show the evolution of the thermal conductivity as a function of the density of the concrete. It is noted that the thermal conductivity of concrete decreases as the density decreases. The addition of the fibers contributes,

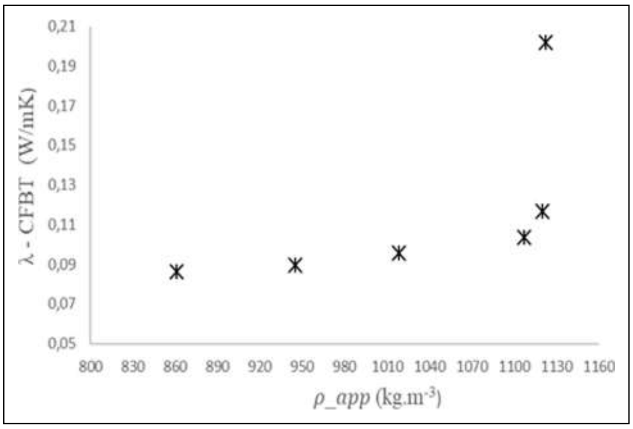

Figure 8. Thermal conductivity of CFBT concrete as a function of density.

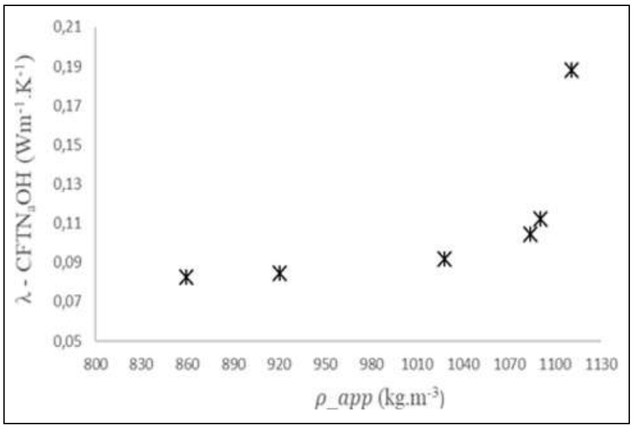

Figure 9. Thermal conductivity of CFTNaOH concrete as a function of density.

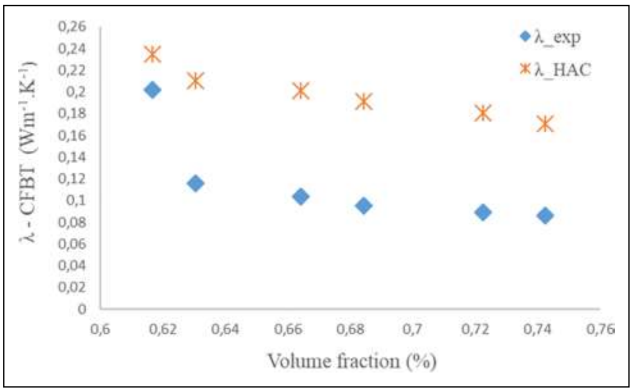

Figure 10. Thermal conductivity of C.F.B.T. concrete as a function of volume fraction.

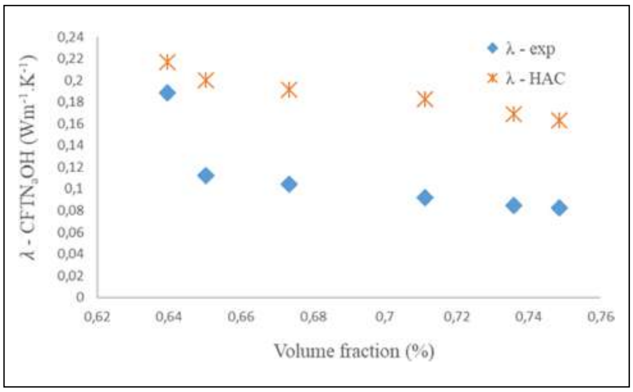

Figure 10. Thermal conductivity of CFTNaOH concretes as a function of volume fraction.

in one sense, to increase the porosity and, in the other sense, to reduce the density of the concrete. However, the increase in porosity leads to a decrease in density, which explains the reduction in thermal conductivity as a function of density.

3.2.5. Comparison of Theoretical and Experimental Results

The variations of the experimental and theoretical thermal conductivity as a function of the fibers' volume fraction are shown in Figure 10 and 11. It can be seen that as the volume fraction of the fibers increases, the difference between the experimental and theoretical values increases. The deviations obtained between the theoretical and experimental values are between 3.3% and 8.5% for C.B.T.F. concretes and 2.9% and 8% for C.F.T.NaOH concretes. This difference can be justified by several factors: the generic pattern of the tri-composite structure for which the three phases are arranged as concentric and continuous spheres and the shape of the inclusions, which should be spherical. In addition, the experimental measurements of the thermal conductivities of the fibers and the cementitious matrix would have measurement errors. Therefore, using these values to calculate the equivalent thermal conductivity could explain this difference. The self-consistent homogenization model has also been used by Cerezo [21] and Benazzouk et al. [26] to estimate the thermal conductivity of bio-based concretes.

4. CONCLUSION

This work focused on the effect of incorporating baobab trunk fibers on the thermo-physical and hygroscopic properties of concrete. The fibers were chemically and thermochemically treated to study the impact of their incorporation on the properties of concrete.

- The results obtained for the hygroscopic characterization showed that the thermo-physical treatment of the fibers contributes to reducing the moisture content and water absorption of the concretes studied.
- From a thermophysical point of view, it was noted that the incorporation of fibers resulted in a significant decrease in the thermal conductivity and density of the composites. For a fiber content of 20%, the thermal conductivity decreased by 58.64% and 58.72%, respectively, for the C.F.B.T. and C.F.T.NaOH composites compared to the control concrete.
- The theoretical results of the self-consistent method are similar to the experimental results with acceptable deviations.
- Regarding the thermal insulation of the building, both types of concrete studied showed good thermal insulation properties.
- Therefore, we propose the use of this material in construction to reduce energy consumption in the building sector.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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Research Article

Use of SCM in manufacturing the compressed brick for reducing embodied energy and carbon emission

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ABSTRACT

Brick is one of the most used building materials in masonry construction. Conventionally burnt clay bricks are used. These bricks are manufactured from clay and burnt in a kiln at a higher temperature. This results in a very high amount of CO_2 emission and has high embodied energy, which highly affects the environment. Compressed bricks are one of the sustainable solutions to overcome these issues of high CO_2 emission and embodied energy. Adopting sustainable alternatives, such as compressed bricks incorporating supplementary cementitious materials or environmentally friendly brick manufacturing processes, can help mitigate these issues and promote more sustainable construction practices. In this study, attempts have been made to manufacture and test the bricks with different proportions of the soil, i.e., the mix of locally available soil with sand, cement as the cementitious materials, and SCMs like fly ash & GGBS. The research methodology involves the formulation of different mixtures with varying proportions of SCMs. The specimens were then prepared using a compression molding technique and cured under controlled conditions. This research paper aims to investigate the effects of incorporating supplementary cementitious materials (SCMs) on the properties of compressed bricks. The study focuses on evaluating the density, compressive strength, water absorption, and efflorescence, as well as calculating the embodied energy and carbon dioxide emissions associated with the production of these bricks. Furthermore, the paper comprehensively analyzes the embodied energy and CO_2 emissions associated with producing compressed bricks. These calculations consider the energy consumed and CO_2 emitted in manufacturing, including raw material extraction, transportation, and brick fabrication. The study's results demonstrate the influence of SCMs on the properties of the compressed bricks. The analysis of embodied energy and CO_2 emissions provided valuable insights into the environmental sustainability of the brick production process.

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1. INTRODUCTION

"Brick" refers to a wide range of items made from clay mixed, prepared, and molded before being slowly dried and fired in an oven or kiln. Brick, the traditional material, is in rectangular shapes of baked clay and is used for many construction activities like building walls, pavements, canal lining, and many other masonry constructions. Brick is usually red or brown.

In India, the predominant construction method for buildings and houses involves cement blocks and burnt clay bricks due to their availability, affordability, and familiarity. However, this approach comes with several disadvantages. One significant drawback is its environmental impact. The production of these materials requires the extraction and processing of raw materials, resulting in substantial carbon dioxide emissions and contributing to climate change.

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Moreover, the depletion of natural resources poses environmental concerns—the high energy consumption associated with manufacturing cement blocks and burnt clay bricks. The kiln firing process for burnt clay bricks requires significant fuel, leading to increased energy demands and carbon emissions. However, exploring alternative construction materials that address these drawbacks can lead to greater sustainability in the long run.

In many nations experiencing significant economic growth, the requirement for brick clay is high, but it is valuable to farmers. It has become overly exploited, resulting in the devastation of agricultural areas. As a result, it is critical to identify alternate materials for replacing clay in bricks to minimize energy consumption caused by clay mining and the exploitation of non-renewable clay minerals. The construction sector has always been open to innovative research on materials [1, 2]. In brick manufacturing, research is being done on producing high-quality bricks using waste-based materials to replace clay as a viable strategy for developing environmentally friendly brick materials [3–6]. Concrete blocks, AAC blocks, and fly ash bricks have emerged as alternatives to traditional burnt clay bricks. But when compared to other construction materials, Compressed Stabilized Earth Blocks (CSEB) provide numerous benefits. It enhances the utilization of local resources, waste, and supplementary cementitious material (SCM), thereby reducing transportation costs. Additionally, constructing with local materials enables the employment of local individuals and fosters sustainability [7–9].

Embodied Energy is the total energy consumed by a product or system during its entire life cycle. The energy is considered comprised or 'embodied' in the product or system [10]. It includes all energy inputs necessary to extract, process, manufacture, transport, and dispose. By considering the energy used during the whole life cycle of a product or system, including the extraction of raw materials, manufacture, usage, and disposal, it offers a comprehensive view of the environmental effect of a given product or system. However, manufacturing bricks, mainly using conventional techniques, may significantly impact carbon dioxide (CO_2) emissions and contribute to environmental problems. The embodied energy of a fired clay brick is nearly 3.75–5.60 MJ/brick [7, 11] or 0.54–3.14 MJ/kg [12]. While the estimated CO_2 emissions for fired clay brick range from 97 - 526 gm/kg of fired brick [13, 14].

According to reports, global fly ash (FA) production is around 1.143 billion tons annually. It is typically utilized at an average rate of 60% [15], while in developing nations such as India, the utilization rate of approximately 50%–60% for fly ash (FA) has been reported [16]. According to reports, the yearly global production of GGBS is around 530 million tonnes [17]. Currently, 65% of that amount is recycled [18]. Previous research has demonstrated that clay-based bricks incorporating FA can have desired properties equivalent to their traditional clay-based counterparts [19, 20]. A recent study on the behavior of clay-based bricks containing GGBS showed that 60% of GGBS content can improve the mechanical and durability properties superior to clay-based bricks without GGBS [21]. A few authors also investigated the manufacturing of bricks by GGBS, which is waste from the iron and steel industry [22, 23]. A study discovered that the bricks produced from the mixture of slag, lime, and sand are of good quality and obtained good wet compressive strength in the range of 80-150 kg/cm^2 after 28 days at ambient temperature in humid curing conditions. The production of slag-based bricks utilizes less energy than traditional burnt bricks [22]. However, the replacement of clay with such SCM has been little investigated in clay-based bricks.

This study investigates the innovative concept of replacing clay with a mixture of GGBS and FA in conventional clay-based bricks. This study evaluates the feasibility of developing SCM-based bricks using appropriate proportions of FA and GGBS. Various tests were performed on the brick samples to determine their water absorption, bulk density, and compressive strength. This study also presents a detailed account of embodied energy and CO_2 emissions to produce and deliver the bricks.

2. MATERIALS AND METHODS

The methodology for the present study, including procurement & properties of all the materials, mixing proportions, production, and curing, is discussed in this section.

2.1. Materials

2.1.1. Soil

A locally available soil sample collected from Chekhla Village of Sanand Taluka, Ahmedabad, Gujarat, India, was used for the study. The natural moisture content of the soil was found to be 22.05%, and the specific gravity was found to be 2.64. The soil contained 16.6% clay fraction, 48.2% silt content, and 35.2% sand as per IS 2720-part IV [24]. The soil used in this study had a 28% liquid limit and a 15% Plastic limit as per IS 2720-part V [25].

2.1.2. Sand

The sand was procured from Sabarmati River, Mahudi, Gandhinagar, Gujarat, India, which conforms to Grading zone II as per IS: 383:1970 [26] having a specific gravity of 2.68, fineness modulus of 2.4, and bulk density of 1610 kg/m^3 was used.

2.1.3. Cement

The Ordinary Portland cement (OPC) used for this study was procured from Nuvoco Vistas Corp. Ltd., India. The specific gravity and surface area were 3.15 and 2410 cm^2/gm, respectively [27].

2.1.4. Fly Ash

Fly ash used for this study was classified as Class F, which was procured from a fly ash pond, Torrent power, Pethapur, Gandhinagar, Gujarat, India. It has a light grey color and specific gravity of 2.3, conforming to IS 3812-2013 [28]. The chemical composition of fly ash provided by Torrent power is shown in Table 1.

Table 1. Chemical composition of fly ash

Sr. No.	Details	Test results	Requirement as per IS: 3812–2013 [28]
1	Specific surface area	416.4 m^2/kg	>200 m^2/kg
2	Loss of ignition	1.10%	<7.0% by mass
3	SiO_2+Al_2O_3+Fe_2O_3	93.00%	>70.00% by mass
4	SiO_2	61.40%	>35.00% by mass
5	Reactive silica	34.70%	>20.00% by mass
6	MgO	1.40%	<5.0% by mass
7	Na_2O	0.60%	<1.5% by mass
8	Retention on 45 μ sieve	21.10%	<50.0% by mass

Table 2. Chemical composition of GGBS

Sr. No.	Details	Test results	Requirement as per IS: 16714–2018 [29]
1	Specific surface area	364 m^2/kg	>275 m^2/kg
2	Loss of ignition	0.60%	<3.0% by mass
3	Magnesium oxide (MgO)	6.07%	<17.00%
4	Manganese oxide (MnO)	0.32%	<5.50%
5	Sulphide sulphur	0.57%	<2.0%
6	Sulphate (as SO3)	0.29%	<3.0%
7	Insoluble residue (IR)	0.21%	<3.0%
8	Chloride content (CI)	0.008%	<0.1%
9	Glass content	92.50%	>85.00%
10	Retention on 45 μ sieve	11.00%	--

2.1.5. GGBS

GGBS used for this study was collected from Suyog Elements India Pvt. Ltd., Bharuch, Gujarat, India. It was white and had a specific gravity of 2.89. The chemical composition of GGBS provided by the firm conforming to IS 16714 – 2018 [29] is shown in Table 2.

2.2. Mix Proportions

The mix adopted for manufacturing bricks was 3:3:1 (Sand: Clay: SCM), and SCM included FA, GGBS, and cement. The proportion of sand and clay used in the mix was taken as given in IS 1725: 2013, and it has been shown that the content of clay should be 5% to 18%, silt content should be 10% to 40%, and sand content should be 50% to 80%. The different SCM mixes considered for the present study are given in Table 3. In all mixtures, the total weight of SCM content was kept constant. The brick with mix label M0 is considered a reference mix to compare all other mixes. In mix label M0 (3:3:1), the amount of soil and sand was kept equal, i.e., 12kg, and instead of using fly ash and GGBS, only cement was used, which has a proportion of 4 kg.

Table 3. Proportions of dry mix

Mix label	Mix proportions (kg)				
	Soil	Sand	Fly ash	GGBS	Cement
M0	12	12	0	0	4
M1	12	12	3	0	1
SM2	12	12	0	3	1
M3	12	12	1.5	1.5	1
M4	12	12	1.75	1.75	0.5
M5	12	12	3.5	0	0.5
M6	12	12	0	3.5	0.5
M7	12	12	2	2	0

2.3. Manufacturing of Bricks

In the present investigation, rectangular brick specimens of 230 mm x 105 mm cross-section with a height of 70 mm were produced using a hydraulic brick-making machine. The mix adopted for brick manufacturing was 3:3:1 (Sand: Soil: SCM) with SCM of different proportions, as shown in Table 3. A total of 8 different ratios were produced, and 15 bricks were manufactured for each proportion. Firstly, the soil and sand were mixed in the dry state in the mixer for 5 minutes. Then, FA, GGBS, and cement were added during mixing and continued for 5 minutes. One liter of water was added into the mix consisting of 12 kg of soil, 12 kg of sand, and 4 kg of cement or SCM. Subse-

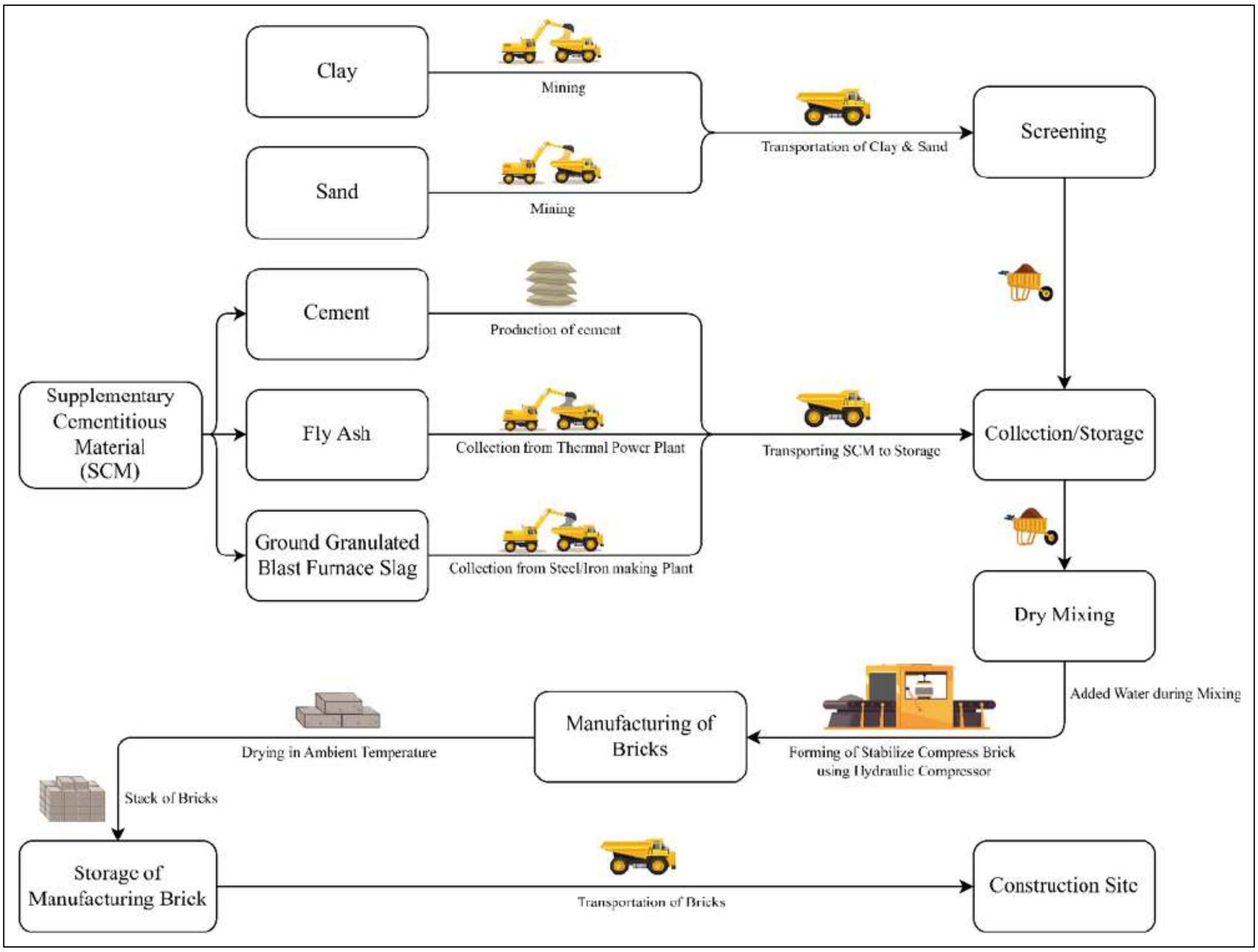

Figure 1. Flowchart for manufacturing of brick.

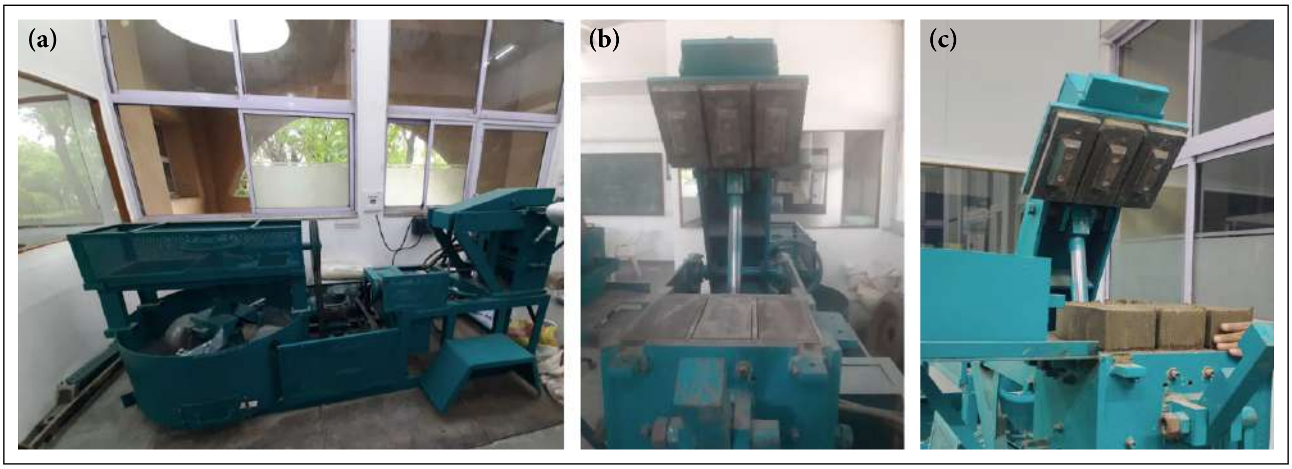

Figure 2. **(a)** Hydraulic brick-making machine. **(a)** Hydraulic compressor. **(c)** Production of brick.

quently, the mixing continued for another 5 minutes. Water was then added, and the blending was for another 5 minutes. The fresh mixture of all these materials was poured into the brick mold of a hydraulic brick-making machine. The freshly poured mixture was hydraulically stressed from above and below so that the height of the brick sample was obtained as required. After demoulding the brick samples, they were transferred for curing purposes. The whole process of manufacturing brick is illustrated in Figure 1. A hydraulic brick-making machine was used to produce brick, and the raw material and water were mixed and compressed in this machine, as shown in Figure 2a–c.

2.4. Curing

The consistency of water content remained uniform across all brick mixes. After demoulding, the brick

Table 4. Properties of bricks with different proportions

Name of test	Mix label							
	M0	M1	M2	M3	M4	M5	M6	M7
Density (kg/m³)	1804	1775	1769	1769	1781	1757	1763	1727
Compressive strength (MPa) - B	4.23	3.57	3.50	3.60	4.21	3.61	3.56	3.77
Water absorption (%)	5.59	6.71	6.40	6.73	6.35	7.46	7.43	7.24
Efflorescence	No	No	No	No	No	No	No	No

Table 5. Dimension tolerance test results

Dimensions	Mix label								Limits as per IS 1725:2013	Remarks
	M0	M1	M2	M3	M4	M5	M6	M7		
Length	4599	4598	4600	4598	4601	4600	4599	4600	4520 mm to 4680 mm	Within the limit
Width	2098	2099	2100	2099	2099	2100	2098	2099	2160 mm to 2240 mm	Within the limit
Height	1403	1394	1402	1401	1400	1401	1396	1401	1360 mm to 1440 mm	Within the limit

samples were kept for drying at a controlled temperature of 27°C±1°C for one day. Then, the brick samples were cured at an ambient temperature of 22°C–24°C for 28 days.

3. RESULTS AND DISCUSSION

The comprehensive test outcomes are detailed in Table 4. It delineates the properties of the bricks, encompassing density, dimensional tolerance, compressive strength, water absorption, and efflorescence.

3.1. Density

Brick density is significant since it affects the material's durability and strength. It directly affects the structural stability and weight of a structure. While ensuring stability and efficiency in construction, the optimal brick density impacts significant parts of a building's operation. The details regarding the density of bricks are illustrated in Figure 3. Analysis of the test outcomes indicates a consistent density range between 1757–1781 kg/m³ for bricks incorporating FA, GGBS, and cement. Notably, this range exceeds the minimum density requirement of 1750 kg/m³ as outlined in the IS 1725: 2013 standard [30].

3.2. Dimensional Tolerance

Brick dimensional tolerance is essential for guaranteeing consistency and accuracy in building. It ensures that bricks follow prescribed size variations, making precise alignment and assembly easier while constructing. Accurate dimensional tolerance helps preserve structural integrity and aesthetic appearance by preventing wall thickness and alignment variations. Table 5 provides a comprehensive overview of the results of the dimensional tolerance of 20 bricks. However, every brick satisfies the requirements listed in IS 1725: 2013 [30].

3.3. Compressive Strength

The compressive strength of bricks is crucial as it signifies their ability to withstand significant loads without deformation or failure. It determines the capacity of brick to bear vertical loads, ensuring structural stability in buildings and other constructions. A higher compressive strength indicates resilience against external forces, ensuring durability and safety in various structures. The compressive strength test of brick was performed on a universal testing machine shown in Figure 4. The compressive strength of bricks for all eight mixes is shown in Figure 5. This assessment was conducted after a 28-day curing period. The reference mix, M0, exhibited a compressive strength of 4.23 MPa. Across all eight mixtures tested, the compressive strength ranged from 3.50 to 4.21 MPa. Notably, the compressive strength of all mixes surpasses the minimum requirement specified for Class 3.5, as outlined in IS 1725: 2013, ensuring compliance with these standards [30].

3.4. Water Absorption

The average value of water absorption for the individual mix is shown in Figure. 6. Notably, the reference mix, M0, demonstrated the lowest water absorption at 5.59%. In contrast, the remaining mixes exhibited a water absorption range between 6.35% and 7.46%. These values comply with the stipulated IS 1725: 2013 standard, which specifies that water absorption should not surpass 20% of the brick's weight. Additionally, it's worth noting that no efflorescence was observed on the surface of any of the bricks.

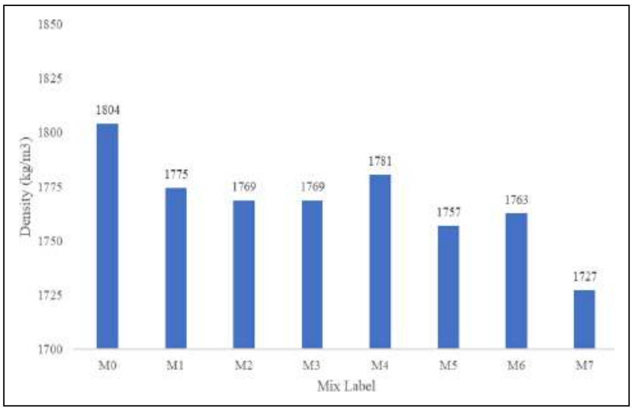

Figure 3. Density.

Figure 4. Universal testing machine.

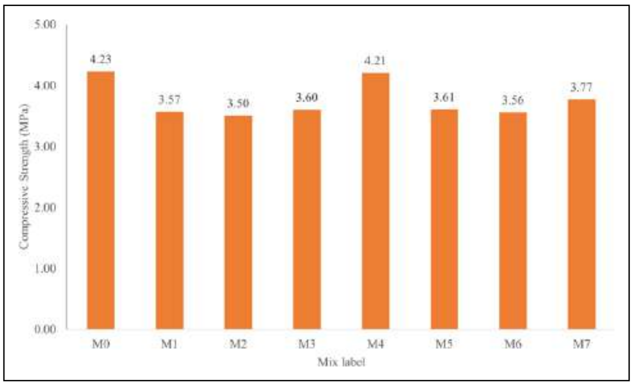

Figure 5. Compressive strength.

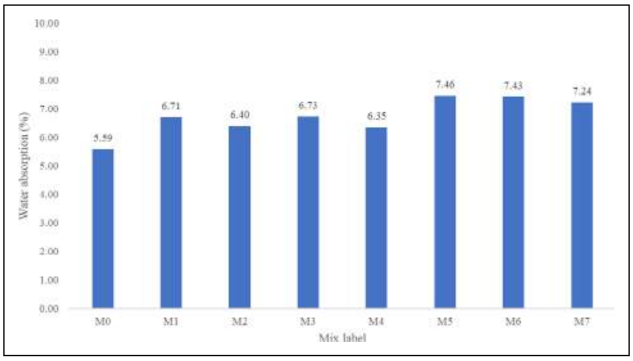

Figure 6. Water absorption.

3.5. Embodied Energy

The energy used for excavation and transportation of raw materials is determined using the gathered field data. The field data of all raw materials, i.e., soil, sand, GGBS, fly ash, and cement, are assessed based on travel distance, time, capacity, and primary energy use. This work's sustainability aspects are limited to energy use and emissions. The calculation of energy use per unit amount of excavation and transportation demonstrates the influence of technological and operational parameters. Several data have been considered for calculating embodied energy regarding the raw material, equipment, and transportation of brick.

The lorry transports a volume of 10 m^3 in a single trip. The actual distance was considered for the transportation of the raw materials. The fuel consumption for the excavation of soil and sand was considered as per field data, which was about 0.35 lire per 1 m^3 excavation [31]. The fuel consumption of a lorry for transporting materials was 5 km per 1 liter of fuel [31], and for energy calculation, both the trips (up trip and down trip) are considered. For all the activities of excavation and transportation, diesel was used as fuel, and it has an energy of 8.7 MJ per 1 liter of diesel [31]. The embodied energy is 3.6 MJ for 1 kg of cement production [31]. The brick-making machine was used to mix the raw materials and compress the brick; it consumes 7.5 kW. The capacity per day of the brick-making machine was 1000 bricks, for which working time was 10 hours per day. The amount of coal used is 0.7 kg for producing 1kWh of electricity, and coal has embodied energy of 20 MJ per 1 kg [31].

The calculated embodied energy for the production, excavation, and transportation of different raw materials, brick-making equipment, and transportation of bricks are enlisted in Table 6.

3.6. Carbon Dioxide Emissions

The CO_2 emission during excavation and transportation of raw materials is determined. Moreover, CO_2 emission during manufacturing and transporting bricks

Table 6. Calculated embodied energy for production and transportation

	Energy (MJ/Cu. m.)	
	Production	Transportation
Raw materials		
Soil	13.55	46.44
Sand	13.55	77.40
GGBS	–	928.80
Fly ash	–	46.44
Cement	5142.86	47.39
Manufacturing process		
Mixing & Compression	525	–
Transportation of bricks	–	77.40

Table 7. Calculated CO_2 emission for production and transportation

	CO_2 Emission (kg/Cu. m.)	
	Production	Transportation
Raw materials		
Soil	0.89	3.05
Sand	0.89	5.08
GGBS	-	60.96
Fly ash	-	3.05
Cement	1142.86	3.11
Manufacturing process		
Mixing & Compression	51.45	–
Transportation of bricks		
Bricks	–	5.08

Table 8. Comparison of various properties of different mixes

Mix label	Compressive strength (MPa)	Water absorption (%)	Embodied energy (MJ/Cu. m.)	CO_2 emissio (kg/Cu. m.)
M0	4.23	5.59	806.15	167.96
M1	3.57	6.71	255.03	45.50
M2	3.50	6.40	283.22	47.35
M3	3.60	6.73	269.12	46.42
M4	4.21	6.35	179.62	26.17
M5	3.61	7.46	163.17	25.09
M6	3.56	7.43	196.07	27.25
M7	3.77	7.24	90.12	5.91

is also determined. The data for all raw materials, i.e., soil, sand, GGBS, fly ash, and cement, during the manufacturing transportation of brick, is assessed based on travel distance, time, and capacity.

As explained earlier, the data for CO_2 emission is the same as embodied energy. Some changed data is also considered; diesel produces 2.54 kg CO_2 per liter [31]. The CO_2 emission was 0.8 kg for 1 kg of cement production [31]. The coal has produced CO_2 of 1.96 kg per 1 kg coal [31]. The calculation of CO_2 emission for the output, excavation, and transportation of different raw materials, brick-making equipment, and transportation of bricks are enlisted in Table 7.

3.7. Comparison

Different mixes are employed in manufacturing bricks, each offering unique properties and characteristics. These mixes are carefully formulated to ensure optimal brick quality and performance. A comprehensive analysis of various brick mixes reveals a range of distinctive properties. The identified properties have been enlisted in Table 8, allowing for easy comparison and informed decision-making in brick manufacturing processes. The embodied energy and calculated CO_2 emission for different raw materials, processing, and transportation computed for the bricks manufactured for different mixes are tabulated in Table 8. The calculation for embodied energy and CO_2 emission is calculated for 1 Cu. m. which approximates 500 nos. of bricks.

These properties include compressive strength, water absorption, embodied energy, and CO_2 emission. After comparing all the data, mix M7 shows a reduction in embodied energy by 88.82% and a reduction in CO_2 emission by 96.48%. Also, it was found that the compressive strength of all mixes satisfies the minimum compressive strength specified for Class 3.5 designated as per IS 1725: 2013 [30]; hence, it can be used for structural members.

4. CONCLUSIONS

The investigation was conceived to adopt a sustainable alternative to the conventional bricks, attempting to reduce the Embodied energy and CO_2 emissions. Based on the experimental studies conducted to evaluate the optimal mix for manufacturing bricks using fly ash (FA), ground granulated blast furnace slag (GGBS), and cement, the following significant conclusions have been drawn:

- All the stabilized compressed earth brick samples with different mixes meet the criteria for density, dimensional tolerance, compressive strength, and water absorption. This indicates that these mixes are suitable for brick production and exhibit satisfactory performance in essential properties.
- Mix M7 demonstrates the lowest embodied energy, measuring 90.12 MJ/m^3 among the various tested mixes. This value is 88.82% lower than the reference mix (M0), with the highest embodied energy of 806.15 MJ/m^3. The significantly lower embodied energy of Mix M7 signifies its superior sustainability in terms of energy consumption during the production process.
- Mix M7, which does not contain cement, exhibits the lowest CO_2 emissions of 5.91 kg/m^3. This value is 96.48% lower than the reference mix (M0), with the highest CO_2 emissions of 167.96 kg/m^3. The substantial reduction in CO_2 emissions achieved by Mix M7 highlights its superior environmental performance, contributing to lower carbon dioxide emissions during brick production.

In summary, the experimental study reveals that the stabilized compressed earth brick mixes, including the recommended Mix M7, i.e., without the use of cement and using only SCMs, meet the required standards for essential properties such as density, dimensional tolerance, compressive strength, and water absorption. Furthermore, Mix M7 stands out as a more sustainable option due to its significantly lower embodied energy and CO_2 emissions than the reference mix. These findings underscore the importance of alternative mixes using fly ash, ground granulated blast furnace slag, and reduced cement content to promote environmentally friendly and energy-efficient brick manufacturing practices.

Furthermore, with a comprehensive understanding of the environmental impact, future research should consider conducting a comparative analysis of additional parameters such as water usage, waste generation, and potential pollutants associated with different brick mixes.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

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Research Article

A comparative study on the use of waste brick and glass in cement mortars and their effects on strength properties

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ABSTRACT

Sustainable development of the construction industry should use recycled materials to the greatest extent to reduce natural hazards due to the increased accumulation of waste and the depletion of natural resources. However, engineering applications using waste materials are always expected to perform satisfactorily. In this aspect, detailed and systematically carried out experimental studies are critical in selecting the type and the quantities of waste materials that will be recycled through their use within engineering applications. This study provides systematically produced experimental data on compressive and flexural strength performance to quantitatively compare the effects of using different percentages of waste glass and brick aggregates in cement mortars with a specified workability characteristic. Results show that mortar samples with waste glass aggregates perform better under compressive loading since only around 14% strength decrease compared to the control mix was yielded with the inclusion of waste glass. In contrast, in both cases, a 30% strength decrease was recorded with the inclusion of waste bricks for 100% replacement of natural sand in the mortars. In the case of flexural strength performance, 50% replacements of natural aggregates with waste bricks and glass yielded around 27% and 38% strength decrease, indicating that using waste brick in cement mortars could result in a better flexural strength performance in comparison, provided that its content is controlled. Replacement of natural sand in cement mortars with waste brick and glass yielded less significant flexural strength, decreasing the difference between the two types of wastes when the replacement ratio was as high as 100%. Hence, based on the presented experimental evidence, it is concluded that the decision on the type and the quantity of the waste materials to be used should be made considering the area of the use of the mortar and its expected service type.

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1. INTRODUCTION

Concrete is undoubtedly one of the most popular construction materials used all around the globe. The fact that 75% of the volume of concrete is composed of aggregates brings two important issues. Firstly, and in the civil engineering aspect, the quality and performance of concrete constructions would be highly affected by the characteristics of the aggregates used within, considering the volume they occupy in the mix [1]. Secondly, and globally, using

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natural (i.e., quarried) aggregates for manufacturing billions of tons of concrete would accelerate the depletion of natural sources of aggregates on planet Earth while posing threats to nature in most cases. Several aggregate quarries on the Beşparmak (Pentadaktylos) Mountains in North Cyprus that are unfortunately mismanaged are observed to cause loss of sources loss of vegetational and animal life in their surroundings, as seen in Figure 1. Another environmental hazard that has been building up simultaneously is the increased quantities of waste generation caused by the needs of modern life when societies do not adopt the concept of sustainability. Engineers and scientists have proposed using waste materials as a replacement for natural aggregates in concrete in the last decades to reduce the two aforementioned environmental hazards, and the published works in the literature yielded promising results for this approach [2–6]. Similar to concrete, cement mortars are also consumed in constructions in huge quantities, mainly for all kinds of repair and maintenance works as well as in masonry works and so forth [7]. Additionally, since the main difference between mortar and concrete is the size of the aggregates used within them, cement mortars are also widely used in civil engineering research studies due to being accepted as highly indicative of concrete's performance and behavior. Hence, the use of waste materials to replace fine aggregates in cement mortars is also of concern.

Regarding the use of waste materials as a replacement for natural (i.e., quarried) fine aggregates in cement mortars, several interesting previous works have been considered. Among these, Bektas et al. [8] propose using crushed waste brick as a replacement for natural sand in mortars and report that the highly porous nature of brick aggregates affects the properties of fabricated mortar bars. This property of brick aggregates has been reported to yield increased water absorption for the mortars. Another noteworthy observation reported by this study was that the compressive strength of the mortars containing waste bricks was not negatively affected up to a limit of 20% (by mass) replacement of natural aggregates [8]. Zhu and Zhu (2020) [9] also report that the porous nature of waste brick aggregates caused increased water absorption and reduced compressive strength of cement mortar samples when added beyond specific contents. However, the surface texture of these waste aggregates has been reported to yield higher splitting tensile strength [9].

Another interesting study was presented by Tan and Du [10], which proposes using crushed waste glass as a replacement for natural sand in cement mortars. This interesting study reports that waste glass aggregates have smooth surface texture, and this characteristic yields weaker bonds between the waste aggregate and the cement paste, eventually yielding a decrease in the tensile strength of the mortar samples. Lu and Poon [11] also reports similar finding on the use of waste glass as a replacement for natural sand in cement mortars, stating that increased contents of glass aggregates yielded decreased tensile strength of mortars due to the smooth texture of this type of waste aggregates. Another noteworthy performance information provided by this study indicates that glass aggregates have very low absorption characteristics. Hence, they do not negatively affect the workability of fresh cement mortar mixes [11].

Figure 1. A view of the damaged nature due to aggregate quarries on Beşparmak (Pentadaktylos) Mountains, North Cyprus.

Table 1. The mortar mixes used and their waste types and contents

Mix name	Natural aggregate (NA)	Recycled brick aggregate (RBA)	Recycled glass aggregate (RGA)
Mix 1 (control set)	100%	0	0
Mix 2a	50%	50%	0
Mix 2b	0	100%	0
Mix 3a	50%	0	50%
Mix 3b	0	0	100%

These noteworthy and interesting research studies provide insights into some characteristics of mortar bars produced using mentioned waste aggregates. However, each study is observed to have an independent experimental campaign design, and hence, it becomes difficult to relate and compare their findings for engineering applications. Therefore, the related literature has detected *a lack of systematical and comparable experimental information* on cement mortars' fresh and hardened properties specifically made with waste glass and bricks. Therefore, the main objective of this study is to provide experimental data to investigate the performance of cement mortars having specified workability characteristics that are produced with recycled glass aggregates (RGA) and recycled brick aggregates (RBA) that were used as replacements for natural (i.e., quarried) sand. In this way, the suitability and the advantages of using waste glass and waste bricks in cement mortars could be directly compared based on the obtained experimental results, yielding potentially beneficial insights for practical applications in the construction sector aiming to contribute to the sustainable development of societies.

2. MATERIALS AND METHODS

Five different mortar mixtures, including 0%, 50%, and 100% waste brick and glass used as replacements (by weight) for natural aggregates, were used in this study, as presented in Table 1.

Figure 2. **(a)** Natural fine aggregates. **(b)** Crushed waste bricks. **(c)** Crushed waste glass.

Table 2. Quantities of materials used in the manufacture of each cement mortar mix

Aggregate particle size	Water (kg/m³)	Cement (kg/m³)	Natural (quarried) fine aggregates (kg/m³)				Waste fine aggregates (waste bricks /waste glass) (kg/m³)			
			0.15 mm	0.3 mm	0.6 mm	1.18 mm	0.15 mm	0.3 mm	0.6 mm	1.18 mm
Mix 1 (control set)	367	611	122	244	367	489	0	0	0	0
Mix 2a (50% waste brick aggregates)	530	726	47	93	142	189	47	93	142	189
Mix 2b (100% waste brick aggregates)	541	721	0	0	0	0	94	187	281	375
Mix 3a (50% waste glass aggregates)	392	603	60	121	181	241	60	121	181	241
Mix 3b (100% waste glass aggregates)	367	611	0	0	0	0	122	244	367	489

Indeed, the workability of a cement mortar mixture is one of its most essential characteristics since it directly affects the practical applications of the mortar on the construction site. A mortar that is not satisfactorily workable is generally not preferred to be used on the site. Its rather difficult application might also affect its proper placement and final strength properties if used. Results of the literature survey showed that 35 35-second flow duration is accepted as an efficient flow according to ASTM-C939, and it also indicates that the efflux time for pure water is 8 seconds. Consequently, the optimum efflux time for cement mortar is between 8 seconds and 35 seconds, where higher efflux time means lower flowability and workability [12]. Also, results of the previous work [13] forming the basis for this study showed that cement mortars having 35 seconds of flow according to ASTM C939 yielded a slump interval of 260–270 mm with Abrams cone according to ASTM C143 procedure [14]. Hence, this slump interval of 260–270 mm was selected as the specified workability range for all mortar mixes, and with several trial batches, the quantity of water to be added to each mix was determined to yield this specified slump value [15].

CEM I 42,5 R cement conforming EN 197-1 [16], having a reported specific gravity value of 3.15 g/cm³ was used for all mortar mixes in this study. Natural aggregates were obtained from the active quarries in the Beşparmak (Pentadaktylos) Mountains of Cyprus, where this study was carried out. Waste bricks and glasses used in this study were wastes collected from nature from North Cyprus. The experimental results presented in this study are a fraction of a broader experimental campaign carried out within the same institution. The gravities of waste bricks and glasses obtained from varying sources used in the experimental campaign ranged between 1.95–2.25 for waste bricks and 2.40–2.53 for waste glass used in the mixes. The natural (i.e., quarried) sand used in this study had a specific gravity of 2.64, which the supplier company reported.

After being collected and cleaned from other impurities, waste bricks and glass were crushed in the laboratory and sieved following the EN 933-1 (2012) procedure [17]. For all types of aggregates, the gradation of particles was maintained between the upper and lower content limits defined for the 0.15 mm–1.18 mm size range, following the specifications described in BS 882:1992 [18]. Figure 2a–c illustrate the natural and the recycled (i.e., waste) fine aggregates used in this study.

Table 2 summarizes the exact quantities of all materials used for this study's five distinct mortar mixes. The mixing procedure for all mortar mixes was conforming EN 00196-1–2005, with all mentioned ingredient contents [19].

Once the fresh mortar is placed on the site and it sets and hardens, its performance is determined according to its behavior and response under loading. The compressive strength behavior of concrete is typically regarded as the most critical indicator of its quality [20–22], which is known to be the case for cement mortars. In addition to

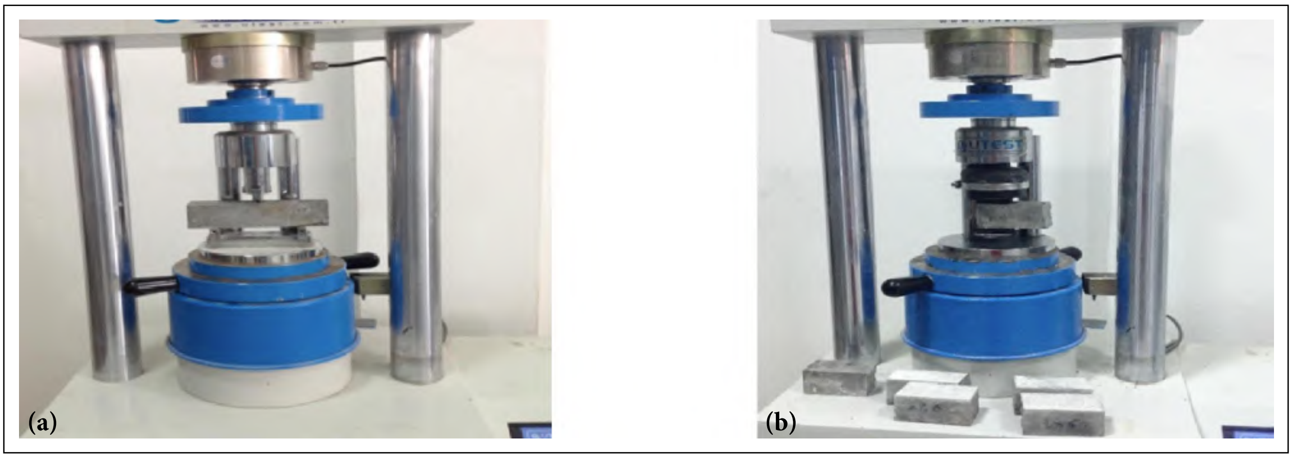

Figure 3. **(a)** Flexural strength testing on mortar prisms. **(b)** Compressive strength testing on halved prisms.

compressive strength, flexural strength behavior will also determine how the mortars would carry on with their service functions since flexural or bending actions could also act frequently on them depending on their service locations on the site. Hence, this study considers compressive and flexural strength testing to observe the efficiency of using waste glass and bricks in cement mortars concerning their hardened-state performance.

Six mortar bars having 40 mm x 40 mm x 160 mm dimensions were produced for each mortar mix. Samples were cast and compacted following the EN 196-1:2005 standard procedure and cured until the testing age [19]. Three of these six bars of each mix were tested at seven days to observe the early strength behavior of the bars, while the remaining 3 bars of each mix were tested at the age of 28 days.

Mortar bars were initially tested under flexural loading, and then, when the bar failed under flexure, the two halves obtained were tested under compressive loading, conforming EN 196-1:2005 part 1 [23]. Figure 3 a and b shows the mortar bars' Flexural and Compressive strength testing.

3. RESULTS AND DISCUSSIONS

The objective of this research study was to provide directly comparable experimental data for the strength behavior of waste brick and glass, including cement mortars that were produced to perform within the same workability range. For this purpose, trial mortar bars, including each specified waste type and content, were fabricated with different water additions, and the water/cement ratio that provided the specified slump range of 260 mm–270 mm was recorded.

Table 3 shows the determined w/c ratios for each type of mortar mix that yielded the targeted slump range.

It was observed that the use of waste glass as a replacement for natural sand in the mortar mix has not caused any significant increase in the water demand of the mix. Similar findings are also reported in the related literature, and this observed behavior was attributed to the non-porous nature of glass, which yielded deficient water absorption [11].

Table 3. Water/cement ratios yield the targeted workability range and the slump values obtained for each mortar mix

Mix	w/c ratio yielding targeted slump range	Obtained exact slump values (mm)
1	0.6	268
2a	0.73	269
2b	0.75	264
3a	0.65	266
3b	0.60	263

The control set (i.e., Mix 1) and waste glass-containing mixes (i.e., Mix 3 a & b) were observed to yield the targeted slump within a w/c ratio range of 0.6–0.65. On the other hand, the mixes made with waste bricks (i.e., Mix 2 a & b) were observed to have higher water demand; the w/c was determined to be 0.75 as the ratio needed to yield the targeted slump, which is 25% higher compared to the w/c of the control mix (i.e., Mix 1). The increase in the water demand of waste brick-containing mortar mixes observed in this study is expected to be due to the relatively porous texture of bricks compared to the texture of waste glass. A similar observation was reported by investigations of the characteristics of fresh mortars, including up to 20% brick replacement [24]. This study also showed that the presence of waste brick in mortar decreased the mix's slump, as noted in this study. Bektas et al. [8] and Zhu and Zhu [9] also report and confirm that the porous nature of the waste brick aggregates yielded adverse effects on the water demand and the workability characteristics of cement mortars.

3.1. Compressive Strength Test Results

Table 4 demonstrates the compressive strength values determined by testing each mortar mix and the strength decrease tendencies observed in each mix compared to control set samples containing no waste aggregates. Figure 4 illustrates the compressive strength development of all mortar mixes until 28 days. Errors bars are equivalent to one standard deviation.

Table 4. Compressive strength test results for each mortar mix used in this study

	w/c ratio	Compressive strength (MPa) 7 days	Compressive strength decrease compared to Mix 1 (7 days) Average	Compressive strength (MPa) 28 days	Compressive strength decrease compared to Mix 1 (28 days) Average
Mix 1	0.60	35.0	0%	42.0	0%
Mix 2a	0.75	31.0	11.43%	36.0	14.29%
Mix 2b	0.73	23.3	33.43%	29.3	30.24%
Mix 3a	0.60	29.3	16.29%	35.4	15.71%
Mix 3b	0.65	28.9	17.43%	36.2	13.81%

The control set (i.e., Mix 1, having only natural aggregates) is observed to yield the highest compressive strength at both seven days and 28 days. Hence, adding any of these waste materials as a replacement for natural sand was observed to cause a reduction in the overall compressive strength of the samples. For all mixes, the compressive strength was observed to have an increasing tendency with the increasing testing age, which is expected to be due to the ongoing hydration of cement in the mixes. Mix 2a and 2b, which are the samples containing 50% and 100% waste brick aggregates, were observed to have up to a 19% strength decrease between each other (when waste brick content was increased) and up to a 30% strength decrease when compared to the control set, at the age of 28 days. The w/c ratio required to yield the targeted slump was observed to have only a 2% difference between the two mixes having brick waste aggregates. Parallel findings are also reported in the related literature. Bektas et al. [8] and Zhu and Zhu [9] reported reduced compressive strength values for cement mortar samples when waste brick aggregates were added beyond certain contents defined their experimental campaigns, and both studies attributed this observed performance change to the porous nature of waste brick aggregates.

Further studies also reported that increasing the addition of waste brick in the mortar decreased the compressive strength of the cement mortars. It is also reported that the increasing addition of waste brick in the mortar decreased the compressive strength of the cement mortars. In their study, Aboutaleb et al. [25] presented that samples including 0% waste brick have 34 and 47 MPa compressive strength values at 7 and 28 days, but samples containing 100% waste brick have 18 and 35 MPa compressive strength values at 7 and 28 days, respectively; indicating a noticeable decrease in strength with the inclusion of wastes within the mortar. The compressive strength decreases recorded in this way with 100% brick aggregate containing mortars (compared to 0%) were 47.06% and 25.53% for 7 and 28 days, respectively. Another study also indicated that waste brick replacement of natural sand in mortar by up to 25% decreased the compressive strength values of mortars considerably. According to Shakir (2017) [26], samples including % five waste bricks yielded 15.12 and 19.12 MPa compressive strength values at 7 and 28 days. On the other hand, samples containing 25% waste brick yielded 2.4 and 8.16 MPa compressive strength

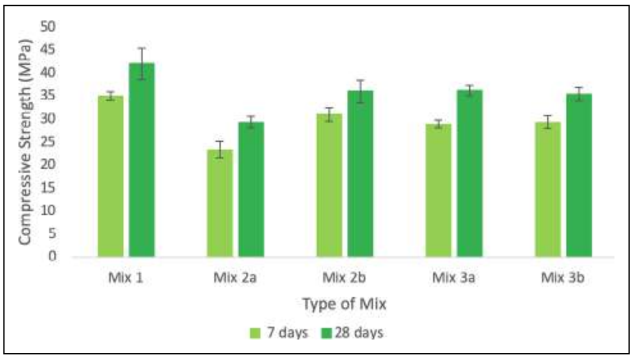

Figure 4. Compressive strength development for each mix between 7 and 28 days.

values at 7 and 28 days, respectively. These results show that the strength decrease was recorded as 84.7% and 57.3% at 7 and 28 days while comparing 5% and 25% brick-containing samples, respectively. The results are in parallel with the results presented in the research conducted. Demir et al. [27] indicate that the compressive strength of the mortar, including 50% waste brick and 50% natural sand, is approximately 31 MPa. The mortar, which included 100% waste brick, had a 7.8% lower compressive strength than the mortar containing 50% waste brick. Hence, the compressive strength of the mortar is reported to decrease with an increased percentage of waste brick inclusion in other studies as well. To illustrate, samples containing %0 waste brick have 33.5 and 42.5 MPa compressive strength values at 7 and 28 days, while samples containing %15 waste brick have 28.8 and 38 MPa compressive strength values at 7 and 28 days, respectively. The results show that strength decreases as much as % 14.03 and % 10.59 at 7 and 28 days while comparing %0 and %15 brick content samples, respectively.

On the other hand, Mix 3a and 3b, the samples having 50% and 100% waste glass aggregates, respectively, were observed to yield only a 3% strength difference at the age of 28 days, even though the waste glass aggregate content was doubled with Mix 3b. Moreover, with these mixed contents, Mix 3b, which has more waste aggregate, is observed to yield slightly higher compressive strength. When the water/cement ratios of the two mixes were compared, the reason for this slight increase could be potentially attributed to the lower w/c ratio of the mix 3b, which was sufficient to yield the targeted slump. Hence, these results indicate that the difference in the water content of the mixtures has a relatively more governing effect; even though the waste content was increased, the lower water content of the mix could positively affect the ultimate compressive strength determined at the age of 28 days. The waste glass aggregate-containing mixes (Mix 3a & 3b) were observed to yield up to a 16% strength decrease in general compared to "no waste-containing" Mix 1 samples at 28 days. This decrease of 16% with waste glass aggregates inclusion (when compared to Mix 1) could be considered as approximately half of the 30% strength decrease (compared to Mix 1) that was observed with the samples that contained waste brick aggregates (i.e., Mix 2a & 2b). Waste glass aggregate inclusion in the mortar bars was reported to yield a decrease in the compressive strength of mortars, as reported in the related literature. Similar studies also report a negative effect on compressive strength upon adding waste brick aggregates. The results presented by Bhandari et al. [28] indicated that compressive strength values for mortar samples, including 20% waste glass, experienced around an 18% strength decrease compared to the case of not using waste aggregates. Additionally, Darshita and Anoop reported a 17% compressive strength decrease when 50% of the aggregates in the mortars were replaced with waste glass aggregates [29].

Mix 2b used in this study, having 100% waste brick aggregates, yielded the lowest compressive strength value, 29.3MPa at 28 days, among all mixes. Even though the type of waste aggregate is expected to be one of the causes of this strength decrease, it is also expected that the unavoidable increase in the water demand of this mix also played a considerable role in the observed reduction in strength. Nevertheless, this increase in the water demand is attributed to the "type" of the waste aggregate since the relatively more porous texture of the brick could be observed when compared to the waste glass aggregates.

Similar to the case in concrete, compressive strength values of mortars are accepted as the main indicator of material quality.

The standard ASTM C270 [30] provides specifications for cement mortars and defines four categories, namely M, S, N, and O types of mortars for different site applications. Among these, type M mortar is defined for uses that require especially high compressive strength, and the mentioned standard defines its strength requirement as a minimum of 17.2MPa. In contrast, type N mortar, known to be used for general-purpose applications, is determined to have a compressive strength of 5.2 MPa in 28 days. As shown in Table 4, all mortar mixes used in this study are observed to yield 28-day compressive strength values that are well beyond the real application requirements defined in ASTM C270 [30]. Mix 2b (50% brick aggregate) and Mix 3b (50% glass aggregate) mortar mixtures proposed and tested within this study yielded 29.3MPa and 36.2MPa strength values, respectively, which enables them to be safely eligible to be used in the site applications according to the standards.

On the other hand, it is known that engineering applications require optimization in materials selection and quantity determination to meet criteria regarding safety and economy, which are both essential. In this study, the research priority and scope have been defined as providing systematical experimental data on *the feasibility of* ***manufacturing cement mortars including up to 100% waste aggregates***, which, *as a first step, considered only the safety aspect of engineering applications* rather than the economy. The achieved strength results within this frame indicate the feasibility of using waste brick and glass aggregates in this preliminary step. The study's next step should focus on manufacturing more economical mortar mixes to eliminate the maximum amount of waste materials. One straightforward approach to reduce the cost is undoubtedly by reducing the cement content of the mix. As the strength values achieved are already higher than commonly expected mortar strength values (based on mortar strength performance defined in ASTM C270), reducing cement content up to a certain level is expected to be tolerated. However, detailed studies should be employed to verify the optimum cement content to be used with maximum allowable waste content while obtaining safe and economical mortar mixes.

3.2. Flexural Strength Results

Table 5 demonstrates the flexural strength values yielded by each mortar mix and the strength decrease tendencies compared to control set samples that contained no waste aggregates, where Figure 5 illustrates the flexural strength development of all mortar mixes between the ages of 7 and 28 days, in comparison with each other. Errors bars are equivalent to one standard deviation.

As was observed within the compressive strength development of the mortar samples, Mix-1 yielded the highest flexural strength values at each testing age compared to the values obtained by other mixes containing waste aggregates. Even though the lowest flexural strength values recorded at the periods of 7 and 28 days were both yielded by 100% waste glass aggregate-containing mix 3b, it was noted that the strength values yielded by Mix 3b, 3a, and 2b were significantly close to each other. Mix 2a was observed to stand out from the rest of the waste aggregate-containing mortar mixes while yielding the second-highest strength values, following the control mix.

In another study, Abbas (2017) [31] indicates that it is also reported that the presence of %30 waste glass content in the samples generally yielded slightly negative effects on the flexural strength development of mortars. Their results demonstrated that flexural strength values for samples, including 30% waste glass, decreased to 1.37% compared to their control mixture. According to Tuaum (2018) [32], The research also investigated the flexural strength behavior of mortar specimens made with CEM I cement and reported that the lowest flexural strength value for 50% waste glass replacement was approximately 9 MPa at 28 days, which is highly by the results presented in the research. In addition, the study reports up to 11.76% flexural strength decrease at 28 days using 50% waste glass aggregates compared to their control set.

Table 5. Flexural strength test results for each mortar mix used in this study

	w/c	Flexural strength (MPa) seven days	Flexural strength decrease compared to Mix 1 (7 days) Average	Flexural strength (MPa) 28 days	Flexural strength reduce compared to Mix 1 (28 days) Average
Mix 1	0.6	8.1	–	9	–
Mix 2a	0.75	5.8	28.40%	6.6	26.67%
Mix 2b	0.73	4.9	39.51%	5.7	36.67%
Mix 3a	0.6	4.8	40.74%	5.6	37.78%
Mix 3b	0.65	4.3	46.91%	5.5	38.89%

Even though the 50% waste brick aggregate-containing Mix 2a and 50% waste glass aggregate-containing Mix 3b were observed to yield very similar compressive strength values, their flexural strength values were observed to differ; since mix 2a's flexural strength value was higher even though it contained higher water content. This behavior could be attributed to the rougher surface texture of the waste brick aggregates compared to the texture of glass aggregates, as the bonding between the aggregate and the cement paste is expected to be enhanced with the increased surface texture of the aggregates. Compressive strength testing is primarily affected by the mortar mixture's porosity. Hence, the effects of the water/cement ratio of the mortar, the general strength of the mortar, and the strength of aggregates are detectable with compressive strength testing. On the other hand, flexural strength testing is known to be more likely to reveal any strength decrease due to lack of bonding of the aggregates since the action of bending the samples would quickly cause detachment of aggregates and the paste very quickly, in case there is lack of adhesion due to aggregates' surface texture [33]. Highly parallel findings were also presented by Tan and Du (2013) [10] and Lu and Poon (2018) [11], as mentioned earlier within the literature information presented in the introduction section. These studies reported that the smooth surface texture of the glass aggregate yielded weaker bonds between the glass aggregate and the cement paste and hence yielded lower splitting tensile strength (known to be correlated with the flexural strength) of the mortar samples tested. Therefore, the difference between the surface texture of glass and brick aggregates and their influence on the mortars' performance should also be evaluated with flexural strength testing observations.

Concrete flexural strength is 10–20% of its compressive strength as a general tendency [33–35]. Mortar behavior is not directly equivalent to concrete behavior; however, a coherent behavior of cement-based materials could reasonably be expected. Within this frame, the 28-day flexural strength values observed for all mortar mixes manufactured in this study yielded a performance higher than at least 16% of their recorded compressive strength. In this case, the obtained results confirm that yielded flexural strength performance is coherent with the engineering performance expectations, especially considering that their compressive strength values are much higher than the high-strength Type M cement mortars defined in ASTM C270.

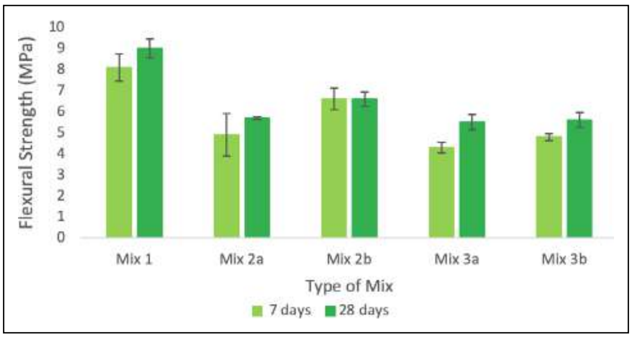

Figure 5. Flexural strength development for each mix at the ages of 7 and 28 days.

4. CONCLUSIVE REMARKS AND RECOMMENDATIONS FOR FUTURE STUDIES

This study investigates the effects of using recycled brick and glass aggregates as a replacement for natural sands used in cement mortars quantitatively and comparably. Recycling waste materials is critical for preserving nature and natural resources and is a key to sustainable development. On the other hand, waste materials within cement mortars, a very widely used construction material, would be considered feasible and acceptable only if the obtained performance could satisfy the civil engineering needs at least at a satisfactory level.

The systematical experimental studies carried out on cement mortars that included waste glass and bricks separately, at %50 and 100% replacement ratios, provided the following quantitative comparisons and conclusive remarks:

I- Using recycled brick aggregates to replace natural sand in the mortar mixes caused a higher water demand to yield the specified workability characteristics when compared with the help of recycled glass aggregates. This is expected to be due to the increased absorption of brick aggregates, which are observed to be relatively more porous.

II- The necessity to increase the water content of the mortar mix with brick aggregates to obtain a satisfactorily workable mix had negative effects on the observed compressive strength behavior yielded by the mortar samples. The minimum compressive strength was obtained with the samples with 100% waste brick aggregates; these samples, on average, yielded a 30% compressive strength decrease compared to the control mix with no waste addition.

III- The mortar samples, including waste glass aggregates, were observed to yield higher compressive strength values. The decrease in compressive strength yielded by 100% waste glass aggregate inclusion into the mortars was only up to 16% compared to the control mix, which could be considered half of the strength decrease yielded when using brick aggregates. The compressive strength performance exhibited by samples with 100% waste glass is very similar to those with waste brick aggregates up to 50%.

IV- When the flexural strength testing results were considered, it was observed that the samples made with waste glass aggregates inclusion yielded much lower strength performance compared to the samples made with waste brick aggregates. The total strength decrease (compared to the control set) recorded for samples having 100% waste glass aggregates is up to almost 39%. This behavior is expected to be due to potentially reduced bonding between the paste and the glass aggregates, which have relatively smooth surface texture compared to the brick aggregates with rougher surface texture.

V- When compared with the standard specifications provided in ASTM C270 defining minimum compressive strength performance expected from cement mortars for real engineering applications on-site, all mortar mixes, including the ones with 50% waste aggregate replacements, have been observed to perform satisfactorily regarding the needs of engineering applications. Additionally, the flexural strength performance of all mortar mixes used in this study was greater than at least 16% of each mix's compressive strength, indicating coherence with the general engineering expectations. Hence, the proposed mortar mixes with up to 50% (by mass) waste aggregate replacement have been observed to be suitable for real engineering applications.

VI- The obtained experimental results show that the type of waste aggregate for cement mortars should be selected considering the specific service location of the mortar used in the construction applications and their designed functions. If the mortar is required to perform well, specifically under compressive loads in the construction site, using waste glass aggregates in the mortar mix, even with high percentages, would yield better performance than waste brick aggregates. On the other hand, if the mortar is required to perform well, specifically under flexural actions in the construction site, the use of waste brick aggregates in the mortar mix, even with high percentages, is expected to perform better under these conditions.

In this way, eliminating higher quantities of waste (through being used in construction materials) would be possible without sacrificing the required engineering performance.

As recommendations for future studies, using further waste brick and glass aggregates with varying ages and properties is expected to yield significant insights into the effects of waste aggregates on cement mortars. Carrying out systematical experiments to determine the characteristics of waste aggregate particles, such as their specific gravity and absorption capacities, would be essential to relate their observed consequences on mortars, mainly if several samples of the same waste type (brick or glass) are employed with varying ages and conditions. Including these waste aggregates with different percentages is also recommended to provide an extended range of experimental data sets. Future studies should also consider carrying out systematical investigations on the optimum cement content that will be used in such mortars together with waste aggregates to provide both safe and economical site applications of mortars. Moreover, the segregation likelihood of the mortar mixes and effects of the characteristics of materials selected to be used should studied as well to provide more complete data that will be beneficial, especially for the actual site applications. Finally, in addition to the fresh and hardened mortar properties such as workability and strength, complementary SEM analyses are recommended for future studies to relate further the surface texture and bonding characteristics of each waste aggregate employed to the ultimately observed mortar properties.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

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Research Article

A Region-based criterion weighting approach for the assessment of post-disaster shelters

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ABSTRACT

The need for shelter after disasters is a common issue, and its planning should occur during the risk management phase, not in the post-disaster process. Following the initial few weeks of emergency aid, the rehabilitation phase comes into play, encompassing the period spent in temporary housing units until a transition to permanent housing is achieved. Like the emergency aid phase, this phase cannot be sustained solely by emergency shelter tents due to its extended duration, which is shorter than the time required to construct permanent housing. Specific designs suited to the rehabilitation phase are necessary. However, many post-disaster temporary housing implementations have failed to meet the requirements. The study aims to establish a decision-making model for assessing temporary housing alternatives in the aftermath of a disaster. The experts must initially identify the criteria and assign their respective weights to build this model. They contend that the significance of criteria should differ depending on the particular attributes of diverse locales. To accomplish this, a methodology for determining criteria weights and an evaluation model is suggested, considering discrepancies in urban density, household size, urban accessibility, and climatic conditions based on regional dissimilarities.

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1. INTRODUCTION

Türkiye, due to its geological structure, is a country vulnerable to natural disasters. It has been hit by numerous major disasters throughout its history, with earthquakes being the most devastating, resulting in heavy casualties. Natural disasters are inevitable, and disaster management systems operate cyclically in our modern world [1].

In the modern disaster management framework, pre-disaster risk reduction efforts are of great importance, especially in mitigating post-earthquake damages, as they can help to reduce both human and material losses after disasters. Addressing the need for shelter that will arise after any disaster is a common issue, and planning for this should be done during the risk management stage, not in the post-disaster phase. In our era, considering factors such as the climate crisis, migration, unplanned settlements, and rapid industrialization, it is thought that all types of disasters will be more severe and frequent. Therefore, governments and, indirectly, architects should consider addressing the post-disaster housing crisis with more effective alternatives as their responsibility.

Although some experiences have been gained in Türkiye regarding post-disaster temporary housing strategies, there is still insufficient research. Additionally, the aftermath of previous earthquakes has yet to be consistently reported, resulting in different approaches after each earthquake. This leads to post-disaster temporary settlements being planned under crisis conditions [2].

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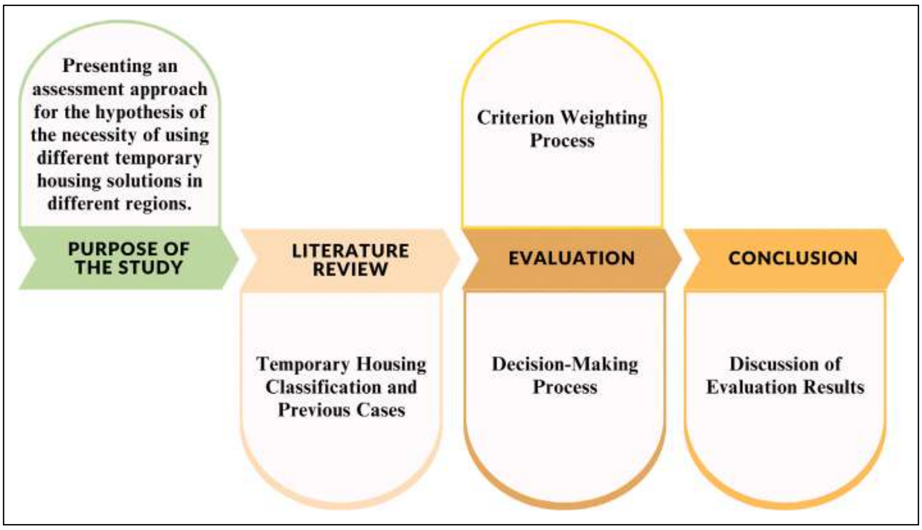

Figure 1. The study's general structure.

It is crucial to evaluate temporary housing properly to make the right system choices. Numerous literature studies have been conducted to achieve this goal, and various criteria have been established. These criteria primarily focus on providing a rapid response in disaster situations without adversely affecting the economy, contributing to permanent housing scenarios, and minimizing the suffering of disaster victims.

We must first understand the decision-making process's parameters to assess the situation appropriately. These parameters include the region's characteristics where temporary housing will be utilized. The study aims to provide decision support for evaluating quick housing systems that can be used after an earthquake and to select appropriate alternatives for different regions. The hypothesis suggests that the criteria weights may vary depending on the disaster region where the temporary housing is used during rehabilitation. With this in mind, the research presents an approach to evaluate post-earthquake quick housing systems applied in the various areas of Türkiye.

In line with this objective, temporary housing is first defined by its classification over time. Firstly, the literature's identified issues with temporary housing in various Turkish regions post-earthquake are presented. Next, the chosen methods for the study's assessment approach are explained while outlining the path from hypothesis testing. The subsequent steps of the assessment are then outlined. Once the evaluation is complete, the results are discussed. The study's general structure is illustrated in Figure 1.

2. MATERIALS AND METHODS

2.1. Classification of Temporary Housing and Problems Encountered in Previous Cases

When classifying temporary housing, it's essential to consider various factors. This is because no one-size-fits-all solution is available, and shelters that meet specific criteria, such as ease of assembly, disassembly, reusability, and ease of transportation, are often used as temporary housing [3].

After a disaster, temporary housing is classified based on post-disaster time frames, which are divided into three different periods in the disaster management system:

The following are the different types of temporary housing used in various phases of disaster management:

- Initial Relief Phase: Temporary housing used in this phase is expected to last about two weeks. It is used immediately after the disaster to shelter the affected people [4].
- Rehabilitation Phase: This phase begins after the initial relief phase and lasts until the construction of permanent housing is completed. The temporary housing used in this phase is expected to last between 6 months and one year [3].
- Reconstruction Phase: This phase is the transition phase that leads to the construction of permanent housing.

Different stages of temporary housing require other characteristics. For instance, tents and pneumatic systems used in the initial relief phase are meant for short-term use. They may lose their features if used beyond their intended period, making them uncomfortable for users. The length of this phase varies depending on the country's level of development. Once this stage is over, users transition to the shelter phase in the rehabilitation phase, which is relatively more comfortable. This transition stage is crucial for users' well-being.

During the second stage of the housing process, also called the rehabilitation or improvement phase, temporary housing units meet specific criteria until the transition to permanent housing is complete. This phase can be resolved in three different ways:

- Temporary housing in another region.
- Collective sheltering in the disaster-affected area in camp-like settings.
- Temporary housing in temporary shelters.

Based on the experiences of post-disaster sheltering so far, temporary housing in temporary shelters is considered the most suitable solution. Planning and evaluating all aspects of the temporary housing used during this phase is crucial to ensure the return to normal living conditions for users who have suffered heavy losses in life and property

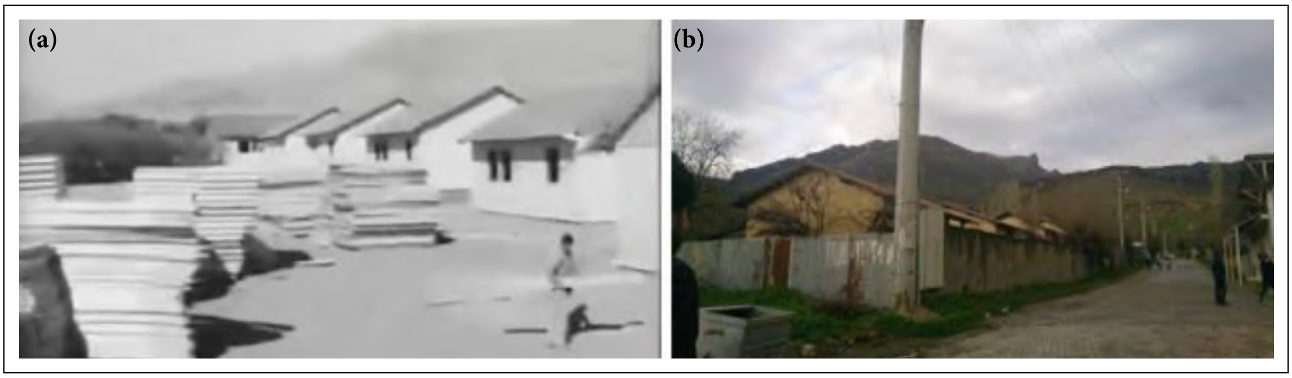

Figure 2. **(a)** The temporary housing units constructed by the Ministry of Construction and Housing [7]. **(b)** Their current conditions (photo taken by Hatice Doğan Keleş) [7].

due to a disaster. This study addresses the criteria and criterion weights for evaluating the different "temporary housing" alternatives to meet the housing needs in the rehabilitation phase [4].

The reconstruction phase marks the completion of permanent housing construction and users' transition to their new homes.

In addition to the classification, temporary housing can be classified based on construction systems. For instance, it can be categorized temporarily, like the "classification of temporary housing used in the rehabilitation phase based on construction systems."

Türkiye has experienced numerous destructive disasters throughout the years. Unfortunately, it has been observed that temporary housing has not always been used as intended in the aftermath of these disasters. To shed light on this issue, a comprehensive study conducted by Özata and Limoncu examined how temporary housing was utilized during the relief, rehabilitation, and reconstruction processes after major earthquakes over five centuries [5]. Additionally, this section will explore the problems that have arisen in the aftermath of disasters over the last fifty years.

1975 Lice Earthquake Case

After the earthquake that hit Lice on September 6, 1975, 1,672 prefabricated temporary shelter units were built within 54 days. However, these houses faced various issues later on. It's worth noting that Oxfam's polyurethane igloos were used for the last time during this earthquake as they were not comfortable in adverse environmental conditions and were vulnerable to fire, leading to their discontinuation by Oxfam [6].

Initially, it was promised that permanent housing would be completed in five years. However, it has been 45 years since the earthquake, and the transition to permanent housing has yet to happen. The temporary housing units have deteriorated over time, as shown in Figure 2 [7]. Upon examination of the materials used in the temporary housing in Lice, it was found that there was a 1.5 cm thick athermic coating on the 5 cm wide external wall, and the interior was covered with wooden materials. Unfortunately, these materials are unsuitable for adapting to the region's environmental conditions. Repairs and modifications were carried out to these housing units over time due to the absence of permanent housing deliveries [7].

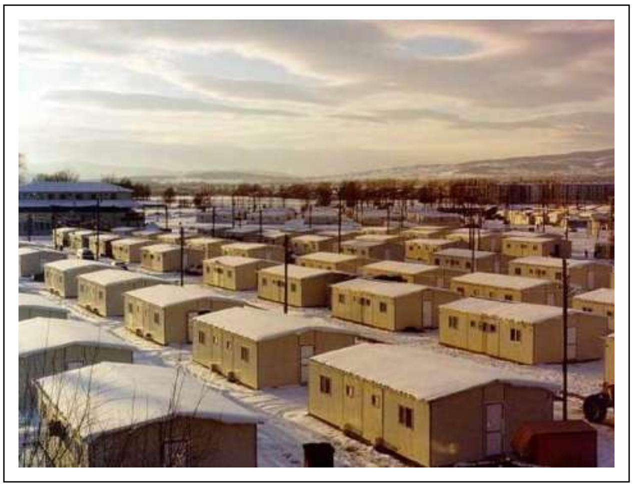

Figure 3. Prefabricated concrete was used to construct temporary shelters [5].

Figure 4. Mevlana houses [42].

1999 Gölcük Earthquake Case

An earthquake, also known as the Marmara Earthquake, with a magnitude of 7.4, struck İzmit on August 17, 1999, causing numerous casualties and property damage across the region [8].

Figure 5. 2nd month report of the tent city on the Diyarbakır Silvan road [12].

After the earthquake, billions of Turkish Liras were spent on tent camps for relief and rehabilitation. However, the bases were unusable within 3–4 months [9].

Following the earthquake, the Ministry of Public Works and Settlement began constructing 44,107 temporary prefab housing units. Kocaeli received 16,314 units, Sakarya 11,707, Yalova 5,514, Bolu 3,903, and Düzce 6,669. The units were handed over to victims on November 30, 1999. Temporary prefab housing units were built for earthquake survivors in the Kocaeli, Yalova, Sakarya, Düzce, and Bolu regions. A total of 44,107 housing units were built, and around 150,000 people lived there for approximately 3.5 months. The infrastructure work for these units was completed in 45 days with an expenditure of 79 trillion 368 billion Turkish Lira [10]. Figure 3 shows the temporary shelters that were constructed using prefabricated concrete.

After examining the relief efforts, it was found that the tents used during the initial phase were used for around three and a half months. As of April 2002, approximately 16,000 temporary housing units were still in use in İzmit. Despite the introduction of permanent housing options, residents were expected to continue living in temporary housing due to housing shortages and high rent prices in the area [8].

2011 Van Erciş Earthquake Case

An earthquake of magnitude 7.2 hit Tabanlı village in Van on October 23, 2011. This is one of Türkiye's top ten strongest earthquakes in the last 110 years [11].

On November 9, 2011, a 5.7 magnitude earthquake hit the same region as the previous earthquake, causing casualties and damages. The second earthquake rendered many buildings unusable, including those undamaged by the first earthquake. 27 buildings collapsed during the second earthquake [11].

After the devastating earthquakes, one of the most urgent needs was shelter. Until permanent housing was built, survivors were provided personal tents, Mevlâna Houses, shared in Figure 4, containers, and tent camps in their neighborhoods [42].

February 6, 2023, Kahramanmaras Earthquake Case

An earthquake on February 6, 2023, resulted in many people facing housing issues. The Turkish Medical Association has reported that during the 2nd month after the disaster, over 3 million people are expected to experience housing problems in 10 provinces affected by the earthquake [12].

The tent settlement on Silvan Road, as shown in Figure 5, caused residents to evacuate in March due to flooding.

Figure 6. The construction of brick houses as temporary shelters in Islahiye [15].

The settlement was established in an unsuitable location by the banks of the Tigris River, with tents closely spaced and no drainage channels [12].

First aid tent spacing is a common issue. The narrow distance between tents can cause tripping and increase the risk of fire spread [12].

Measures were not taken despite observations. A fire caused injuries and damages in the third month after the earthquake. There are different practices in planning temporary housing units for the rehabilitation phase. Some of these practices need discussion to ensure the appropriateness of the temporary housing features.

The construction of 2,264 brick houses and container installations on a 190,000 square meter area in İslahiye, as shown in Figure 6, has been initiated [13]. Adıyaman is constructing temporary housing for 15,000 individuals using prefabricated materials and light steel following the earthquake, as confirmed by the Ministry of Environment and Urbanization [14].

Scientific studies on temporary housing practices after disasters in Türkiye have addressed the following issues:

- Due to its geographical location and unplanned urbanization, Türkiye is heavily impacted by economic crises and experiences significant destruction in its cities. Public buildings are often too damaged for use during first aid or rehabilitation, and there is a need for temporary housing in post-disaster settlement strategies as permanent housing options are inadequate. Public buildings are often too damaged for use during first aid or rehabilitation, and there is a need for temporary housing in post-disaster settlement strategies as permanent housing options are inadequate. Insufficient research has been conducted on post-disaster temporary housing strategies in Türkiye, and previous earthquakes have not been consistently reported, resulting in different experiences after each earthquake and crisis-driven post-disaster settlements [2].
- During the rehabilitation phase, the transition to temporary housing takes longer than necessary due to a lack of research and strategies on the locations and types of temporary housing.
- The transition from rehabilitation to permanent housing takes years for economic and social reasons. Temporary housing units have limited comfort and reusability over time [7].
- Temporary housing units with the same materials often fail to meet expected performance under varying climatic conditions, requiring user repairs over time [16].
- Insufficient pre-disaster planning can result in substantial economic losses [4].
- Temporary housing is not just for initial aid but also rehabilitation and should be planned separately [17].

Apart from the issues, there is an additional concern regarding the placement of temporary housing units. It is crucial to have pre-planned strategies to deal with the urgency and chaos that follows a disaster. Multiple location options should be considered for temporary housing, and the chosen alternatives must be implemented after the disaster, considering the specific characteristics of the affected area.

2.2. Evaluation Method

Post-disaster temporary housing requires a comprehensive approach. Various criteria need individual examination, and production and process aspects must be tackled separately [17].

Using temporary housing during rehabilitation is more complex than during the initial relief and reconstruction processes and involves different criteria. Temporary housing for initial relief is designed for short-term use and is evaluated on simple criteria. Tents are preferred as they provide optimal conditions. However, the reconstruction process is like constructing permanent housing [17].

To determine the most suitable temporary housing system, it is essential first to examine the characteristics of the production and construction processes involved in creating the system. Defining the goals and objectives of the temporary housing system is a crucial step in this process. A construction system has a unique identity that takes specific inputs through a process to produce specific outputs aligned with certain goals. This process consists of subsystems that create the structure, such as production and construction sub-processes.

An evaluation process is necessary to choose the best possible option. One of the stages in this process involves

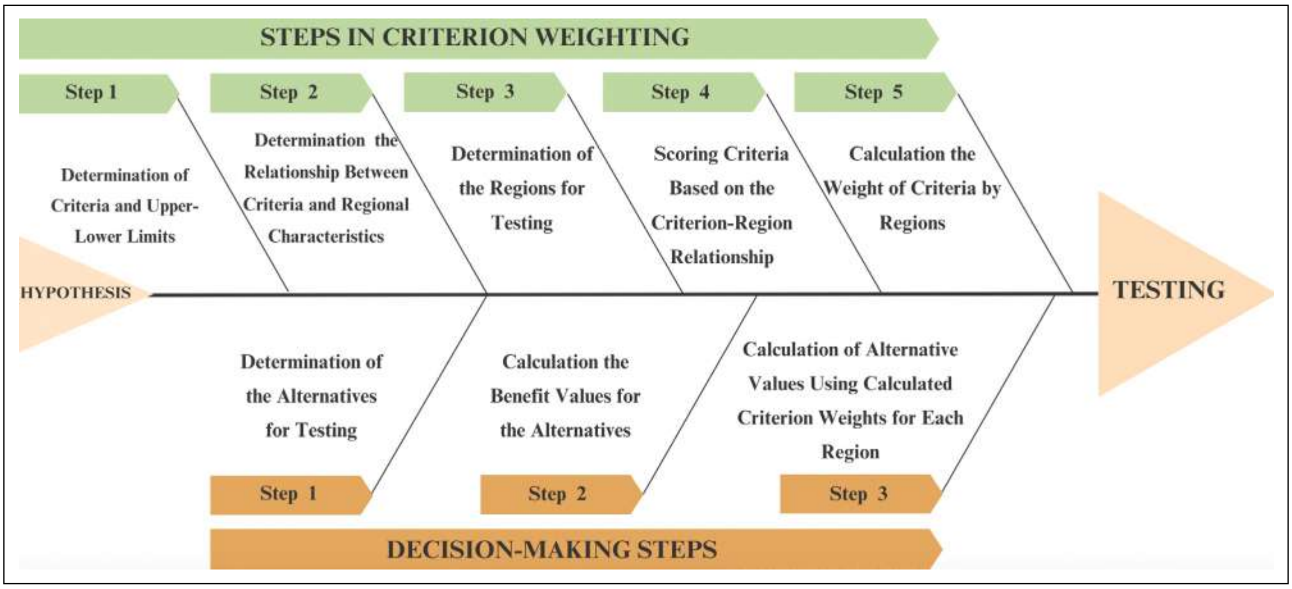

Figure 7. Diagram showing the evaluation steps.

Table 1. Commonly used criteria in the literature

	Criteria															
	SC	AC	AD	FR	CR	DAU	TI	FF	RWS	LUF	L (TC)	R	S	EV	VC	S
Mustafa K. Ervan (1995) [4]	x	x	x	x	x	x	x	x	x	x	x					
Demet Songür (2000) [21]	x		x	x					x	x	x	x	x	x		
Sibel Acerer (1999) [6]	x	x		x	x	x				x	x		x			
Belinda Torus, Sinan M. Şener (2015) [22]		x	x						x	x	x					x
Berna Baradan (2002) [3]	x	x	x			x	x				x	x		x		

SC: Storage convenience; AC: Assembly convenience; AD: Assembly duration; FR: Fire resistance; CR: Climate resilience; DAU: Durability against usage; TI: Thermal insulation; FF: Functional flexibility; RWS: Reproducibility with the same; LUF: Land use flexibility; L (TC): Lightness (transportation convenience); R: Reusability; S: Security; EV: Economic viability; VC: Visual comfort; S: Sustainability.

evaluating the alternatives based on specific criteria. The value of a choice is determined by its performance in achieving a particular goal [18].

When faced with multiple alternatives that need to be evaluated on various criteria, it is essential to determine the level of importance of each criterion. This is because each criterion can have a different significance level, and the selection of alternatives depends on how much weight is given to each criterion. Therefore, assigning weights to each criterion is crucial in decision-making methods involving multiple criteria. Several criterion weighting methods are available in the literature, such as AHP, SWARA, ENTROPY, etc. [19].

To ensure that an alternative meets the desired quality, it must satisfy the boundary values specified by the criteria. However, when evaluating multiple criteria, it is essential to consider certain factors. While some requirements can be quantified using measurable units, others rely on abstract values. Moreover, different systems use different units to describe the characteristics of criteria and alternatives. Furthermore, the difference in value between two alternatives that fulfill the same need may carry extra weight from a needs perspective. For instance, exceeding the threshold value for comfort against environmental conditions may be beneficial, while exceeding the desired lifespan for a building may not matter much [18].

The chosen evaluation method in this study is the benefit and value analysis. This method enables the consideration of both quantitative and qualitative evaluation criteria for alternative selection. Additionally, the evaluation process becomes variable as alternatives gain weight based on different characteristics. This method allows for obtaining further results through the same evaluation method when the consequences change [20].

In conclusion, the evaluation steps followed in this research are illustrated in Figure 7.

2.3. Steps in Criterion Weighting

Step 1: Determination of Criteria and Upper-Lower Limits

A building system is designed to achieve specific objectives by transforming inputs into outputs. This process involves various subsystems that include production and construction processes. The connection between environmental data and the objectives determines the building system's evaluation criteria [20].

In previous research on temporary housing, several evaluation criteria have been established. Table 1 shows

Table 2. Hierarchy of characteristics and criteria for suitability of temporary housing for rehabilitation phase

Overall objective	Lower level objectives	Criteria	Description
Suitability for the rehabilitation phase of temporary housing	Suitability of structural features	Variability of spatial organization	According to potential user diversity, the construction system of temporary housing should be capable of meeting users' different capacities, spatial organization preferences, and functional requirements. The construction system's ability to allow various spatial arrangements during the initial construction phase and to modify the spatial qualities of the dwelling to address changing user needs during the usage phase also signifies the adjustability and transformability of the housing's spatial characteristics.
		Variability of unit compositions	According to different conditions such as varying ground, land, urban settings, etc., the concept explains the ability of temporary housing to be multiplied by stacking them on top of each other or placing them side by side. It highlights the units' capacity to be interconnected, allowing for different placement patterns on the layout plan.
	Suitability of process features	Assembly convenience	The construction system of temporary housing signifies the ease of installation with minimal labor without requiring special equipment or expertise.
		Transportation convenience	It expresses the ease of transportation of temporary housing and components to the designated installation site.
		Storage convenience	It signifies the compactness of the elements and components constituting the temporary housing, their stackability, the ability to reduce their volume, and the fact that they do not require special protection conditions (against environmental factors) while stored.
	Suitability of environmental condition-related features	Providing comfort against Environmental conditions	It describes the protection of users and the structure against physical environmental conditions such as wind, solar effects, etc., by providing necessary values in terms of insulation against heat, water, sound, etc.

Table 3. Criteria's upper and lower limits

Evaluation criteria	Lower	and	Upper
A. Variability of spatial organization	Too little	–	Too much
B. Variability of mass compositions	Too little	–	Too much
C. Assembly convenience	10 days	–	5–6 hours
D. Transportation convenience	1 unit at a time	–	5–6 units at a time
E. Storage convenience	Storage in big modular units	–	Storage in small panels
F. Providing comfort against environmental conditions	Too weak	–	Very strong

the most prominent standards. However, to simplify the evaluation method, this study excludes cost-effectiveness, safety, and fire resistance, essential for temporary housing in any region. Instead, the evaluation model incorporates criteria related to the unique characteristic features of different areas.

We can classify the other criteria into three sub-objectives: structure, process, and environment. Table 2 shows the hierarchy of features and criteria for the main objective.

When assessing an alternative option, it is crucial to establish the upper and lower boundaries of the criteria. This is because the value of the alternative must meet the limits set by the criteria. To produce temporary housing units to be used in the rehabilitation phase, Table 3 provides the lower and upper limits for the evaluation criteria. These limits are determined based on the need for quick assembly and transportation during rehabilitation, the requirement to manufacture within a limited timeframe, the reusability factor, and the provision of options for various family sizes.

Step 2: Determination of the Relationship Between Criteria and Regional Characteristics

To test the research hypothesis about the appropriateness of temporary housing for the rehabilitation phase, it's essential to understand the factors that may impact the top-level criteria used for this purpose. This involves exploring the various characteristics of the regions where the housing will be installed before weighing the criteria based on their significance. This will help determine how these region-specific factors might affect temporary housing during rehabilitation.

This study explains the impact of regional characteristics on temporary housing in Table 3–7 after examining factors such as population density, household size, climate conditions, and urban accessibility in the regions.

Table 4. The effects of urban accessibility on the criteria

Transportation convenience	The vehicle choice depends on the transportation network's condition in disaster-affected areas. Efficiently delivering personnel to the region is crucial, and therefore, well-developed urban transportation performance is necessary. Transportation operations should be carried out using pre-determined transportation network maps and vehicles based on these maps before the disaster occurs [4]. In areas with limited urban accessibility, it can be suggested that transport convenience holds a higher significance level.
Storage convenience	The selection of vehicles and organization of storage conditions should be planned based on the accessibility options to the city through roadways, railways, waterways, or airways for adequate post-disaster transportation. Each storage location should cover predetermined areas, and necessary facilities should be set up accordingly [4]. Therefore, accessibility to depots is essential for transportation, and it should be equally important for every region since it needs to be preplanned.
Assembly convenience	The condition of transportation networks is essential during the assembly phase to ensure the arrival of assembly personnel to the disaster-affected area. Specialized vehicles like cranes might be necessary to assemble modular systems [6]. In such cases, urban accessibility becomes significant for anchoring temporary housing units to the ground or other places.

Table 5. The effects of household size on the criteria

Variability of spatial organization	In addition to providing shelter, temporary housing units can serve as educational, healthcare, dining, and worship facilities. To accommodate these various functions, the units need to be spatially flexible [4]. Therefore, flexibility in household size is equally important in regions with varying household size averages as it relates to space usage.
Variability of unit compositions	Temporary housing units should be adaptable to varying user counts, especially for larger families, to function as sufficient shelter units for single families [6]. In regions where the average household size is larger, this criterion holds a relatively higher significance level.

Table 6. The effects of climate conditions on the criteria

Transportation convenience	During the transportation of temporary housing to disaster-stricken areas, various options such as air, land, and sea transportation can be [4]. In all scenarios, the region's climate conditions are a criterion that must be considered during the transportation phase. It could be argued that transportation convenience holds higher significance in areas with extremely cold climates than in other regions.
Storage convenience	Storage refers to the stage where temporary housing elements are stacked and kept in optimal condition until they are ready for use. When selecting a storage location, it is essential to consider the area's climate conditions to protect it from potential environmental damage—establishing adequate ventilation systems to prevent damage to the materials and ensure protection against disasters such as floods and landslides [4]. In regions that experience extreme cold or hot climates, the criterion of storage convenience may hold a relatively higher significance level than the other areas.
Providing comfort against environmental conditions	Temporary housing units must provide minimum living conditions, thermal insulation, and security while acting as a barrier against harmful plants and insects [21]. In areas with particularly low or high temperatures, ensuring comfort against environmental conditions may be deemed of higher importance than in other regions.

Urban Accessibility

Accessibility is crucial in disaster contexts for transportation networks to function continuously. It is necessary to meet people's needs and provide aid and services post-disaster [23]. The accessibility of a region affects transportation, storage, and assembly ease for temporary housing. A city's accessibility impacts these criteria and is correlated in Table 4.

Household Size

According to the Turkish Statistical Institute (TUIK), household size refers to the number of individuals residing together at the same address. This information is crucial in determining the appropriate number of people to accommodate in a single temporary housing unit and for varying spatial and mass compositions. In areas with larger households, temporary housing units with flexible designs are recommended [24]. The Table 5. correlates the potential impacts of household size on these criteria using the features of temporary housing described in the literature.

Climate Conditions

When considering climate conditions, Türkiye's climates are categorized into hot-dry, hot-humid, temperate-dry, temperate-humid, and cold. Varying structural requirements for temporary housing are expected in different regions to provide comfort against environmental conditions [25]. Table 6. correlates the potential impacts of climate conditions on these criteria using the features of temporary housing described in the literature.

Table 7. The effects of urban-population density on the criteria

Variability of spatial organization	In addition to providing shelter, temporary housing units can function as educational, healthcare, dining, or worship facilities, requiring flexible spatial qualities [4]. In densely populated areas, spatial functions may increase.
Variability of unit compositions	Temporary housing units should be adaptable to different user counts, including more prominent families, and flexible in their mass compositions to align with social life. Site planning should be completed before disasters, as a linear or rigid layout might not always be feasible in regions with different topographic features [27]. In areas with high urban density, it may be beneficial to consider giving more importance to the criterion related to the diversity of mass compositions compared to regions with low viscosity.
Assembly convenience	During the design phase, determine assembly details for the temporary housing unit. It should be able to be set up without special tools or equipment [4]. A ready-made modular system can provide easy assembly, but attaching units or toe ground might require cranes, which could be hindered by population and building density in the city after a disaster. Quick assembly is a critical essential aid phase due to the aim to move into a healthier environment during the rehabilitation stage [6]. Assembly convenience might be influenced by urban density proportional to the number of people affected by the disaster. In regions with high urban density, the importance of the assembly ease criterion can be considered higher than in areas with low density.
Transportation convenience	If pre-made modular systems are utilized, assembly is easy, but transportation and attachment to the ground may require heavy equipment, which can be hindered by post-disaster population density. Temporary housing elements should be designed to use existing vehicles [6]. However, transportation may also be considered more critical in densely populated cities. Therefore, the importance of the transportation ease criterion may be directly proportional to urban density.
Storage convenience	Warehouses should be established in safe locations, away from disaster zones like floods and landslides, and city density and transportation networks should be considered. During disasters, it's essential to plan for temporary housing based on the population and store appropriate stock quantities in the warehouses [4]. There may be a greater need for temporary housing units in densely populated areas, so the ease of storage could be considered more important and directly proportional to urban density. Packaging temporary housing elements for easy transport is also crucial, as transportation features can affect storage conditions [6].

Table 8. The characteristics of four regions in Türkiye

City name(s)	Urban-population density [26]	Transportation performance [28]	Average household size [24]	Climatic characteristics [25]
İstanbul	High-density urban	%80.1–100	3.18	Cool winters, hot summers, semi-arid
Muğla-Aydın	Medium-density urban	%20.1–40	2.77	Cool in winter, very hot in summer, dry-semi-humid
Muş-Bitlis-Van	Rural area- medium-density urban	%0.1–20	4.26	Cold in winter, warm in summer, humid-semi-humid
Sakarya-Kocaeli	Medium-density urban	%40.1–60	3.23	Cool in winter, hot in summer, semi-humid

Urban Population Density

Regarding population density, settlements are categorized as high-density urban, medium-density urban, and rural. High-density urban areas have at least 50% of their population living in cities, rural areas have at least 50% living in rural areas, and medium-density urban areas do not meet the criteria of high-density urban or rural settlements [26]. Urban population density impacts these criteria and is correlated in Table 7.

Considering this information, the diagram illustrating the relationship between the characteristics of regions and the evaluation criteria for temporary housing is shown in Figure 8.

Step 3: Determination of the Regions for Testing

When examining the effects of these factors on the criteria, selecting regions with diverse characteristics can provide a suitable assessment environment to discuss the necessity for temporary housing to have different structural requirements according to regions. The characteristics of four groups of cities located in the other areas of Türkiye at risk of disasters are presented in Table 8, along with their features.

Step 4: Scoring Criteria Based on the Criterion-Region Relationship

In the second step, the identified characteristics of the region and the criteria were evaluated based on the relationship scale. The relationship scale comprises five levels - extreme, strong, sufficient, weak, and very weak, ranging from 1 to 5. The scoring procedure is illustrated in Figure 9.

Step 5: Calculation the Weight of Criteria by Regions

The criterion weights were determined based on scores assigned using the relationship diagram in Figure 9, the relationship between region characteristics and criteria

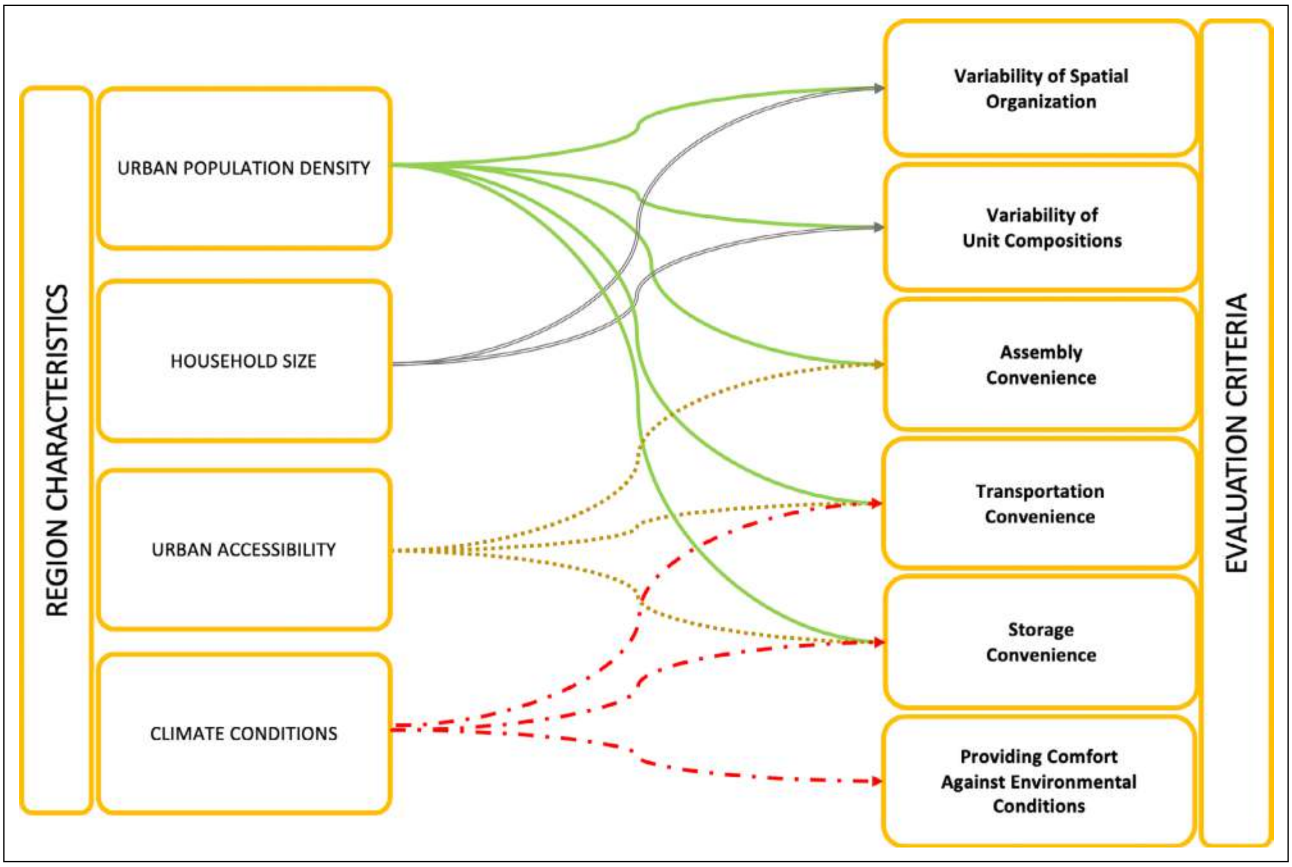

Figure 8. Diagram showing the relationships between region characteristics and temporary housing evaluation criteria.

Table 9. Weights of criteria importance in İstanbul region

İstanbul / Criteria	Urban density	Household size	Urban accessibility	Climate conditions	Relation total score (r_n)	Weight (W_n)
A. Variability of spatial organizations	5	3	0	0	**8**	**0,1667**
B. Variability of unit compositions	5	4	0	0	**9**	**0,1875**
C. Assembly convenience	5	0	1	0	**6**	**0,1250**
D. Transportation convenience	5	0	5	2	**12**	**0,2500**
E. Storage convenience	5	0	3	2	**10**	**0,2083**
F. Providing comfort against environmental conditions	0	0	0	3	**3**	**0,0625**
		Total value ($r_A+r_B+r_C+r_D+r_E+r_F$)=			**48**	

1: Very weak; 2: Weak; 3: Sufficient; 4: Strong; 5: Very strong relation.

established in Tables 3–7, and a literature review. The weights were normalized, transformed into standard values for four regions, and presented in Table 9, for İstanbul Region; Table 10, for Muğla-Aydın-Denizli; Table 11, for Muş-Bitlis-Van Region and Table 12 for Sakarya Region. The formula for calculating the criteria weights is shown in Equation 1 as follows [18].

W: Criterion Weight
r_n: Relation Total Score
r_A: Value of Criteria A
r_B: Value of Criteria B
r_F: Value of Criteria F

Equation 1 Calculating Criterion Weight: (W_n:$\frac{r_n}{r_A+r_B+r_C+r_D+r_E+r_F}$)

According to this formula, the calculation of criterion weights for each region is as follows: Based on the relationship between the criteria and the part characteristics in Figure 4, the relationship scores for each measure are summed to find a separate Relation Total Score (r_n) for each criterion. Then, the Relation Total Scores for all requirements are added to find the Total value. Dividing each criterion's Relation Total Score (r_n) by the Total value gives the criterion weights for each region.

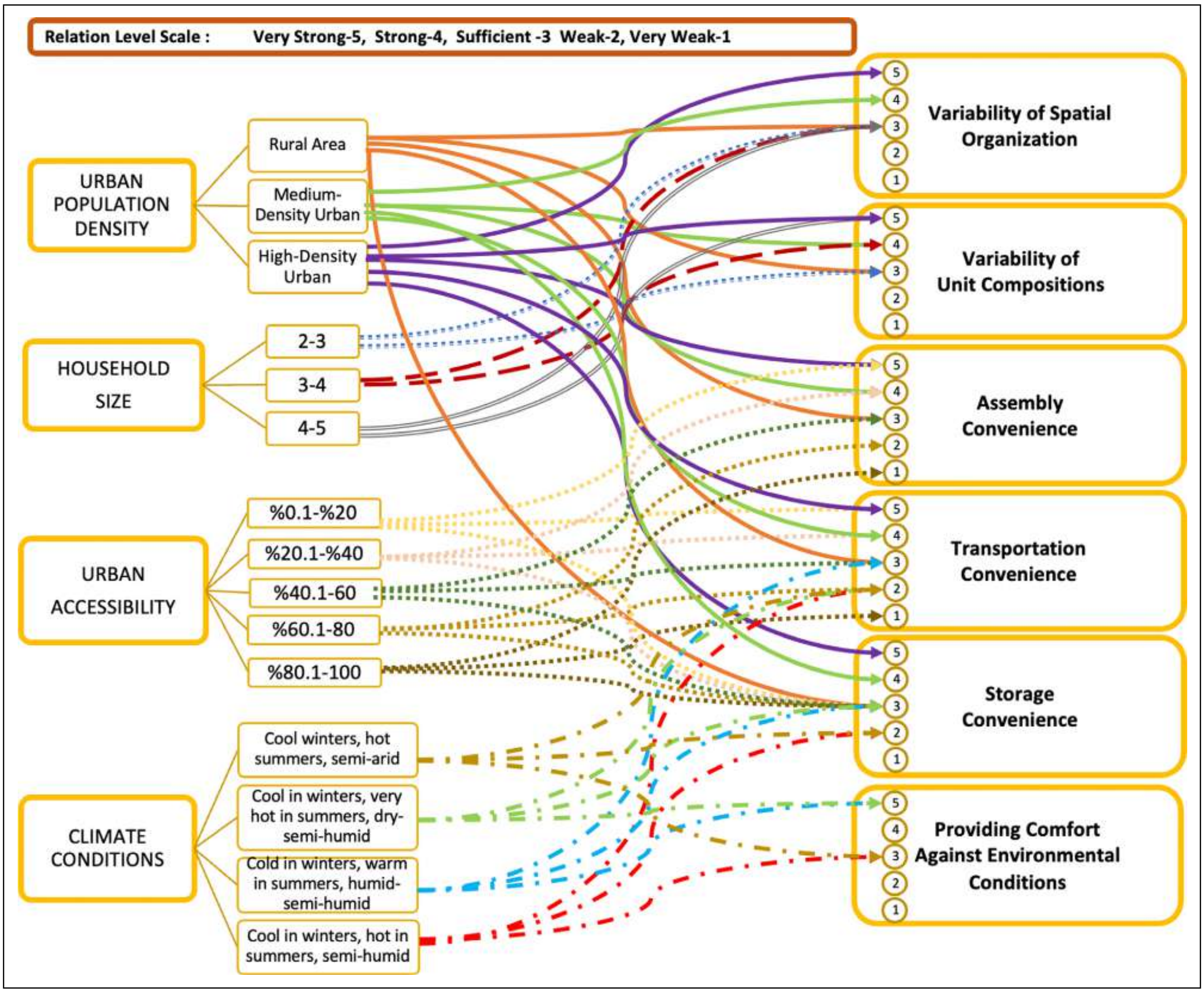

Figure 9. Diagram Illustrating the Relation Level Scale Between Region Characteristics and Criteria.

Table 10. Weights of criteria importance in Muğla-Aydın-Denizli region

Muğla-Aydın-Denizli / Criteria	Urban density	Household size	Urban accessibility	Climate conditions	Relation total score (r_n)	Weight (W_n)
A. Variability of spatial organization	4	3	0	0	7	0,1489
B. Variability of unit compositions	4	3	0	0	7	0,1489
C. Assembly convenience	4	0	4	0	8	0,1702
D. Transportation convenience	4	0	4	2	10	0,2128
E. Storage convenience	4	0	3	3	10	0,2128
F. Providing comfort against environmental conditions	0	0	0	5	5	0,1064
		Total value ($r_A+r_B+r_C+r_D+r_E+r_F$)=			47	

1: Very Weak; 2: Weak; 3: Sufficient; 4: Strong; 5: Very strong relation.

2.4. Decision-Making Steps

Step 1: Determination of the Alternatives for Testing

Table 13 presents the characteristics and features of temporary housing solutions used worldwide, including prototype studies suggested for disaster areas. The table includes examples of temporary housing that have been previously used or are currently in use. Despite regional variations, all the examples are expected to meet the requirements, such as economic efficiency, fire safety, and sustainability.

Step 2: Calculation the Benefit Values for the Alternatives

The features of the alternatives and the differences in their displayed values can be determined using an interval scale. An interval scale allows the transformation of the features of options into other options, aiding in ag-

Table 11. Weights of criteria importance in Muş-Bitlis-Van region

Muş-Bitlis-Van / Criteria	Urban density	Household size	Urban accessibility	Climate conditions	Relation total score (r_n)	Weight (W_n)
A. Variability of spatial organization	**3**	**3**	**0**	**0**	**6**	**0,1277**
B. Variability of unit compositions	**3**	**5**	**0**	**0**	**8**	**0,1702**
C. Assembly convenience	**3**	**0**	**5**	**0**	**8**	**0,1702**
D. Transportation convenience	**3**	**0**	**5**	**3**	**11**	**0,2340**
E. Storage convenience	**3**	**0**	**3**	**3**	**9**	**0,1915**
F. Providing comfort against environmental conditions	**0**	**0**	**0**	**5**	**5**	**0,1064**
		Total value ($r_A+r_B+r_C+r_D+r_E+r_F$)=			**47**	

1: Very weak; 2: Weak; 3: Sufficient; 4: Strong; 5: Very strong relation.

Table 12. Weights of criteria importance in Sakarya region

Sakarya / Criteria	Urban density	Household size	Urban accessibility	Climate conditions	Relation total score (r_n)	Weight (W_n)
A. Variability of spatial organizations	4	3	0	0	**7**	**0,1591**
B. Variability of unit compositions	4	4	0	0	**8**	**0,1818**
C. Assembly convenience	4	0	3	0	**7**	**0,1591**
D. Transportation convenience	4	0	3	2	**9**	**0,1750**
E. Storage convenience	4	0	3	2	**9**	**0,1750**
F. Providing comfort against environmental conditions	0	0	0	4	**4**	**0,1000**
		Total value ($r_A+r_B+r_C+r_D+r_E+r_F$)=			**44**	

1: Very weak; 2: Weak; 3: Sufficient; 4: Strong; 5: Very strong relation.

gregating results measured in a single unit [18].Values have been considered benefit values, and the interval scales shown in Tables 14–19 have been used.

Step 3: Calculation of Alternative Values Using Calculated Criterion Weights for Each Region

After calculating the benefit values of each alternative based on the criteria, the total weights for each option are computed using Equation 2 [18]. The resulting values are shown in Tables 20–23.

W_n: Weight of Criteria**VB_n**: Value of Benefit of the Criteria **G**: Total Score of Alternative

Equation 2: ($G=W_n x VB_n$)

The total score for each alternative is calculated by multiplying the benefit values of the criteria with their corresponding weights and then summing these products. For example, the total score for the calculation of Alternative NO 1 is:

$G_1=((W_A x VB_A)+(W_B x VB_B)+ \ldots\ldots +(W_n x VB_n))$

For the Istanbul region, the total values received by the alternatives calculated with Equation 2 based on the criteria weights have been calculated and shown in Table 20. As a result of the calculation, Alternative NO 3 has received the highest score.

The total values received by the alternatives calculated with Equation 2 based on the criteria weights for the Muğla-Aydın-Denizli regions have been calculated and shown in Table 21. As a result of the calculation, Alternative NO 1 has received the highest score.

The total values received by the alternatives were calculated with Equation 2 based on the criteria weights for the Muş-Bitlis-Van regions, which have been calculated and shown in Table 22. As a result of the calculation, Alternative NO 1 has received the highest score.

The total values received by the alternatives calculated with Equation 2 based on the criteria weights for the Sakarya region have been calculated and shown in Table 23. As a result of the calculation, Alternative NO 1 has received the highest score.

3. RESULTS AND DISCUSSION

In a 'multi-criteria decision-making process for identifying (or evaluating) suitable temporary housing that can be used after a disaster, it is essential to differentiate the importance weights of criteria according to the different characteristics of the regions. In this context, a 'criteria weighting method' and an evaluation model that focuses on the effects of factors such as varying urban density, household size, urban accessibility, and climate conditions for regions are proposed in the study.

The importance weights of criteria for the four regions have been determined based on the degree of relationship between the factors defining the characteristics of the areas and evaluation criteria (Table 9–12). The findings related to the results are as follows:

Table 13. Temporary housing alternatives and their features

Alternative No. 1: Hex House [29]	 Manufacturer: Architects For Society	**Area:** 40 sqm **Flexibility:** Can be added side by side and multiplied **Structural System:** Panel walls support themselves. **Assembly Method and Time:** Simple tools are required, and assembly does not require expertise. **Transportation Method of the System:** Panels stacked flat are transported to the construction site with trailers. **Resistance to Environmental Conditions:** Conforms to LEED standards. **Flexibility:** Units can be arranged side by side in appropriate patterns or combined for better thermal insulation performance and shared walls.
Alternative No. 2: Onagawa Temporary Container Housing [30, 31]	 Manufacturer: Shigeru Ban Architects	**Area:** There are three mass compositions, each with an area of 19.86, 29.79, and 39.72 sqm, respectively. **Flexibility:** Containers can be stacked up to three levels, with open spaces between each unit. **Structural System:** Containers carry their weight. **Assembly Method and Time:** Containers are placed using cranes. **Primary Materials:** Repurposed shipping containers are used. **Transportation Method of the System:** Modules are transported to the site by truck and placed using a crane when needed. **Lifespan:** Housing units can be converted into permanent housing.
Alternative No. 3: AbleNook [32]	 Manufacturer: Sean Verdecia (Designer), AbleNook	**Area:** Each unit is approximately 25 sqm. **Flexibility:** Can be expanded for more extensive space requirements. **Structural System:** Aluminium frame **Assembly Method and Time:** Units can be assembled by unskilled individuals without using power tools. **Primary Materials:** Consists of flat-packed, on-site assembled kits made from SIPs (Structural Insulated Panels) and a sliding lightweight aluminum structural frame. **Transportation Method of the System:** Units are shipped as flat-packed. **Lifespan:** Can be used for 15 years or more. Reusable.
Alternative No. 4: NY House Prototype [33]	 Manufacturer: Garrison Architects Design	**Area:** Options range from 44 sqm to 75 sqm with additions. **Flexibility:** Plans include configurations with 1 and 3 bedrooms. Each unit features a living space, a bathroom, a fully equipped kitchen, and storage. **Structural System:** The prefab system carries its weight. **Assembly Method and Time:** Multi-story, multi-family units with various arrangements can be deployed in less than 15 hours. Units are stacked using cranes. **Primary Materials:** Made from recyclable materials. **Transportation Method of the System:** Modules are transported to the site by truck and placed using a crane when needed.
Alternative No. 5: Ex -container House [34]	 Manufacturer: Yasutaka Yoshimura Architects-Japan	**Area:** When placed side by side, two 20 ft containers create approximately 28 sqm of space (Bathroom with sink, bathtub, toilet / Kitchen / Living room). When stacked, two 20 ft containers provide around 26 sqm of space (Bathroom with sink, bathtub, toilet / Kitchen / Living room). Placing two vertically positioned old containers with a gap between them results in an approximate area of 50–60 sqm (Sink, bathtub, toilet / Kitchen / Living room, and bathroom). **Flexibility:** Units can be expanded by stacking them vertically or placing them side by side. **Structural System:** Containers carry their weight. **Assembly Method and Time:** Factory-produced units are transported to the site in their finished form and are stacked or placed side by side using a crane.

Table 13 (cont). Temporary housing alternatives and their features

		Primary Materials: The interior materials of the structure, made from ISO shipping containers, are applied on-site. **Transportation Method of the System:** Completed units are transported to the site via trailers and placed using a crane. One trailer can carry two housing units. **Lifespan:** Beyond the short term, the Ex-Container Project can be initially constructed as temporary housing and later transformed into a permanent architectural structure.
Alternative No. 6: IKEA Better shelter [35]	 Manufacturer: IKEA	**Area:** 17.5 sqm. It has a rectangular open plan. **Flexibility:** The lifespan of Better Shelter is strengthened through a progressive approach based on multiple shelter uses depending on local climate conditions and cultural characteristics. Existing units can be reinforced with local materials, reused over time, and recycled. **Structural System:** The metal frame can be wrapped in standard-sized tarpaulin for emergencies. Meanwhile, walls and roofs can be elevated using locally sourced building materials and attached to the frame using various techniques. The metal frame is fire-resistant. **Assembly Method and Time:** Assembled by a team of 4 people in 4–6 hours. **BaPrimary Materials:** Each package includes a lockable door, four windows, four vents, a semi-rigid opaque roof and wall panels, a steel frame assembled with floor anchors, a PV system, and a portable lamp. **Transportation Method of the System:** Stacked in packaged form. Each package is 1.07 m^3 and weighs 160 kg. **Lifespan:** Without maintenance, 1.5 years; with simple maintenance, three years of use.
Alternative No. 7: Uber Emergency Shelter [36, 37]	 Manufacturer: Rafael Smith	**Plan:** After a disaster, Uber is dispatched as a basic unit to meet the initial shelter needs. Over time, additional units are mounted onto the shelter units by sending a separate upgrade package (for light, compact stove, and refrigerator). **Flexibility:** Units can be added side by side or stacked. Structural System: Self-supporting. **Assembly Method and Time:** Easy assembly with minimal or even no tools. **Transportation Method of the System:** Panels are stacked flat. Stacked packages can be transported using trucks, transporting multiple units at once. **Lifespan:** Made from recyclable materials.
Alternative No. 8: Hush2 Shelter [38, 39]	 Manufacturer: Extremis Technology	**Area:** 12 sqm **Flexibility:** Cannot be added side by side or stacked. **Assembly Method and Time:** This can be easily set up in under two hours without requiring expertise or tools. Hush2 is a flat-packed structure made of marine plywood. **Primary Materials:** Made from plywood material. **Transportation Method of the System:** Panels are stacked flat. Stacked packages can be transported using trucks, transporting multiple units at once. **Lifespan:** Can be disassembled and reassembled up to 20 times.
Alternative No. 9: Cortex Shelter [40, 41]	 Manufacturer: Cutwork Studio	**Area:** 24 sqm **Flexibility:** Cannot be added side by side or stacked. **Assembly Method and Time:** Can be assembled within one day. **Primary Materials:** Concrete material rolled onto a steel framework. **Transportation Method of the System:** Panels are stacked flat. Stacked packages can be transported using trucks transporting multiple units at once. **Lifespan:** 30 years.

Table 14. Finding the benefit values of alternatives for criterion A using an interval scale

Value of benefit (VB)	1	2	3	4	5
	Too little	**Little**	**Right amount**	**Much**	**Too much**
A-variability of spatial organization	No. 4	No. 5	No. 1	No. 2	
	No. 7	No. 6		No. 3	
	No. 8	No. 9			

Table 15. Finding the benefit values of alternatives for criterion B using an interval scale

Value of benefit (VB)	1	2	3	4	5
	Too little	**Little**	**Right amount**	**Much**	**Too much**
B-variability of mass compositions		No. 6	No. 4	No. 1	
		No. 7	No. 5	No. 2	
		No. 8		No. 3	
		No. 9			

Table 16. Finding the benefit values of alternatives for criterion C using an interval scale

Value of benefit (VB)	1	2	3	4	5
	10 days	**5–6 days**	**2–3 days**	**1 day**	**5–6 hours**
C. Assembly convenience		No. 2	No. 3	No. 1	No. 6
		No. 4		No. 7	
		No. 5		No. 8	
				No. 9	

Table 17. Finding the benefit values of alternatives for criterion D using an interval scale

Value of benefit (VB)	1	2	3	4	5
	1 unit at a time	**2 unitst at a time**	**Unitsit at a time**	**4 unitunitsa time**	**5–6 unitunits more**
D. Transportation convenience	No. 2		No. 1	No. 3	No. 6
	No. 4		No. 8	No. 7	No. 9
	No. 5				

Table 18. Finding the benefit values of alternatives for criterion E using an interval scale

Value of benefit (VB)	1	2	3	4	5
	Storage in big modular units	**Storage in small modular units**	**Hybrid system**	**Storage in big panels**	**storage in small panels**
E. Storage convenience	No. 2		No. 1	No. 6	
	No. 4		No. 3	No. 7	
	No. 5			No. 8	
				No. 9	

For the İstanbul region, the 'Transportation Convenience' stands out with an importance weight of 0.2500 (25%). The criteria 'Storage Convenience' and 'Variability of mass composition' with importance weights of 0.2083 (21%) and 0.1875 (19%) are relatively secondary in importance compared to the 'Transportation Convenience' criterion. Relative to the other measures, the 'Providing Comfort Against Environmental Conditions" criterion' is less critical. The characteristics of Istanbul, especially urban density and accessibility, have influenced the results. Urban density restricts suitable areas for storage and installation of temporary housing units while posing a barrier to accessing these areas during a large-scale earthquake. Additionally, the appropriately limited regions due to density will necessitate stacking and densely placing teams on top of each other, making the criterion of variability in mass

Table 19. Finding the benefit values of alternatives for criterion F using an interval scale

Value of benefit (VB)	**1**	**2**	**3**	**4**	**5**
	Too weak	**Weak**	**Sufficient**	**Strong**	**Very strong**
F. Providing comfort against environmental conditions	No. 6	No. 3	No. 9	No. 2	No. 1
	No. 7	No. 8			No. 4
					No. 5

Table 20. The total value obtained by alternatives in the İstanbul region

Alternatives / Criteria	İstanbul									Weight of criteria (W_n)
	NO1	**NO2**	**NO3**	**NO4**	**NO5**	**NO6**	**NO7**	**NO8**	**NO9**	
A	3	4	4	1	2	2	1	1	2	0,1667
B	4	4	4	3	3	2	2	2	2	0,1875
C	4	2	3	2	2	5	4	4	4	0,1250
D	3	1	4	1	1	5	4	3	5	0,2500
E	3	1	3	1	1	4	4	4	4	0,2083
F	5	4	2	5	5	1	1	2	3	0,0625
Total score of alternative (G)	3,44	2,38	**3,54**	1,75	1,92	3,48	2,94	2,75	3,48	

Table 21. The total value obtained by alternatives in the Muğla-Aydın-Denizli regions

Alternatives / Criteria	Muğla-Aydın-Denizli									Weight of criteria (W_n)
	NO1	**NO2**	**NO3**	**NO4**	**NO5**	**NO6**	**NO7**	**NO8**	**NO9**	
A	3	4	4	1	2	2	1	1	2	0,1489
B	4	4	4	3	3	2	2	2	2	0,1489
C	4	2	3	2	2	5	4	4	4	0,1702
D	3	1	4	1	1	5	4	3	5	0,2128
E	3	1	3	1	1	4	4	4	4	0,2128
F	5	4	2	5	5	1	1	2	3	0,1064
Total score of alternative (G)	**3,53**	2,38	3,40	1,89	2,04	3,47	2,94	2,83	3,51	

Table 22. The total value obtained by alternatives in the Muş-Bitlis-Van regions

Alternatives / Criteria	Muş-Bitlis-Van									Weight of criteria (W_n)
	NO1	**NO2**	**NO3**	**NO4**	**NO5**	**NO6**	**NO7**	**NO8**	**NO9**	
A	3	4	4	1	2	2	1	1	2	0,1277
B	4	4	4	3	3	2	2	2	2	0,1702
C	4	2	3	2	2	5	4	4	4	0,1702
D	3	1	4	1	1	5	4	3	5	0,2340
E	3	1	3	1	1	4	4	4	4	0,1915
F	5	4	2	5	5	1	1	2	3	0,1064
Total score of alternative (G)	3,55	2,38	3,43	1,94	2,06	3,49	2,96	2,83	3,53	

composition another weighted measure for the Istanbul region. Climatic conditions are relatively less important for this region than other factors.

In the Muğla-Aydın-Denizli region, an importance weight of approximately 21% for the "Storage Convenience” criterion and the "Transportation Convenience " criterion can be associated with the region's access and transportation infrastructure status. Although relatively less dense than Istanbul, the area has a much weaker transportation network. Additionally, the "Installation Convenience" criterion, weighing 17%, is related to the effect of urban accessibility. Spatial diversity and the standard of mass composition have a medium level of importance, likely influenced by region-specific characteristics, such as the availability of suitable areas for installation and the smaller household size.

Table 23. The total value obtained by alternatives in the Sakarya region

Alternatives / Criteria	Sakarya									Weight of
	NO1	NO2	NO3	NO4	NO5	NO6	NO7	NO8	NO9	criteria (W_n)
A	3	4	4	1	2	2	1	1	2	0,1591
B	4	4	4	3	3	2	2	2	2	0,1818
C	4	2	3	2	2	5	4	4	4	0,1591
D	3	1	4	1	1	5	4	3	5	0,1750
E	3	1	3	1	1	4	4	4	4	0,1750
F	5	4	2	5	5	1	1	2	3	0,1000
Total score of alternative (G)	**3,39**	2,43	3,27	1,87	2,03	3,15	2,66	2,58	3,19	

In the Muş-Bitlis-Van region, the "Transportation Convenience " takes precedence with an importance weight of 23%. The harsh and challenging transportation network, coupled with the impact of climatic conditions, makes transportation ease a top priority. Similarly, the region's difficult transportation and harsh climate make storage requirements prominent, affecting the importance of the "Storage Convenience " criterion. Although the region has low urban density, a larger household size than other regions makes measuring spatial diversity more critical.

In the Sakarya region, all criteria have been calculated to have similar or equal weights except for the "Comfort Against Environmental Conditions" criterion, which weighs 10%. This is likely associated with the region's average values for urban density, accessibility, household size, and climate characteristics. The criterion of "Variability in Mass Composition" has a slightly higher weight of 18% compared to others. The mild and semi-humid climate leads to a relatively lower importance weight of 10% for the "Providing Comfort Against Environmental Conditions" criterion.

The multi-criteria decision-making method based on the weighting of criteria by region was tested on a selected group of temporary housing alternatives from the literature. As a result of the test:

For the İstanbul region, alternative NO 3 scored the highest points. The benefit values corresponding to all criteria for choice NO 3 are close to the average level, allowing the option to fulfill all requirements optimally.

In the Muğla region, alternative number 1 received a high score, influenced by the alternative's transportation and storage convenience. Additionally, choices NO 3, 6, and 9 follow closely, with high scores. All these three alternatives have optimal benefit values.

Alternative NO 1 is at the top for the Mus-Bitlis-Van region, and alternative option nine also scored highly. The benefit values for these three alternatives are generally close to the average level. However, considering the region's harsh winter conditions, alternative number 1's higher benefit value for providing comfort against environmental conditions influenced its top placement.

In the Sakarya region, while alternative NO 1 is in first place, choices NO 3, 6, and 9 are close in scores. With similar criteria weights in the Sakarya region, alternatives with generally average or above-average benefit values are favored as optimal choices.

When these findings are generalized, it can be concluded that the portability and storability of alternatives are generally emphasized. This is because of the strong influence of urban accessibility, urban density, and climatic factors, particularly portability. Increased urban density reduces the availability of suitable areas for storing and installing units. Urban density is also a significant factor in hindering post-disaster accessibility. Additionally, harsh climate conditions are another factor that restricts the portability and storability of units. This relationship and interaction between criteria and regional characteristics align with the findings obtained from the evaluation.

4. CONCLUSIONS

When determining the importance weights of criteria based on regional characteristics, decision-makers can consider additional factors representing site-specific attributes such as topography, terrain, orientation, and demographic details such as household diversity, user diversity, and city cosmopolitanism. The decision-makers can also include extra criteria specific to the region, such as sustainability, durability, land settlement flexibility, dismantling, reusability, cost, etc. As a result, the method and process can become more detailed, complex, straightforward, and general.

It is essential to understand that the "factors influencing criteria weights" and "criteria" are inputs and data used in the evaluation method. Any changes in these factors and criteria may affect the evaluation results, but they do not alter the methodology and process of the evaluation. In other words, even if different factors and standards specific to the region are used, the basic structure and method of the approach remain unchanged. Therefore, the study provides a systematic process for identifying and evaluating post-disaster housing systems and proposes a hypothetical approach.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

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Research Article

Effect of calcination on the physical, chemical, morphological, and cementitious properties of red mud

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ABSTRACT

Red mud (RM), a by-product of aluminum production, poses environmental concerns with its disposal. This study explored calcining RM at 600 °C for 0–6 hours to utilize it as a cement substitute. Calcination up to 2 hours decreased particle size and increased surface area due to moisture loss, while further calcination reversed these effects. XRF analysis showed high Fe_2O_3, Al_2O_3, SiO_2 contents. XRD revealed goethite transformed to hematite and gibbsite to alumina. SEM images displayed a loose then denser structure over time. 10% calcined RM incorporated into cement showed 2-hour calcined RM exhibited optimal properties, including high strength (46.27 MPa) and strength activity index (117.24%). SEM confirmed improved C-S-H gel formation with 2-hour calcined RM. In summary, calcining RM optimally at 600 °C for 2 hours allows its effective use as a sustainable cementitious material, providing environmental and technical benefits of RM utilization in cement composites.

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1. INTRODUCTION

In recent years, there has been a growing emphasis on the development of novel technologies to transform waste into value-added products, particularly within industrial and mining sectors. This is due to the increased recognition that reducing waste is a significant environmental concern. By recycling these industrial products, it is possible to mitigate potential environmental and health-related complications, as well as enhance sustainability [1–3]. The present study is mainly focused on utilizing alumina industrial residue (i.e., red mud) as a cementing material. Red mud is a semi-solid residue produced during the extraction of alumina from bauxite, known as the Bayer process, in alumina production. Specifically, for every tonne of alumina extracted, 1.5 tonnes of red mud is generated as a residue [4, 5]. According to the Alam [6] & Mymrin [7], 4 billion tonnes of red mud is accumulated on open lands. Additionally, more than 140 million tonnes of red mud is added to this accumulation from throughout the world every year. Disposal of this large amount of red mud is very difficult due to its alkaline nature and is uneconomical as it requires much land [8]. Moreover, this disposal creates several environmental problems, such as air, water, and land pollution. Recycling of red mud is limited due to its fineness and high alkalinity, which may create an environmental imbalance [9, 10]. Besides, as a waste product, RM does not incur any additional production costs nor does it increase emissions; rather, it decreases emissions from cement production. Utilizing RM as a substitute for cement not only addresses storage concerns but also has the potential to enhance concrete properties, provided that it is used in appropriate quantities [11].

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There are mixed opinions regarding the potential of red mud as a cementing material in cement/concrete composites, based on its strength and durability properties. Nikbin [12] reported that red mud has low cementing activity and shows a negative impact on compressive strength. Therefore, the usage of red mud is limited to the construction of non-structural elements. Su & Li [13] study revealed that incorporating 10% RM resulted in a minor reduction in the compressive strength of concrete, whereas incorporating more than 10% led to a significant decrease. A study by Yang [14] examined cement mortars that were based on red mud. The researchers replaced red mud in varying amounts, ranging from 0% to 9%. The results showed that the addition of red mud increased the mortar's density and improved its compressive strength. According to Ghalehnovi [15], the use of red mud in self-compacting concrete (SCC) resulted in a decrease of 10% and 20% in compressive strength when the red mud content was 7.5% and 10%, respectively. Similarly, Venkatesh [16] reported a 19% decrease in the compressive strength of concrete with the addition of 15% red mud. However, another study found that as the amount of red mud used in concrete increased, the concrete's strength decreased [17]. The decrease in strength can be attributed to the fact that replacing cement with red mud, which has low reactivity, reduces the amount of hydration products per unit volume. Contrarily, W. C. Tang et al. [18] replaced fly ash with red mud in concrete. The study found that as the replacement percentage of red mud increased, the compressive strength improved. Specifically, when 50% of the fly ash was replaced with red mud, higher compressive strength was observed along with good improvement in Interfacial Transition Zone (ITZ). Furthermore, XRD analysis showed the presence of hatrurite and larnite. For instance, many investigations have started using red mud as a secondary or tertiary cementitious material in both normal and geopolymer concretes. In their studies, researchers have blended red mud with various cementing materials, including Slag [19], Metakaolin [20, 21], Fly ash [22], GGBFS [23], Phosphogypsum [24], Granite powder, and marble powder [25], and silica fume [26]. When red mud blend with other cementing materials has shown the considerable improvement in their strength and durability than its individual usage.

Although using red mud to prepare cement and concrete has promising application prospects, the presence of sodium in red mud can be detrimental to the strength and durability of cement and concrete. As a result, the amount of red mud utilized must be carefully controlled, or alternatively, the red mud must undergo a process of dealkalization, which ultimately restricts its application in cement and concrete production [27]. The conventional methods of dealkalization, such as acid neutralization, water leaching, and wet carbonation, are efficient. However, they also reduce the reactivity of red mud and have a negative impact on the performance of concrete. High-temperature treatment is an efficient method for enhancing the reactivity of red mud, as it can decompose some of its inert phases, such as cancrinite, gibbsite, and aragonite, into reactive ones that can easily dissolve in the pore solution [28]. According to Luo [29], the ideal temperature for calcination to completely decompose cancrinite and birnessite in red mud is 1000 °C for one hour, while Danner [30] indicated that calcination at 800 °C for 15 minutes significantly enhanced the reactivity of red mud while decreasing the solubility of sodium. Manfroi [31] performed a calcium hydroxide consumption test and found that calcination at temperature of 600 °C for one hour was the optimal temperature for activating the pozzolanic reactivity of red mud. Liu et al. [32] stated that red mud demonstrated its highest pozzolanic activity when it was calcined for 3 hours at a temperature of 600 °C, which was attributed to the development of poorly-crystallized Ca_2SO_4. Therefore, the general consensus is that calcination is a necessary precondition for red mud to exhibit reactivity. Without calcination, red mud would remain chemically unreactive in Portland cement blends, potentially resulting in weakened strength.

Research significance: Between 2010 and 2023, a total of 6,350 research articles were published on red mud as a cementing material, but less than 50 articles focused on the effect of calcination on red mud (The data was collected from Google Scholar using the following search limitations: a custom range in years from 2010 to 2023, article type set to research articles, and the keyword 'red mud as cementing material'.) There are varying opinions on the ideal calcination temperature for red mud, as its chemical composition differs from one location to another. The red mud produced by Indian aluminium industries, in particular, has limited usage in cement and concrete production due to a lack of literature on its cementing properties. Addressing this research gap, the present study conducted a comprehensive investigation into the physical and chemical properties of red mud, as well as its cementing activity when calcined at temperatures ranging from 600 °C for 1 hour to 6 hours.

2. MATERIALS AND METHODS

2.1. Materials

The present study obtained red mud from the NALCO in Orissa, India, which was in the semi-solid form with 30–40% moisture content during collection. It was dried in a laboratory (approximately 30 °C) for 3 days and then ground in ball mills. OPC-53 Grade cement was used for compressive strength and strength activity index tests, and all properties were within the limits of ASTM C150 [33]. Specifically, the specific surface area was 300 m^2/kg, and the specific gravity was 3.12. Table 1 illustrates the Non-calcined red mud (NC-RM) and cement chemical compositions. The fine aggregates were used in accordance with IS: 383–2016 [34] and Table 2 shows its physical properties.

2.2. Calcination Process

In this study, a high-temperature muffle furnace was used for the calcination of red mud (RM), and a heating rate of 10 °C/min was maintained throughout the calcination process. The RM was calcined at a temperature of 600 °C for 1–6 hours and it is cooled at ambient air temperature for 5 hours in the laboratory after which it was ground in ball mills.

Table 1. Chemical composition (weight %)

	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	TiO_2	K_2O	LOI
OPC	21.26	4.81	4.99	63.71	1.32	0.36	–	0.38	3.17
NC-RM	13.98	21.37	20.97	4.49	0.39	8.12	11.87	3.6	15.21

Table 2. Physical properties of aggregates

	Specific gravity	% of water absorption	Fineness modulus	Bulk density
Fine aggregates	2.69	1.10	2.56	1.46

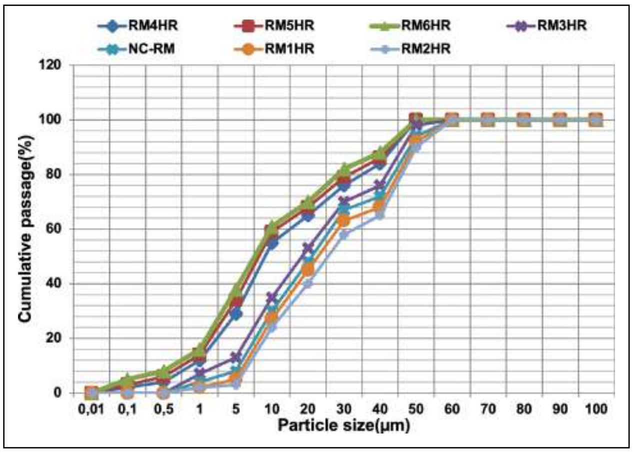

Figure 1. Particle size distribution of various calcined red muds.

2.3. Characterization Methods

In this study, the specific surface area of both calcined and non-calcined red mud samples was determined using the Micromeritics Gemini 237 and Gemini V instruments. Similarly, the particle size of the red mud samples was measured using the SZ-100Z nanoparticle analyzer from Horiba Ltd., Japan. The STA72000 thermal analyzer was used in this study to perform TG-DTA. Nitrogen (N_2) was used as a stripping gas, and all red mud samples were heated at a temperature range of 20 °C to 600 °C with a heating rate of 10 °C/min, as per Wu [35]. The Rigaku MiniFlex 600 with the following parameters was used to identify XRD patterns/phases: 40 kV voltage and 15 mA current, step scan of 0.0200º, scan range from 10º to 70º (2), a scan speed of 100.00 deg/min, and CuKa/1.541862 A wavelength. VEGA 3 SBH, TESCAN Bmo. S.R.O., CZECH REPUBLIC, was used for identifying the surface morphology of calcined and non-calcined red mud samples. In the present study, the X'pert HighScore software tool has been used to analyze the XRD results, and it is supported by the new ICDD PDF-4+/Web licenses.

2.4. Mix Proportions

According to ASTM C109/C109M [36], the mix proportions of cement mortar samples are calculated, and the proportional ratios are as follows: 1:3:0.52 (i.e., binder: fine aggregates: water-to-cement ratio). In this study, 10% of various calcined red mud has been replaced with cement in all the mixes. A total of 48 mortar samples (with a size of 50 mm on each side of the cube) are prepared and cured for 7 and 28 days in portable water, following ASTM C31/C31M [37].

2.5. Strength Activity Index

The compressive strength and strength activity index (SAI) tests are evaluated on the red mud-induced cement mortar samples according to the ASTM C109/C109M [36] and ASTM C311/C311M [38] standards. Equation 1 is used to evaluate the strength activity index of red mud-induced cement mortar samples.

$$SAI(\%)=\frac{\text{Compressive strength of red mud induced cement mortar samples}}{\text{Compressive strength of normal cement mortar samples}}\times 100 \quad \text{Eq.1}$$

3. RESULTS AND DISCUSSION

3.1. Calcination Effect on Physical Properties of Red Mud

In this study, particle size analysis was conducted on the calcined red mud particles, as shown in Figure 1. The results show that all the red mud particles fall within the range of 1–50 µm, with an average particle size of 8 µm. The specific surface areas were measured using the BET apparatus and are illustrated in Table 2. Non-calcined red mud has a specific surface area of 1.86 m^2/g, which increases to 2.2 m^2/g after 2 hours of calcination. This increase is attributed to the loss of moisture in the particles and the destruction of alumina silicates present in the red mud particles, as mentioned by Liu [32]. They also state that specific surface area values decrease to 1.95 m^2/g after 6 hours due to particle aggregation. According to Wu [35], the crystallinity of red mud particles increased with the enlargement of red mud particle size and the reduction in specific surface area resulting from calcination. Nath [39] have made similar conclusions, stating that particle size is enriched up to 200 ^{0}C of heating due to improved crystallinity. However, particle collision observed at a temperature of 500 ^{0}C leads to a reduction in particle size.

In this study, the specific gravity of red mud was measured according to IS 4031 Part-11 (1988) [40]. Table 3 illustrates the variations in the specific gravity of red mud when calcined at a temperature of 600 °C for 1 to 6 hours, and it is compared with non-calcined red mud. The specific gravity of red mud decreased by about 1.65% during 2 hours of calcination compared to non-calcined red mud, attributable to moisture loss in the particles. However, after 2 hours of calcination, the specific gravity values increased from 0.4% (at 3 hours) to 3.25% (at 6 hours). This effect can be attributed to agglomeration between the red

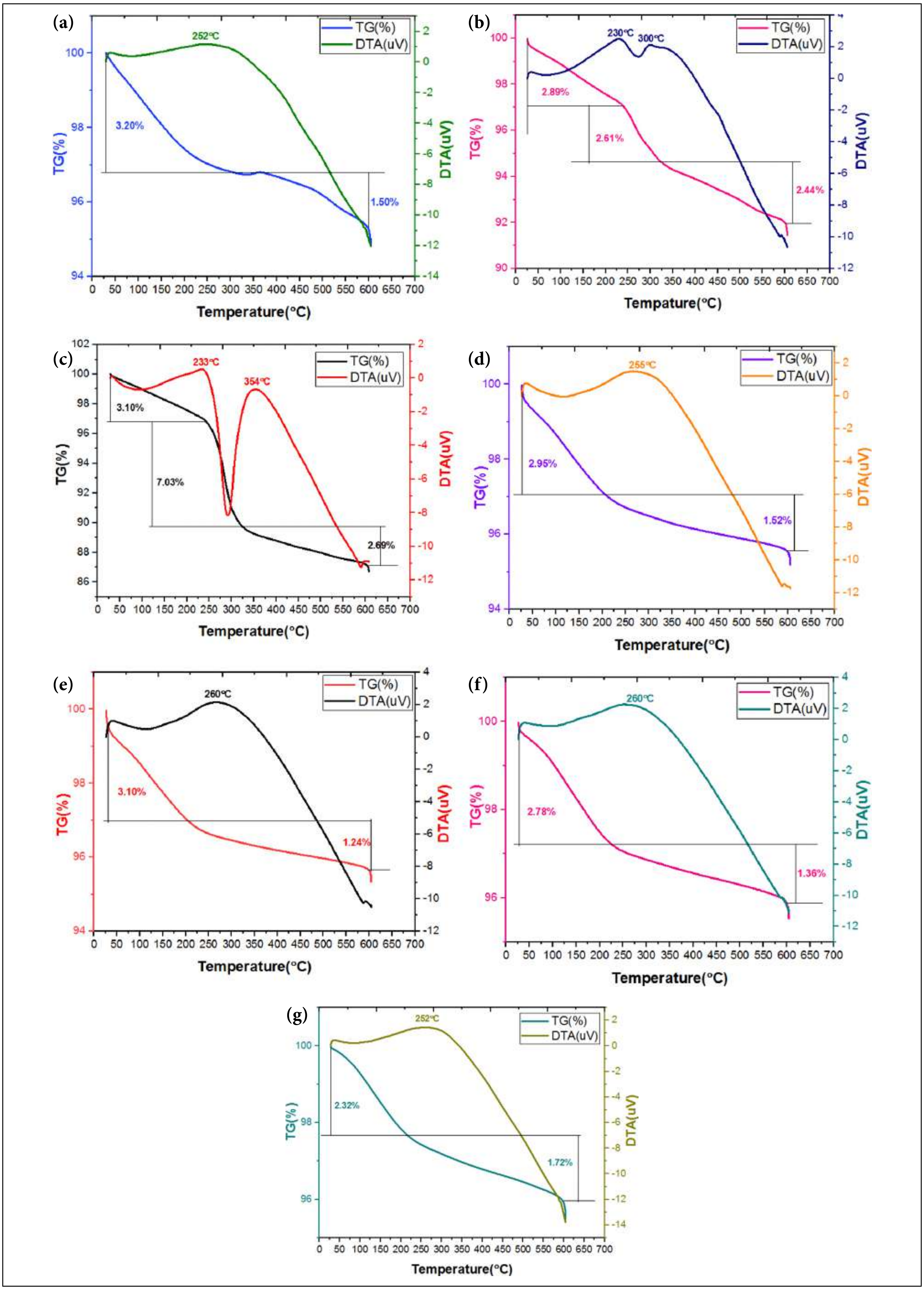

Figure 2. TG-DTA analysis of calcined red muds **(a)** NC-RM, **(b)** RM1HR, **(c)** RM2HR, **(d)** RM3HR, **(e)** RM4HR, **(f)** RM5HR and **(g)** RM6HR.

Table 3. Physical properties of red mud after calcination

	NC-RM	RM1HR	RM2HR	RM3HR	RM4HR	RM5HR	RM6HR
SSA (m^2/g)	1.86	1.95	2.2	2.16	2.1	2.05	1.95
Mass loss (%)	4.7	7.94	12.82	4.47	4.34	4.14	4.04
Specific gravity	2.46	2.44	2.42	2.47	2.5	2.51	2.54

Table 4. Chemical composition of calcined red mud (weight %)

Temp/time	CaO	Al_2O_3	Fe_2O_3	SiO_2	Na_2O	K_2O	TiO_2	MgO	LOI
NC-RM	4.49	20.97	21.37	13.98	8.12	3.6	11.87	0.39	15.21
RM1HR	7.53	26.15	22.54	17.6	5.44	3.03	7.92	0.84	8.95
RM2HR	10.84	22.62	21.79	21.92	3.87	1.89	5.5	0.65	10.92
RM3HR	9.66	24.63	22.47	19.82	5.03	2.48	6.72	0.92	8.27
RM4HR	8.44	21.08	24.01	19.46	5.81	2.19	7.01	1.26	10.74
RM5HR	8.54	22.54	24.06	18.47	8.24	2.27	7.19	0.41	8.28
RM6HR	12.3	20.2	21.46	16.89	10.35	2.22	8.17	0.33	8.08

mud particles Zhang [41] and Wang [42] reported that specific gravity values significantly varied when red mud was thermally activated.

In this study, thermogravimetry analysis was conducted on all calcined red mud particles to measure the mass loss, as shown in Table 3. Figure 2 depict the TG-DTA curves of all calcined red mud particles. The mass of the red mud particles varied with different calcination durations: 4.7% for non-calcined, 7.94% for 1 hour at 600 ^{0}C, 12.82% for 2 hours at 600 ^{0}C, 4.47% for 3 hours at 600 ^{0}C, 4.34% for 4 hours at 600 ^{0}C, 4.14% for 5 hours at 600 ^{0}C, and 4.04% for 6 hours at 600 ^{0}C. However, the reason for the mass loss observed up to 2 hours of calcination was attributed to dissipation of physical and chemically bound water.

Based on the obtained results, it was observed that all the physical properties, namely specific gravity, particle size, specific surface area, and mass loss, exhibited similar behavior. The calcination of red mud significantly influenced its physical properties. However, moisture loss was observed in the red mud for up to 2 hours of calcination. Subsequently, the physical properties were enhanced, which can be attributed to particle agglomeration.

3.2 Calcination Effect on Chemical Properties of Red Mud

Table 4 displays the chemical composition of red mud under different calcination durations at a temperature of 600 ^{0}C. Alumina, silica, and iron oxides were found to be the major components in all calcined red mud samples. Among them, the red mud subjected to a 2-hour calcination at 600 ^{0}C exhibited higher levels of silica and calcium oxide compared to the other calcined red mud samples. This increase in silica and calcium oxide content contributes to the enhanced cementitious activity of the red mud particles.

In this study, X-ray diffraction analysis was conducted to evaluate the phase transformations in red mud during calcination at a temperature of 600 ^{0}C for different durations (1 to 6 hours), as shown in Figure 3. The following mineralogical phases/compounds were identified: 1. Goethite (FeO(OH)), 2. Hematite (Fe_2O_3), 3. Gibbsite $Al(OH)_4$, 4. Boehmite (AlO(OH), 5. Alumina-(Al_2O_3), 6. Lawsonite-($CaAl_2Si_2O_7(OH)_2(H_2O)$), 7. Margarite-($CaAl_2(Si_2Al_2O_{10})(H_2O)$), 8. Rutile-($TiO_2$), 9. Perovskite ($CaTiO_3$), 10. Sodium titanium oxide(Na_2TiO_3), 11. Quartz-(SiO_2), 12. Sodalite-($Na_{7.89}(AlSiO_4)_6(NO_3)_{1.92}$), 13. Sillimanite-($Al_2(SiO_4)O$).

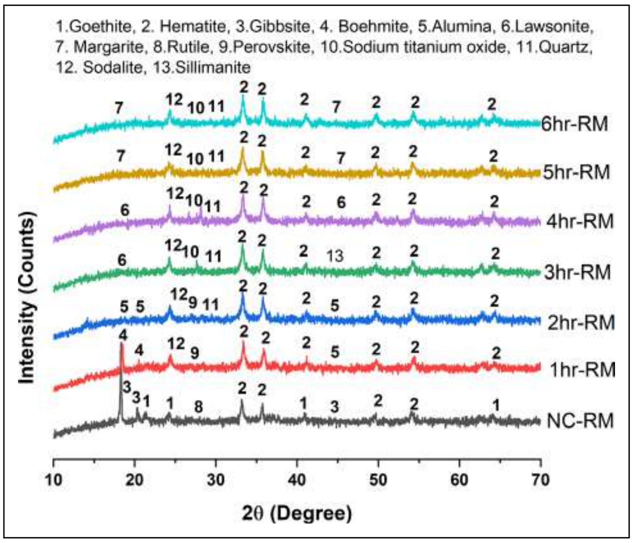

Figure 3. X-ray diffractogram of calcined red muds.

Gibbsite was observed at 2□=14.47 with a d-spacing of 6.1215 in non-calcined red mud. However, after 1 hour of calcination at 600 ^{0}C, it transformed into boehmite due to moisture loss in the particles. Subsequently, boehmite further converted into alumina after 2 hours of calcination at 600 ^{0}C. Hematite showed no significant phase changes throughout all the calcined durations, with traced positions at 2□=33.20, 35.68 and d-spacing of 2.6982, 2.5164. According to Nath [39], hematite remains stable up to 1200 ^{0}C.

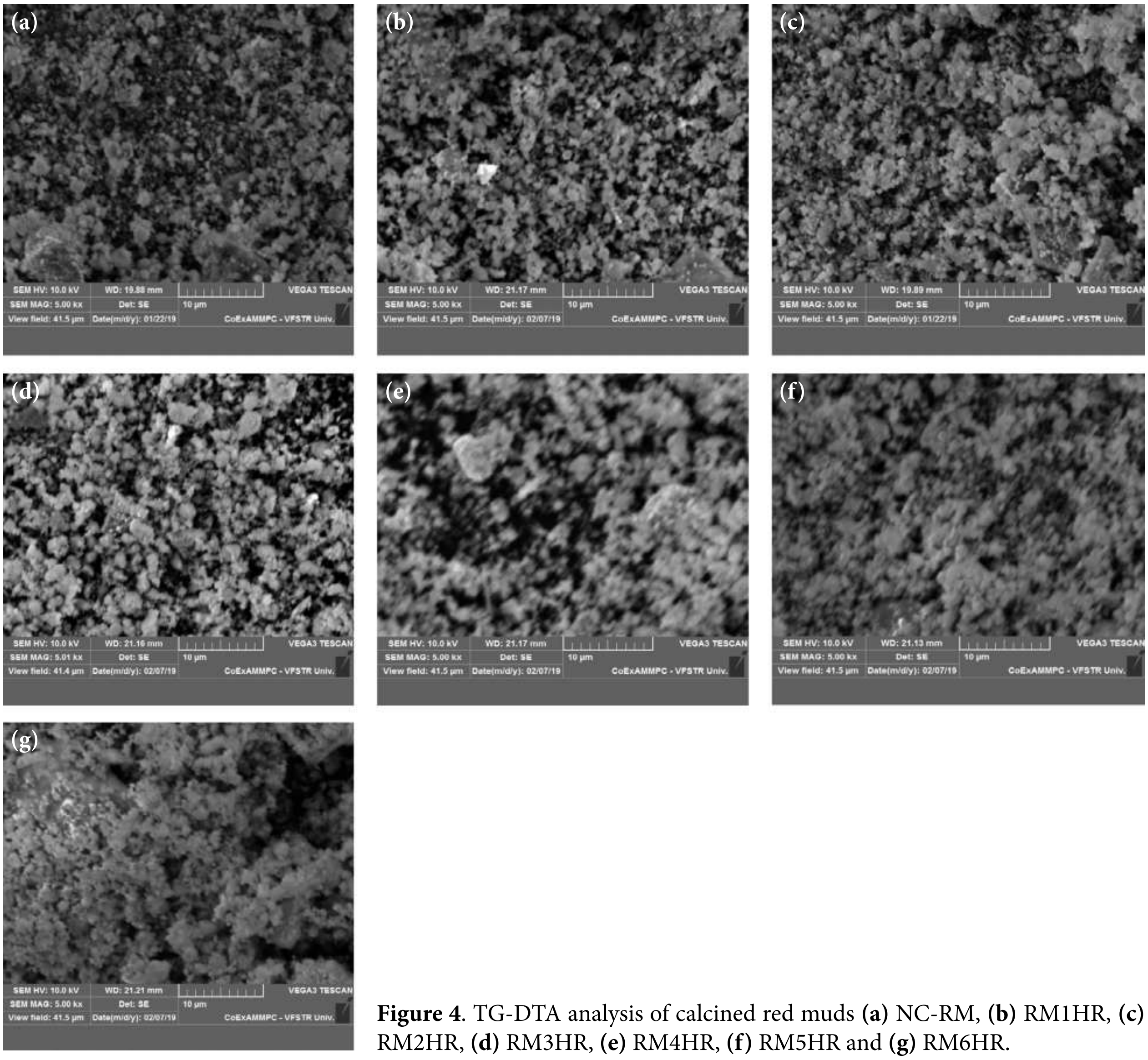

Figure 4. TG-DTA analysis of calcined red muds **(a)** NC-RM, **(b)** RM1HR, **(c)** RM2HR, **(d)** RM3HR, **(e)** RM4HR, **(f)** RM5HR and **(g)** RM6HR.

Table 5. Elemental composition of calcined red mud replaced mixes (weight %)

Mixes	28 days						
	O	Ca	Si	Al	Fe	Ca/Si	Total
NC-RM	56.51	22.69	16.91	3.19	0.7	1.34	100
RM1H	56.45	21.42	18.17	3.1	0.86	1.18	100
RM2H	58.71	18.2	19.19	3.09	0.81	0.95	100
RM3H	57.89	18.91	19.1	3.05	1.05	0.99	100
RM4H	61.01	21.05	15.25	2.24	0.45	1.38	100
RM5H	55.52	25.59	15	3.19	0.7	1.71	100
RM6H	55.52	24.42	16.1	3.1	0.86	1.52	100

Lawsonite transformed into sodalite, which explains the separation of calcium oxide during the calcination process. Rutile, initially present in the non-calcined red mud, changed to perovskite after 1 hour of calcination at 600 ^{0}C, and further calcination resulted in the complete transformation to sodium titanium oxide. S.N. Meher [43] also observed similar phase transformations, from rutile to perovskite. This phase change suggests that the calcium oxide present in the red mud may react with titanium oxide and form perovskite ($CaTiO_3$).

Quartz was detected between 2θ values of 25 to 30 in the 2-hour calcined red mud, and it continued to be present in further calcined red mud samples as well. The chemical

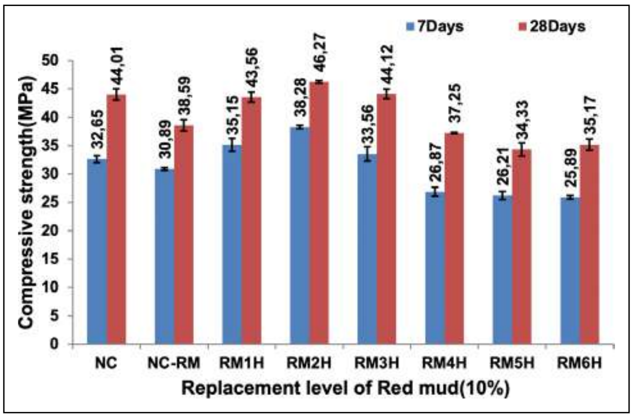

Figure 5. Compressive strength.

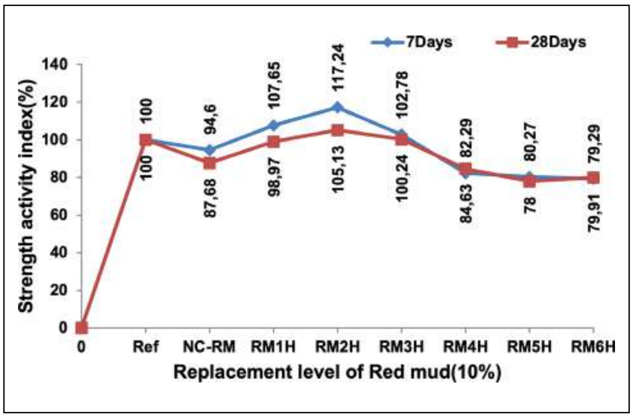

Figure 6. SAI Vs. Compressive strength.

composition results (mentioned in Table 3) also indicated the presence of stable or higher levels of silica (SiO_2) after 2 hours of calcination.

Scanning electron microscopy (SEM) analysis was conducted to examine the surface morphology of red mud particles during various calcination processes. Figure 4 illustrates the SEM images of different calcined red mud particles. Microscopic observations revealed that the red mud particles exhibit an irregular shape. However, up to 2 hours of heating at 600 ^{0}C, the red mud particles maintain a loose structure. In particular, Figure 4c shows a more poorly crystalline structure compared to others, which may indicate higher reactivity and better cementitious activity. A similar conclusion was made by Liu [32], stating that red mud forms a poorly crystalline structure when thermally activated, providing ideal cementitious activity. Subsequently, a dense structure is observed from 2 hours to 6 hours of heating at 600 ^{0}C as the particles undergo agglomeration, resulting in their combination with surrounding particles. Similar observations regarding the physical properties of red mud were made in this study.

3.4. Calcination Effect on Cementitious Properties of Red Mud

The present study conducted the strength activity index test according to ASTM C311/C311M [38] to investigate the cementitious properties of red mud particles. In this regard, the cement mortar mixes were prepared by replacing the 10% of cement by calcined red mud (Calcined at a temperature of 600 ^{0}C during 1 to 6hours). The results showed that the cement mortar samples containing 600 ^{0}C@2hr (i.e., RM2HR) calcined red mud exhibited high strength, specifically 46.27 MPa, as shown in Figure 5. This effect can be attributed to the higher percentage of silica and the increased specific surface area of the red mud particles, which enhance the hydration process of the cementitious matrix.

Figure 6 illustrates the strength activity index percentages of calcined red mud induced cement mortar mixes; 107.65% for RM1HR, 117.24% for RM2HR, 102.78% for RM3HR, 82.29% for RM4HR, 80.27% for RM5HR, and 79.29% for RM6HR. According to the ASTM C311/C311M [38], Wang et al. [44] and [45, 46] If the strength activity index values exceed 75%, the material exhibits good cementitious properties and is suitable for use as a cementitious material in concrete/mortar. Microstructure analysis revealed that red mud possesses significant cementitious properties as like cement. SEM images in Figure 7 indicate the formation of C-S-H (calcium silicate hydrate) and CH (calcium hydroxide). Notably, the cement mortar mixes with 2hr calcined red mud replacement exhibited better C-S-H gel formation than other mixes, as observed through the Ca/Si ratios in the elemental composition of red mud replaced mixes, as shown in Table 5. The RM2HR calcined red mud containing mortar mix has low Ca/Si of 0.95 this is the reason for achievement of high strength (i.e., 46.27 MPa) and strength activity index values (i.e., 117.24%). According to Rossignolo [47] and MSR chand [48], the presence of C-S-H can be justified by the Ca/Si ratio of the EDXA (Energy-Dispersive X-ray Analysis) elemental weight percentages. A Ca/Si ratio ranging from 0.8 to 2.5 confirms the presence of C-S-H gel, while a lower Ca/Si ratio indicates a stronger or higher C-S-H gel formation Venkatesh [49].

4. CONCLUSIONS

In this study, red mud, a by-product of the Indian alumina industry (specifically NALCO), was calcined at a temperature of 600 °C for 1 to 6 hours to evaluate its potential usage as a cementing material in cement/concrete production. The following conclusions were drawn after comprehensive assessments of its physical, chemical, morphological, and cementing properties.

- Chemical evaluation studies have identified that red mud contains abundant amounts of silica, iron oxide, and alumina. In the case of calcined red mud at 600˚C for 2 hours (600˚C@2hr), it was found to contain 10.84% CaO, 21.92% SiO_2, and 22.62% alumina, making it more suitable as a cementing material.
- Based on the XRD analysis, hematite remained stable throughout the calcination process. However, gibbsite in non-calcined red mud transformed into boehmite at RM1HR, and further calcination at 600 °C for 2 hours resulted in its conversion into alumina.
- The RM2HR calcined red mud replacement mixes exhibited high compressive strength and strength activity index values, specifically 46.27 MPa and 117.24%. It

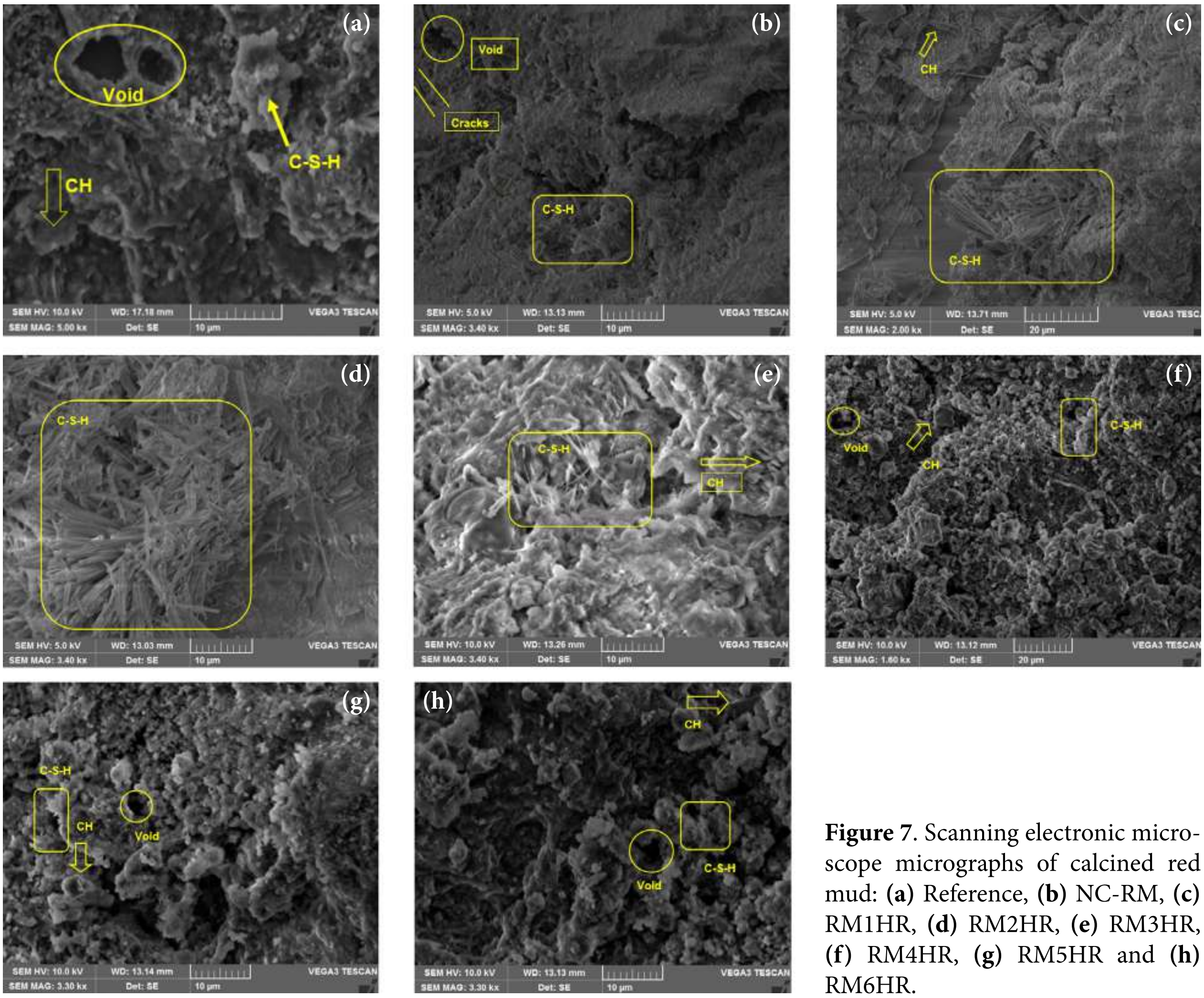

Figure 7. Scanning electronic microscope micrographs of calcined red mud: **(a)** Reference, **(b)** NC-RM, **(c)** RM1HR, **(d)** RM2HR, **(e)** RM3HR, **(f)** RM4HR, **(g)** RM5HR and **(h)** RM6HR.

was observed that this particular red mud contained a higher amount of silica (21.92%), a large specific surface area (2.2 m^2/g), and a poorly crystalline structure. These factors played a positive role in the cementing activities.

- Finally, NALCO-produced red mud can be utilized as a cementing material in cement/concrete production after undergoing calcination at a temperature of 600 °C for 2 hours.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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Research Article

Mechanical, freeze-thaw, and sorptivity properties of mortars prepared with different cement types and waste marble powder

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ABSTRACT

The cement production process contributes significantly to CO_2 gas emissions and environmental pollution. To reduce this adverse effect, the substitution of waste marble powder as a cement additive was investigated. In this study, the properties of mortar specimens were analyzed by using waste marble powder as a partial substitute for three different cement types: CEM I 42.5R Ordinary Portland Cement (OPC), CEM II/B-L 42.5R White Cement (WC) and CA-40 Calcium Aluminate Cement (CAC). Waste marble powder has been replaced with cement at 5%, 10%, and 15%. The compressive and flexural strength, capillary water absorption, and sorptivity values of the prepared mixtures were determined before and after freezing and thawing. It was carried out after 28 days of water curing on 50 x 50 x 50 mm specimens for compressive strength and 160 x 40 x 40 mm specimens for flexural strength test. Freeze-thaw testing of the mixture samples was conducted according to ASTM C666 Procedure A. Test results showed that the highest compressive strength before freeze-thaw was obtained in calcium aluminate cement-based mortars containing 10% by weight waste marble powder replacement for cement. The appropriate waste marble powder ratio was determined as 10% in all cement types used in the study. Before freeze-thaw, the mechanical properties of CAC-based mixtures were higher than those of other cement types. However, as the number of freeze-thaw cycles increased, the strength losses were more significant compared to OPC and WC.

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1. INTRODUCTION

Concrete is the most widely used building material worldwide due to its low price, easy accessibility of its components, ability to give the desired shape, and provide the necessary strength and durability [1, 2]. Cement, the most used binder material in concrete production, is the primary source of CO_2 emissions. Ordinary Portland Cement (OPC) production contributes about 5% to 7% of global CO_2 emissions [3, 4]. It has been determined that the concrete production in Türkiye as of 2014 is approximately 70 Million Tonnes (Mt); therefore, about 65 Mt of CO_2 has been released [5, 6].

Cement production significantly impacts CO_2 emissions and can be reduced using waste materials that improve concrete's fresh and mechanical properties. Among these waste materials, marble powder, mainly found in Turkey, India, China, and Italy, is used as a cement substitute in concrete production. The production of marble waste is estimated to be around 3 Mt annually [5]. During the processing of natural marble, a significant amount of powder particles are released into the environment, creating waste.

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Disposing waste materials from these powder particles can be complex and contribute significantly to environmental damage by contaminating natural resources [6].

Marble powder is used in concrete and mortar production due to its chemical structure and filling properties. This can reduce environmental damage and contribute to a sustainable approach in the construction industry. The filling effect of marble powder forms a denser mixture, improving the transition zone and cement matrix. This may cause an increase in the strength of the mixtures by adding low amounts of marble powder. Additionally, dolomite ($CaMg(CO_3)_2$) found in WMP reacts with the alkalis of cement to form calcium carbonate ($CaCO_3$). As a result of the reaction between calcium carbonate and the C_3A component of cement, a more compact structure is formed that increases the binding capacity of the matrix [7]. Munir et al. [8] reported that calcite in WMP reacted with C_3A to form calcium carbo-aluminate, and better compressive strength was obtained in mixtures containing WMP. There are several studies in the literature on the substitution of waste marble powder (WMP) for Ordinary Portland Cement (OPC). Uysal and Yılmaz [9] determined that the properties of fresh concrete were improved by replacing the cement with marble powder at 10%, 20%, and 30% by mass. Aliabdo et al. [10] determined that the 28-day compressive strength decreased by 7%, 4%, 5%, and 14% when replacing 5%, 7.5%, 10%, and 15% marble powder with OPC compared to the control specimen. Ergün [11] reported that substituting 5% and 7.5% WMP for cement increased the compressive strength, but using 15% decreased the strength. Ashish [5] observed that adding 15% WMP to the concrete increased the compressive strength by 4.5% and 10.4% at 28 and 91 days of curing times, respectively, compared to the control specimen. Rodrigues et al. [12] determined that replacing cement with marble powder up to 10% in concrete does not adversely affect the compressive strength. Still, replacing 20% marble powder reduces the compressive strength by 25%.

Studies in the literature on the durability of concrete are attracting increasing attention. Freeze-thaw (FT) is among the main reasons for the loss of durability of concrete, especially in cold climates [13, 14]. Due to the porous structure of concrete, repetitive FT cycles cause the concrete to lose strength and crumble by exfoliating [15]. Freeze-thaw studies in the literature on waste marble powder have generally focused on substituting WMP with fine aggregate in concrete [15–18]. İnce et al. [16] reported that the FT resistance of concrete to which waste marble powder was added increased.

Another issue is that the Ordinary Portland Cement (OPC) was used in all studies based on the literature above. However, due to the large amount of CO_2 released by OPC, studies on the discovery and application of cementing materials to ensure sustainability in cement production continue [19]. Calcium aluminate cement (CAC) releases approximately 30% less CO_2 than OPC during production. In addition, CAC is preferred in refractory material production, wastewater, and industrial floor applications due to its high early strength and resistance to harsh environmental conditions such as acid and high temperature [20, 21]. However, the use of CAC in structural system elements is prohibited due to instability in compressive strength due to the transformation of hydration products that contribute to the early high strength of CAC [22, 23].

Table 1. Chemical characteristics of OPC, CAC, WC, SF and WMP

Compound	OPC (%)	CAC (%)	WC (%)	SF (%)	WMP (%)
SiO_2	17.73	3.60	21.60	95.60	0.80
Al_2O^3	4.56	39.80	4.05	0.40	0.60
Fe_2O_3	3.07	17.10	0.26	0.80	0.80
CaO	62.81	36.20	63.70	0.40	57.20
MgO	2.07	0.65	1.30	0.60	9.60
K_2O	0.62		0.35	0.40	0.03
SO_3	2.90	0.04	3.30	0.20	0.04

2. RESEARCH SIGNIFICANCE

Studies on sustainability in the building sector have attracted much attention in recent decades. In most studies, WMP has been used by replacing fine aggregate. Although this situation contributes to the use of waste materials, it does not positively affect the CO_2 emission originating from the cement. In addition, most of the studies in the literature have focused on OPC. However, regarding sustainability, examining and using CAC, which causes less CO_2 emissions, is very valuable in reducing environmental problems. This study aims to investigate the freeze-thaw effect, lacking in the literature, by substituting waste marble powder in the mortar instead of cement. Another important aim is to examine the usability of CAC and white cement (WC) with WPM and compare it with OPC. The study was considered to compare CEM I cement, which is frequently used in practice, with two particular types of cement (white and calcium aluminate). The use of CAC and WMP together is important in terms of sustainability. In this context, mortar specimens were prepared by replacing 5%, 10%, and 15% WMP with three different types of cement. In addition, silica fume (SF) was used at the ratio of 10% by weight of cement in all mixtures. These specimens were subjected to compressive strength, flexural strength, and capillary permeability tests. In addition, the specimens were left to 3 different freeze-thaw cycles, and the same tests were repeated.

3. EXPERIMENTAL PROGRAMME

3.1. Materials

In this study, three different types of cement were used in the preparation of mortar mixes: OPC (CEM I 42.5 R), CAC (CA-40), and WC (CEM II/B-L 42.5R). WMP was replaced by weight with three different cement types at 5%, 10%, and 15%. In addition, since the risk of segregation was observed in the mixtures as a result of preliminary experiments, 10% of the binder amount of SF was used in all mixtures to increase the viscosity. The chemical and physical properties of OPC, CAC, WC, SF, and WMP are in Tables 1 and 2, respectively.

Table 2. Physical properties of OPC, CAC, WC, SF and WMP

Property	OPC	CAC	WC	SF	WMP
Specific gravity	3.15	3.25	3.06	2.20	2.73
Loss on ignition (%)	2.05	0.30	3.20	0.60	42.60
Insoluble residue (%)	0.66	0.16	0.18		0.91
Specific surface	3450[a]	3000[a]	4600[a]	19800[b]	
Compressive strength of cement (Mpa)					
Two days	25	60	24		
28 days	48		46		

a: Blaine method (cm^2/g); b: BET method (m^2/kg).

Table 3. Mix proportions of mortars (kg/m^3)

Mixture codes	Cement	Silica fume	WMP	Fine agg.	Water	Superplasticizer
OPC-0	540	60		1404	252	6
OPC-5	510	60	30	1398	252	6
OPC-10	480	60	60	1396	252	6
OPC-15	450	60	90	1391	252	6
CAC-0	540	60		1416	252	6
CAC-5	510	60	30	1412	252	6
CAC-10	480	60	60	1409	252	6
CAC-15	450	60	90	1404	252	6
WC-0	540	60		1391	252	6
WC-5	510	60	30	1386	252	6
WC-10	480	60	60	1383	252	6
WC-15	450	60	90	1380	252	6

Within the scope of the experimental study, the specific gravity and water absorption ratio of the sand were determined according to EN 1097-6 [24]. River sand with a specific gravity of 2.60, water absorption value of 1.80%, and fineness modulus of 3.42 was used as fine aggregate. In addition, in this study, a new generation superplasticizer polycarboxylate-based with the pH and specific gravity of 6 and 1.065, respectively.

3.2. Mix Proportions

The mixing ratios of the mortar specimens prepared within the scope of this study are given in Table 3. In similar studies in the literature, it has been determined that generally, between 500–600 kg/m^3 of binder material is used. In EFNARC 2005 [25], the total powder content was recommended to be 400–600 kg/m^3. All mixtures kept the binder amount constant at 600 kg/m^3 for these reasons. In addition, 10% of the binder amount of SF was used in all the mixtures. Waste marble powder was replaced with cement at 5%, 10%, and 15% of the total binder amount. The water/binder ratio was determined as 0.42 in all mixtures. To ensure the workability of the fresh mortar, 1% of the binder amount was used as a superplasticizer. According to these parameters, 13 different mortar mixtures were prepared. Each mixture is named according to the type of cement used in the mix and the ratio of waste marble powder. For example, in a CAC-10 code, the first three letters (CAC) indicate the use of calcium aluminate cement, and the adjacent numbers (10) represent the amount of waste marble powder in the mortar mix.

3.3. Test Methods

To determine the workability of the self-compacting mortar (SCM), the mini-slump flow test was applied according to EFNARC [25]. The workability values of the SCMs were evaluated according to criteria of 240–260 mm for the slump flow diameter. The mortar specimens' compressive and flexural strength tests were carried out by ASTM C109 [26] and ASTM C348 [27] standards, respectively. It was carried out after 28 days of water curing on 50 x 50 x 50 mm specimens for compressive strength and 160 x 40 x 40 mm specimens for flexural strength test.

Also, within the scope of the experimental program, 50 × 50 × 50 mm cube specimens were tested at age 28 days according to ASTM C1585-13 [28] to calculate the capillary water absorption and sorptivity coefficients of SCM mixtures. For the capillary water absorption test, the four side surfaces of the specimens were covered with a seal using vinyl electrician tape and exposed to 1–3 mm of water from only one surface. All mixture specimens' weight and cross-sectional area were measured before the capillary water absorption test. Capillary water absorption was deter-

Figure 1. SCM specimens **(a)** in mixture, **(b)** slump test, **(c)** in water curing pool, **(d)** sorptivity test, **(e)** flexural strength test.

mined by measuring the weights of the specimens at 5, 10, 30, 60, 120, 180, 240, 300, and 360 min time intervals. Laboratory images of experimental studies are given in Figure 1.

Freeze-thaw (F-T) testing of mixed specimens was performed according to ASTM C666 [29] Procedure A. The specimens were subjected to 3 different cycles (30, 60, 90) after 28 days of curing, and then compressive strength, flexural strength, and capillary permeability tests were performed. Ambient conditions were set to have cycles of freezing at -18°C and thawing at 4°C.

4. RESULTS AND DISCUSSIONS

4.1. Workability

The slump-flow diameter test results of the mixtures are presented in Figure 2. Significant decreases were detected in the slump flow diameters of the mixtures with WMP added, and this was more evident in the mixtures using 10% and 15% WMP. This can be attributed to the fact that the specific surface area of waste marble powder is higher than cement, thus reducing workability by increasing internal friction [5]. Rashwan et al. [30] reported that waste marble powder's angular, rough shape and high fineness reduce workability. Li et al. [31] stated that drier mixtures were obtained by substituting cement paste with waste marble powder at higher rates than the control mixture. It was determined that the flow diameters of all mixtures were between 240–260 mm, specified in EFNARC, with the effect of the superplasticizer. OPC-based mixtures were obtained with slump flow diameters of 258, 257, 252, and 248 mm

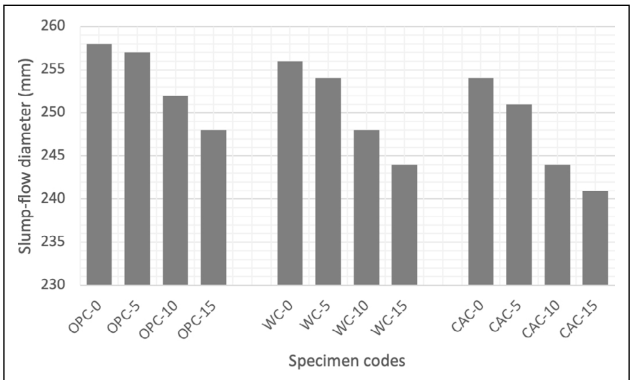

Figure 2. Slump-flow diameters of mixtures.

for OPC-0, OPC-5, OPC-10, and OPC-15, respectively. The slump-flow diameters of the WC-based mixes ranged from 24.4 to 25.6 cm. The lower flow diameter of WC-based mixtures compared to OPC can be attributed to the higher specific surface area of WC (4600 cm^2/g) compared to OPC (3450 cm^2/g). The most significant reduction in flow diameter was obtained in CAC-based mixtures. While the flow diameter of the CAC-0 series was 254 mm, this value was measured as 241 mm in the CAC-15 series.

4.2. Properties of Mortar Specimens Before Freeze-Thaw Cycles

4.2.1. Compressive Strength

The 28-day compressive strength results of SCM specimens before freezing and thawing are given in Figure 3.

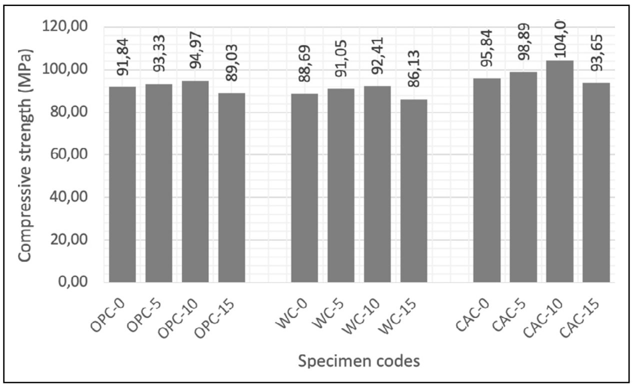

Figure 3. Compressive strength results of mixtures.

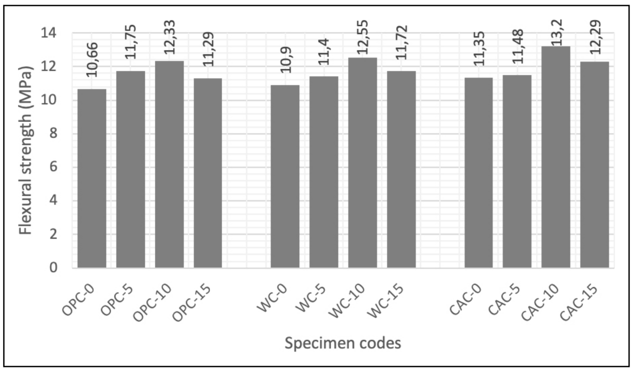

Figure 4. Flexural strength results of mixtures.

Adding WMP up to 10% in all cement series increased compressive strength. This result can be attributed to fine WMP enhancing the properties of the transition zone surrounding the aggregate through its pore-filling effect [10]. As a result of the replacement of cement with 5% WMP at 28-day curing ages, an increase of 1.62%, 2.66%, and 3.18%, respectively, in the compressive strength of the OPC, WC, and CAC series was observed. When replacing 10% WMP with cement, it was determined that the compressive strength of OPC, WC, and CAC series increased by 3.41%, 4.19%, and 8.60%, respectively. Ashish [5] found that adding 10% marble powder instead of cement increased the compressive strength by 8.44% compared to the control specimen. Aliabdo et al. [10] detected that using 5% and 10% WMP caused an increase in compressive strength of 1% and 12%, respectively. It is observed that the strength of the mortar slightly decreased at the 15% level of WMP used as a cement substitute. This is due to reduced cementing materials such as C_3S, C_2S, and C_3A. While 15% WMP substitution reduced the strength by 3.06% in the OPC mixtures, it decreased it by 2.88% and 2.29%, respectively, in the WC and CAC mixtures.

Ergün [11] observed that substituting 5% and 7.5% of cement with WMP increases the compressive strength and decreases the strength by 15%. The optimum WMP ratio was determined as 10% for all cement types. In their research, Vardhan et al. [32] reported that the substitution of 10% WMP is optimum for cement in terms of workability and compressive strength.

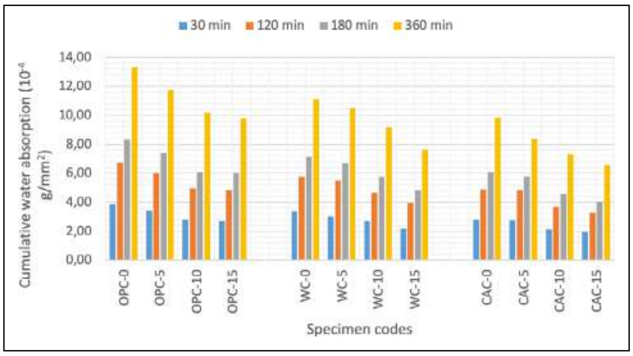

Figure 5. Cumulative capillary water absorption results of mixtures.

As a result of examining the compressive strength in cement types, the highest compressive strength value in all WMP replacement ratios was obtained in the mixtures using CAC. The highest compressive strength value of 104.09 MPa was found in CAC using 10% WMP in all mixes. Although WMP is not pozzolanic, it is not entirely inert because it can react with the alumina phases of cement [9]. If there is an excess of C_3A in the cement, carbo aluminate will be produced from the reaction between $CaCO_3$ and C_3A in WMP [33, 34]. This reaction, which increases compressive strength, increases with the C_3A content in the cement (OPC and WC). In the series without WMP, the highest compressive strength value was obtained from the CAC-0 series, while this value was 8.06% and 4.35% higher compared to the WC-0 and OPC-0 series. In the series using 5%, 10%, and 15% WMP, the compressive strength of CAC-based mixtures was 5.96%, 9.60%, and 5.19% higher, respectively, than OPC. Idrees et al. [35] investigated the properties of CAC and OPC at different curing temperatures using various mineral additives. As a result of the study, they observed that the 28 and 90-day strength values of the CAC-based mixtures were higher than the mixtures with OPC at low curing temperatures (20^{0}C). The high early strength of CAC compared to OPC was attributed to the formation of CAH_{10} and C_2AH_8, which are the dominant hydration products of CAC at low curing temperatures. The compressive strength values of WC-based mixtures using 0%, 5%, 10%, and 15% WMP were approximately 3.43%, 2.44%, 2.70% and 3.26% lower than OPC-based mixtures, respectively. The higher surface area of WP compared to OPC resulted in a decrease in its workability. This may cause small voids in SCMs that self-compact under their weight without requiring additional processing. As a result, this phenomenon may be why the compressive strength of OPC-based mixtures is slightly higher than that of WP-based mixtures.

4.2.2. Flexural Strength

The flexural strength results of the mixtures are given in Figure 4. The highest flexural strength was obtained from the CAC-10 series with 13.20 MPa. Similar to the compressive strength results, flexural strength increased in all cement types up to 10% WMP use. Substitution of 5% and 10% WMP in OPC-based blends increased flexural strength by 10.23% and 15.67% compared to the OPC-0 blend. Ergün

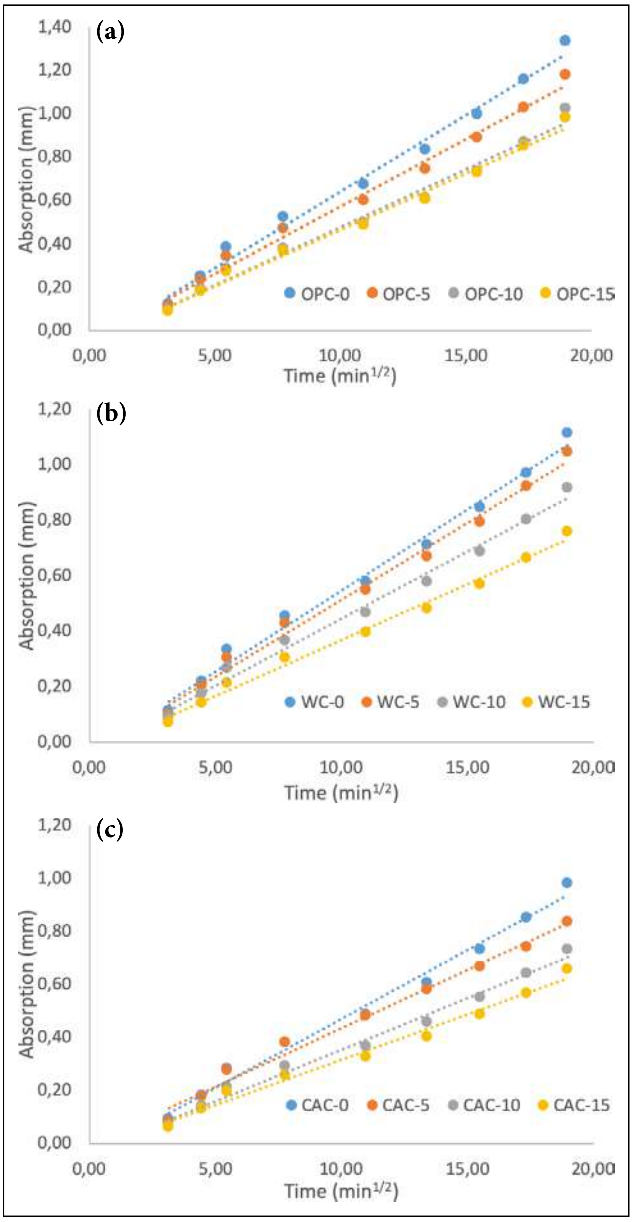

Figure 6. SCM specimens absorption (mm) **(a)** OPC-based mixtures, **(b)** WC-based mixtures, **(c)** CAC-based mixtures.

[11] observed that using WMP did not cause a significant change in the relative flexural strength of the mixture samples. As a result of the study, a 5% increase in the 90-day flexural strength of mixtures containing 5% WMP was reported compared to the reference sample. Kumar et al. [36] stated that 5% WMP replacement increased the flexural strength of the mixtures by 3% and 7% in 7 and 28 days, respectively. It was observed that 5% WMP substitution increased the flexural strength of WC and CAC-based mixtures by 4.59% and 1.15% compared to WC-0 and CAC-0 mixtures. 10% WMP substitution improved flexural strength by 15.14% and 16.30% compared to WC and CAC-based reference specimens. This can be attributed to the positive effect of WMP substitution at low rates, as WMP reduces the porosity of mortar samples. In addition, 5% WMP did not significantly affect WC and OPC-based mixtures, while using 10% WMP significantly improved the strength.

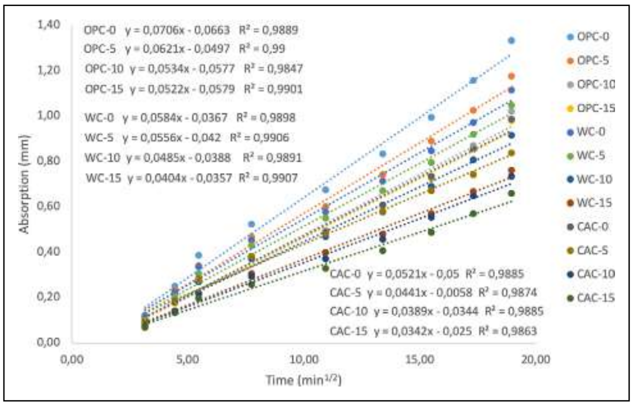

Figure 7. Sorptivity coefficient results of mixtures.

Although adding 15% WMP in all cement types decreased the flexural strength, it was higher than the reference specimens. The flexural strength of the OPC-15, WC-15, and CAC-15 series was 5.91%, 7.52%, and 8.28% higher than the control specimens.

4.2.3. Capillary Water Absorption and Sorptivity Coefficients

Capillary water absorption values of the mixtures are presented in Figure 5. Capillary water absorption values decreased with increased WMP ratio in all cement types. This can be attributed to the reduction of porosity in mortar specimens due to the filling effect of WMP use. Topçu [37] reported that adding WMP fills the voids in self-compacting concrete (SCC) and reduces capillary voids due to high workability. Aliabdo et al. [10] reported that the porosity of concrete decreased with the increase of WMP in the case of partial substitution of cement with WMP for different w/b ratios. Increasing the WMP ratio from 0 to 15 in OPC-based mixtures decreased the 6-hour surface water absorption value by 26.7%. Increasing the WMP ratio from 0% to 15% in WC and CAC-based mixtures decreased the capillary water absorption value by 31.65% and 33.30%, respectively. The least capillary water absorption was obtained from CAC-based mixtures among the different cement types. Ashish et al. [38] observed that substituting WMP instead of cement in concrete reduced the water absorption rates of concrete mixtures. Gupta et al. [39] stated that substituting up to 10% WMP reduced water absorption. This result is attributed to the pore-filling effect decreasing the void percentage due to the fineness of the WMP. Khodabakhshian et al. [40] and Zhang et al. [41] determined that the substitution of 5% SF along with 5–20% WMP reduces water absorption due to additional C-S-H gel filling the pores and improving the microstructure. The absorption and time relationship of OPC, WC, and CAC-based mixtures are presented in Figure 6a–c, respectively.

To calculate the sorptivity coefficient, the amount of water adsorbed (mm^3) per the cross-section of the specimen in contact with water (cm^2) (Q/A) was plotted against the square root of time (t), then k was determined from the slope of the linear relationship between Q/A and t. The sorptivity and correlation coefficients of all mixtures are given in Figure 7. As can be seen from Figure 7, the sorptivity coefficient decreased as the WMP ratio increased for all cement types. Due to the small particle size of WMP, the pores at the interfaces between the paste or aggregate and the cement paste are filled with WMP, resulting in smaller capillary pores. The lowest sorptivity coefficient in OPC-based mixtures was obtained from the mixture series using 15% WMP with 0.0522 mm/min$^{1/2}$. This value was 26.06% lower than the OPC-0 series without WMP. Adding 5%, 10%, and 15% WMP in WC-based mixtures decreased the sorptivity coefficient by 4.79%, 16.95% and 30.82%, respectively. The lower sorptivity values of WC-based mixtures compared to OPC-based mixtures can be attributed to the reduction of capillary pores due to the finer particle size of WC compared to OPC. The lowest sorptivity value among all mixes was calculated with 0.0342 mm/min$^{1/2}$ in the CAC-15 series. This value was 34.36% lower compared to the CAC-0 series. In addition, the sorptivity value of the CAC series using 15% WMP was 34.48% and 15.34% lower, respectively, compared to the OPC-15 and WC-15 series. The lower sorptivity coefficient of CAC-based mixtures compared to OPC and WC can be explained by the denser structure of CAC's metastable phases (CAH_{10} and C_2AH_8) compared to the C-S-H phases in OPC. Moffatt [42] reported that CAC samples had a lower chloride diffusion coefficient than OPC samples and attributed this to the denser structure of CAC.

4.3. Properties of Mortar Specimens After Freeze-Thaw Cycles

4.3.1. Residual Compressive Strength

All mixture specimens were subjected to freeze-thaw cycles after a 28-day curing period. The number of cycles was determined as 30, 60, and 90. After the process counts, no significant deterioration occurred in the specimens, which can be attributed to the high amount of binder. Residual compressive strength results of the mixtures after 30, 60, and 90 cycles are presented in Figure 8. The reduction in compressive strength of OPC-based mixtures after 30 cycles varies between 3.1% and 5.3%. While the least strength drop was obtained in the OPC-5 series, the highest decrease was calculated in the OPC-15 series. Similar to the compressive strength results before the freeze-thaw cycles, the residual compressive strengths of the mixtures using 5% and 10% WMP were higher than the OPC-0 series.

After 60 freeze-thaw cycles of the OPC-based mixtures, the residual compressive strengths of the OPC-0, OPC-5, and OPC-10 series were obtained as 86.39 MPa, 87.95 MPa, and 89.26 MPa, respectively. However, despite being high in compressive strength, the relative residual compressive strength (the ratio of residual compressive strength after freeze-thaw to initial compressive strength) was determined as 0.941, 0.942 and 0.940 at 0%, 5%, and 10% WMP change, respectively. A similar situation was observed after 90 cycles. Although the residual compressive strength of the OPC-5 and OPC-10 mixture series was higher than the OPC-0 series, the relative residual compressive strength was determined as 0.893, 0.892, and 0.891 for the OPC-0, OPC-5 and OPC-10 mixtures, respectively. As a result, the addition of 5% and 10% WMP did not cause a significant effect on the strength of the mixtures after 60 and 90 freeze-thaw cycles. This can be attributed to the fact that the C-S-H gel content decreased due to WMP without pozzolanic activity, but the low range (5% and 10%) of WMP compensated for the decrease in strength due to the filling effect. Ince et al. [16] reported that concrete samples containing silica fume and waste marble powder suffered less strength loss after freeze-thaw cycles than the reference sample. Gencel et al. [43] stated that using waste marble powder instead of aggregate in concrete paving blocks increases the freeze-thaw resistance. With an increased WMP ratio of 15%, the freeze-thaw resistance of OPC-based mixtures decreased. After 60 and 90 cycles, the relative residual compressive strength of the OPC-15 series was obtained as 0.930 and 0.864. Increases in the amount (%15) of WMP cause a further reduction of hydration products, creating a loose structure that will increase free water and expansion stress during freeze-thaw cycles, resulting in more strength loss.

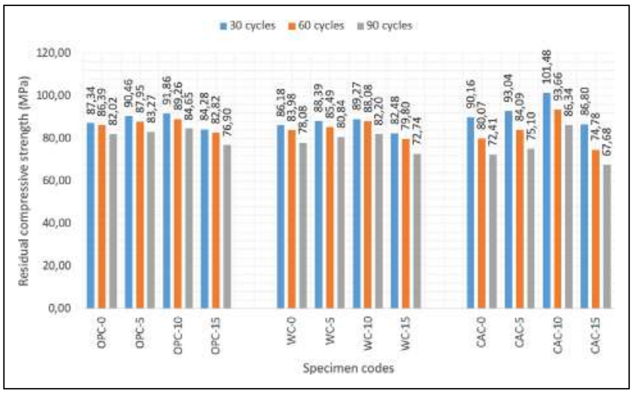

Figure 8. Residual compressive strengths after freeze-thaw.

When the compressive strengths of WC-based mixtures after freeze-thaw cycles are examined in Figure 8, it is observed that the strength loss after 30 cycles varies between 2.8% and 4.2%. When the cycle number increased to 60 in WC-based mixtures, 5.3%, 7.1%, and 4.7% loss occurred in the compressive strength of the mixtures containing 0%, 5%, and 10% WMP, respectively. Similar to the compressive forces before exposure to freeze-thaw, the residual compressive strengths of 5% and 10% WMP were higher compared to the WC-0 series. After 90 freeze-thaw cycles, 0%, 5%, and 10% WMP substitution to WC-based mixes reduced the relative residual compressive strength to 0.880, 0.888, and 0.890, respectively. Similar to OPC-based mixtures, using WMP in low proportions showed a filling effect, making the mortar structure denser and preventing a further decrease in strength despite the decrease in C-S-H structure. In the case of 15% WMP addition, the reduction in strength after 60 and 90 cycles was obtained as 7.3% and 15.5%, respectively. The freezing and thawing resistance of concrete or mortar highly depends on the amount of hydration products and pores. Due to the absence of significant differences in the chemical composition of OPC and WC, the strength drops after cycles are also significantly similar.

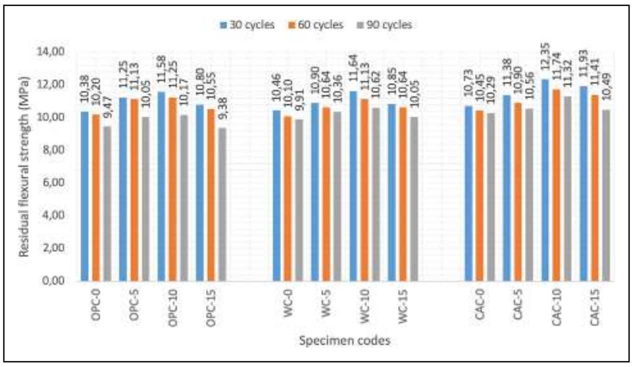

Figure 9. Residual flexural strengths after freeze-thaw.

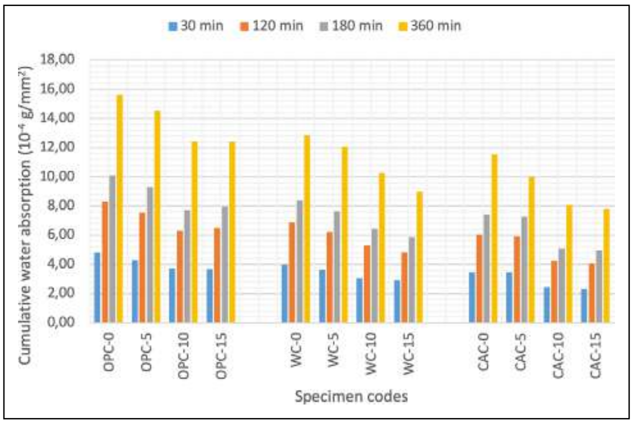

Figure 10. Cumulative capillary water absorption results after 30 freeze-thaw cycles.

When the results of CAC-based mixtures are examined, the reductions in strength after 30 cycles range from 2.5% to 7.3%. The least strength loss was calculated from the CAC-10 series, and the maximum strength reduction was calculated from the CAC-15 series. Significant strength losses occurred in CAC-based mixtures when the number of cycles increased to 60. After 60 freeze-thaw cycles, strength loss happened in the CAC-0, CAC-5, CAC-10, and CAC-15 series at 16.5%, 15%, 10% and 20.1%, respectively. Although there was a decrease in strength loss with an increase in WMP ratio to 10%, the addition of 15% WMP increased the strength loss. After 90 freeze-thaw cycles, the compressive strength loss in CAC-based mixtures using 0%, 5%, 10%, and 15% WMP was obtained as 24.4%, 24.1%, 17.1%, and 27.7%, respectively. Although the compressive strength losses are higher than other cement types, the highest compressive strength was determined in the CAC-10 series in all cycle numbers.

The lower freeze-thaw resistance of CAC-based mixtures compared to other cement types can be explained by the transformation of the metastable phases (CAH_{10} and C_2AH_8), which are the hydration products of CAC, into stable C_3AH_6. With this phase transformation, the porosity of the concrete increases, and its compressive strength decreases [44]. This conversion reaction accelerates at high temperatures and moisture content [45]. As a result, moisture changes in the specimens during the freeze-thaw cycles may cause a decrease in strength by accelerating phase transformations.

4.3.2. Flexural Strength

The flexural strength results of the mixture specimens after freezing and thawing are given in Figure 9. After 30 cycles, the flexural strength of the OPC-based mixtures decreased between 2.6% and 6.1%. When the number of cycles increased to 60, a decrease in bending strength of 4.3%, 5.3%, 8.8%, and 6.6% were detected in the OPC-0, OPC-5, OPC-10, and OPC-15 series, respectively. Relative residual flexural strength values of the mixtures using 0%, 5%, 10%, and 15% WMP after 90 cycles were determined as 0.888, 0.855, 0.825, and 0.831, respectively. Although the strength losses increased with the addition of WMP, the residual flexural strengths were higher than the OPC-0 series without WMP. The highest residual flexural strength of OPC-based mixtures in all cycles was obtained in the OPC-10 series.

Flexural strength loss in WC-0, WC-5, WC-10, and WC-15 mixture series after 30 cycles in WC-based mixtures was determined as 4%, 4.4%, 7.3% and 7.4%, respectively. After 30 cycles, the highest flexural strength was obtained from the WC-10 series. The flexural strength reduction after 60 cycles was determined as 6.7% to 11.3% in WC-based mixtures. After 90 cycles, the strength drops became more pronounced. The relative residual flexural strengths of the WC-0, WC-5, WC-10, and WC-15 mixture series were obtained as 0.909, 0.909, 0.846, and 0.858, respectively. After all cycles, the residual flexural strengths of WMP-added mixes were higher than those without WMP.

As seen in Figure 8, the residual compressive strengths of the WMP-added CAC-based mixtures were higher than the non-WMP mixture after freeze-thaw cycles. Similar to OPC and WC-based mixes, the highest residual flexural strength after all cycles was determined in the CAC-10 series. Using 0.5%, 10%, and 15% WMP in CAC-based mixtures after 30 cycles decreased compressive strength of 5.5%, 0.9%, 6.4%, and 2.9%, respectively. The lowest decrease in strength after 60 cycles was obtained in the CAC-5 series with 5.1%. Strength losses in the CAC-10 and CAC-15 series were 11.1% and 7.2%, respectively. After 90 cycles, the relative residual flexural strengths of the CAC-0, CAC-5, CAC-10, and CAC-15 series were determined as 0.907, 0.920, 0.858, and 0.854. Although using WMP in all three cement types increased overall freeze-thaw flexural strength reductions, the residual flexural strengths were still higher than in non-WMP mixtures. This can be attributed to improving the flexural strength of WMP before the freeze-thaw cycles of the mixes using WMP. In all cement types, the highest residual flexural strength after 30, 60, and 90 cycles was observed in the series with 10% WMP replacement.

4.3.3. Capillary Water Absorption and Sorptivity Coefficient

The capillary water absorption and sorptivity values of all cement types after 30 freeze-thaw cycles are given in Figures 10 and 11. After the freeze-thaw cycle, capillary water absorption values increased in all mixtures. As the WMP content in the mixtures increased, a decrease was observed in the capillary water absorption values. After 30 cycles, the 6-hour water absorption value of the OPC-0, OPC-5, OPC-10, and OPC-15 series increased by approximately 17.42%, 23.47%,

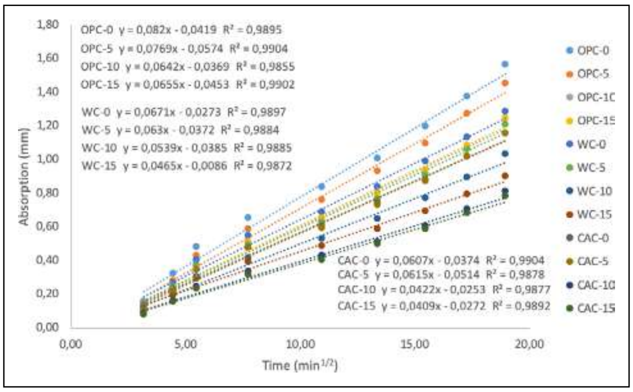

Figure 11. Sorptivity coefficient results after 30 freeze-thaw cycles.

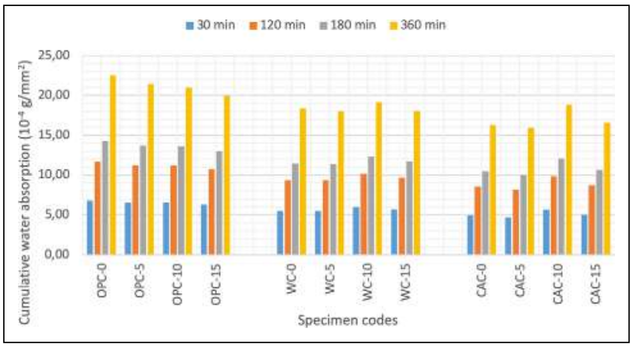

Figure 12. Cumulative capillary water absorption results after 60 freeze-thaw cycles.

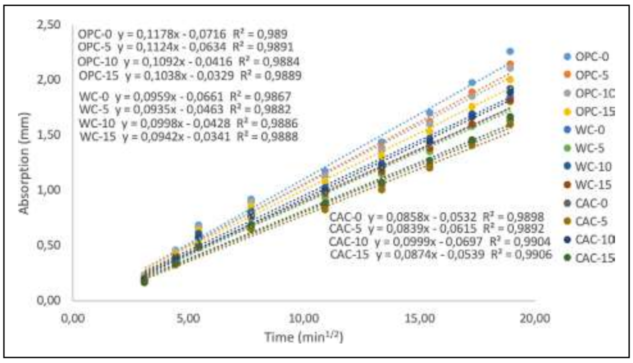

Figure 13. Sorptivity coefficient results after 60 freeze-thaw cycles.

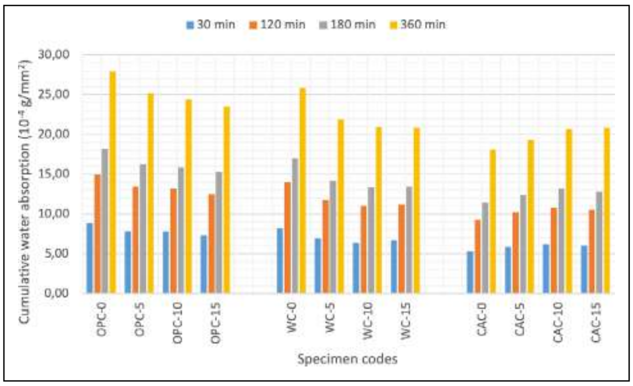

Figure 14. Cumulative capillary water absorption results after 60 freeze-thaw cycles.

21.96%, and 27.05%, respectively, compared to before exposure to freeze-thaw. This was obtained as 15.47%, 15.27%, 12.23%, and 18.42% for the WC-0, WC-5, WC-10, and WC-15 series, respectively. The capillary water absorption of CAC-10, which has the highest strength after 30 freeze-thaws, was obtained as the lowest value at 10.38%. It was determined that the capillary water absorption values of 0%, 5%, and 15% WMP substituted mixtures before freezing and thawing increased by 17.07%, 19.62%, and 18.90%, respectively.

As the WMP ratio in the mixtures increased, the sorptivity values decreased. This can be attributed to the filling effect of WMP. The lowest sorptivity value after 30 freeze-thaw was obtained from the CAC-15 series with 0.0409 mm/min$^{1/2}$. The sorptivity values of OPC-based mixtures vary between 0.0655 and 0.082 mm/min$^{1/2}$. The sorptivity values of the WC-based mixtures were lower compared to the OPC-based mixtures. This can be attributed to WC's smaller average grain size than OPC. The lowest sorptivity values in all cement types occurred in CAC-based mixtures. In CAC-based mixtures, the sorptivity value decreased from 0.0607 mm/min$^{1/2}$ to 0.0409 mm/min$^{1/2}$ as the WMP ratio increased.

Capillary water absorption and sorptivity values after 60 freeze-thaw cycles are presented in Figures 12 and 13. After 60 freeze-thaw cycles, the highest capillary water absorption value in OPC-based mixtures was obtained from the OPC-0 series with 22.52x10^{-4} g/mm^2. Capillary water absorption values decreased as the WMP ratio increased in OPC-based mixes. As the WMP ratio increased in WC and CAC-based mixtures, the capillary water absorption values, except for the CAC-10 series, approached. This shows that the degradation of hydration products is more important than the effect of WMP as the number of cycles increases.

After 60 cycles, the sorptivity of the OPC-based mixtures ranged from 0.1038 mm/min$^{1/2}$ to 0.1178 mm/min$^{1/2}$. Similar to capillary water absorption values, the increase in WMP decreased the sorptivity in OPC-based mixtures. After 60 cycles, the OPC-0, OPC-5, OPC-10, and OPC-15 series showed an increase in sorptivity of approximately 66%, 80%, 104%, and 98%, respectively, compared to the before freeze-thaw cycles. The lowest sorptivity value of 0.0935 mm/min$^{1/2}$ in WC-based mixtures was determined in the WC-5 series. After 60 cycles, the sorptivity values of the WC-based mixtures increased in the range of approximately 64% to 133% compared to the initial sorptivity values. The lowest sorptivity values were obtained from CAC-based mixtures. However, the increase ratio compared to the initial sorptivity values is higher than other cement types. The increase in porosity can explain this situation as a result of the transformation of metastable phases in CAC into stable phases. In the CAC-0, CAC-5, CAC-10 and CAC-15 series, these values were 64%, 90%, 156% and 155%, respectively. This may be the reason for significant reductions in compressive strength compared to other cement types.

Capillary water absorption and sorptivity values after 90 freeze-thaw cycles are presented in Figures 14 and 15. Capillary water absorption values decreased as the WMP

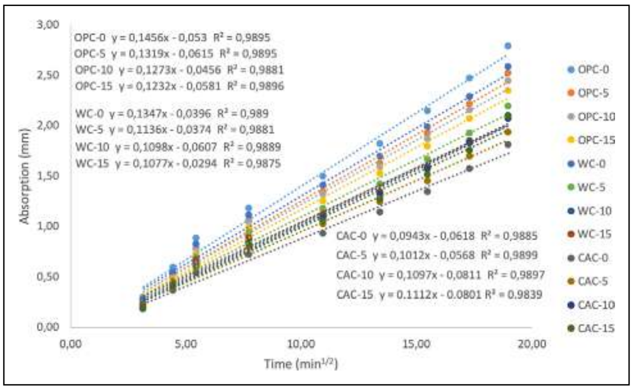

Figure 15. Sorptivity coefficient results after 90 freeze-thaw cycles.

ratio increased in OPC and WC-based mixtures. However, the opposite situation is seen in CAC-based mixtures, and capillary water absorption increased with increased WMP.

When the sorptivity values after 90 cycles were examined, the lowest sorptivity in OPC-based mixtures was obtained in the OPC-15 series. The sorptivity of OPC-based mixtures ranges from 0.1232 mm/min$^{1/2}$ to 0.1456 mm/min$^{1/2}$. In addition, 106%, 112%, 138%, and 136% increases were detected in the OPC-0, OPC-5, OPC-10, and OPC-15 series, respectively, according to the sorptivity before exposure to freeze-thaw cycles. In WC-based mixtures, the sorptivity values decreased as WMP increased. Sorptivity values vary between 0.1077 mm/min$^{1/2}$ and 0.1347 mm/min$^{1/2}$. Contrary to OPC and WC, the increase in WMP ratio increased the sorptivity value in CAC-based mixtures. In contrast to OPC and WC, it was observed that CAC and WMP reacted to increase the strength before exposure to freeze-thaw. The sorptivity values of the CAC-0, CAC-5, CAC-10, and CAC-15 series were determined as 0.0943, 0.1012, 0.1097, and 0.1112 mm/min$^{1/2}$, respectively. These values were approximately 81%, 129%, 182%, and 222% higher than the baseline values. When this situation is examined, it can be thought that the capillary void ratio increases significantly compared to other cement types. As a result, it causes significant decreases in compressive strength.

5. CONCLUSIONS

- While adding 5% WMP did not affect the slump-flow diameter much, the flow diameter decreased as the use of WMP increased. However, the slump-flow diameter of all mixtures was in the range of 24 to 26 cm. The greatest loss of workability was observed in CAC-based blends.
- The highest compressive strength values before freeze-thaw cycles were obtained from CAC-based mixtures. The compressive strengths of CAC-based mixtures with 5% and 10% WMP replacement were obtained as 98.89 MPa and 104.09 MPa, respectively. The compressive strengths of the OPC and WC-based mixtures were not significantly different.
- The highest flexural strength was obtained from the CAC-10 series with 13.20 MPa. The flexural strength of the OPC-15, WC-15, and CAC-15 series was 5.91%, 7.52%, and 8.28% higher than the control specimens.
- The most appropriate WMP ratio was 10% in mechanical properties before the freeze-thaw cycles. Decreases in the strength of CAC-based mixtures after 30 cycles vary between 2.5% and 7.3%. This was calculated between 3.1%–5.3% and 2.8%–4.2% in OPC and WC-based mixtures, respectively.
- The mixtures with the lowest sorptivity values before the freeze-thaw cycles were CAC-based, and this situation was similar to the strength results.
- Significant strength reductions occurred in CAC-based mixtures, especially at 60 and 90 cycle numbers, in mixtures exposed to freeze-thaw.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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Review Article

A comprehensive review on methods, agents and durability factors for stabilization of expansive soils

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ABSTRACT

Expansive soils cover a huge portion of the total land area in the world. They absorb water and expand, then shrink when they dry out. The volume change exerts pressure on engineering structures causing deformations, cracks, and movement of walls. This has a detrimental effect on serviceability and reduces the service life of structures constructed on expansive soil. Therefore, stabilizing expansive soil is important to lessen the negative characteristics of the soil and improve its general toughness and durability. This paper provides an overview of the methods of soil stabilization, stabilizing agents, testing of stabilized soil, and factors that have an impact on the durability of stabilized soil. The most common stabilizing agents which include lime and Ordinary Portland Cement (OPC) are studied. In addition, eco-friendly stabilizers like calcium chloride, sodium chloride, and modern stabilizers like geopolymers, zeolites, and nanomaterials are thoroughly discussed in the paper and potential areas for further research are also recommended. The study shows that the type and amount of stabilizer used, as well as the method of soil stabilization employed determines the extent of soil improvement.

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1. INTRODUCTION

A report by UN-HABITAT [1] on world cities, indicated that cities are home to half of the global population. According to the report, urban cities across the world are facing enormous challenges, especially in infrastructure, with only 13% of the cities having affordable housing. Around the world, 330 million reside in substandard houses, or were overstretched by housing costs by the year 2014, a number expected to rise to over 440 million households by the year 2025, and 2.5 billion by the year 2050 [2]. One of the factors that make housing unaffordable is the cost of construction as well as the availability of land for construction purposes [3].

For the creation of economic possibilities and the delivery of social services to the population, access to basic infrastructure services is essential. The economic growth of all the countries in the world is on a continuous rise, with African countries expected to experience a growth of at least 6% a year from 2022 to the year 2040 [4]. To achieve this growth, then infrastructural development and extension all over the world are inevitable. A report by African Center for Economic Transformation (ACET) (2020) and Organization for Economic Co-operation and Development (OECD) indicates that the population in Africa will grow by 70% in the next 25 years, with the urban population growing by 56%. 40% of the population in the world resides in developing nations with popu-

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lation growth being the fastest in these countries. In addition, 65% of the urban population in low-income countries live in slums. It is important, therefore, to scale up the investment in physical infrastructure to accommodate the fast-growing population. Extension of roads and housing projects should be done at the same rate as demographic growth.

According to Deloitte [5], about 60 billion US dollars are required annually for new physical infrastructure in sub-Saharan Africa, and about 30 billion US dollars for maintenance of the existing infrastructure. However, it is only about 25 billion US dollars are allocated for capital expenditure annually. This creates a huge shortage in the physical infrastructure in Africa, particularly in developing nations. It has been reported that the world would be excited to do business in Africa but it is difficult to access African markets, especially those in the interior due to poor access to roads [5]. Around 840 million people live more than two kilometers from all-weather roads worldwide [6]. For this reason, countries in Africa and the world at large need to invest in physical infrastructure especially the construction of roads and housing to meet the increasing demand. All physical infrastructures are founded on soil, and therefore, with the increase in demand for roads, pavements, housing, and other physical infrastructure, it is necessary to investigate the characteristics of soil as a foundation material before construction work begins on such soil. According to Sindelar [7], a lack of knowledge of soils can lead to catastrophic structural failure.

The stability of structures calls for suitable soil to ensure the foundation is sound. Roy & Kumar [8] stated that to determine the appropriateness of soil for foundation or as a construction material, an assessment of its properties should be done. Properties of soil such as plasticity index, compressibility, or bearing capacity determine the design that is suitable for construction on that soil. Geotechnical properties such as bulk density, specific gravity, compaction, consistency limits, permeability, consolidation, and shear strength determine the suitability of soil as the foundation surface for earth construction [9]. The interactions that happen between these properties help civil engineers in designing the foundations for different civil structures. Therefore, failure to put these properties under consideration when designing the foundation can lead to construction errors. Among the properties of good soil for construction is stability during wetting and drying seasons [7]. In addition, good soil should have pressure stability so that engineering structures do not sink when a huge load is applied to them.

It is important to carry out a site survey before construction work begins on any soil mass. The main properties considered during the survey are; project design, soil-bearing capacity, and swell-shrink behavior [10]. In most geotechnical works, a construction site will not satisfy the design requirement without alteration and this makes it a challenge for geotechnical engineering. Makusa (2012) reported that in the past, the options for unsuitable soil included changing the design of the project, removing the in-situ soil, and replacing it with a desirable soil type or abandoning the site. Abandoning the site led to a scarcity of land for construction purposes. In modern days, soil modification is being undertaken to improve the soil properties to make it suitable for the construction of the desired design [11]. Around the world, expansive soils are common, especially in arid and semi-arid areas [12]. According to Indiramma & Sudharani [13], expansive soils cover about 20% of the world's total land area. Numerous approaches have been used to address the issues related to expansive soils, owing to their widespread global distribution. This review article focuses on various methods of soil stabilization and soil stabilizers and their application in improving the properties of expansive soils. Mechanical stabilization and chemical stabilization (in-situ and ex-situ) have been discussed extensively in this paper. The performance of the unstabilized and stabilized soil has been evaluated majorly based on Plasticity Index (PI), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), and comparison done.

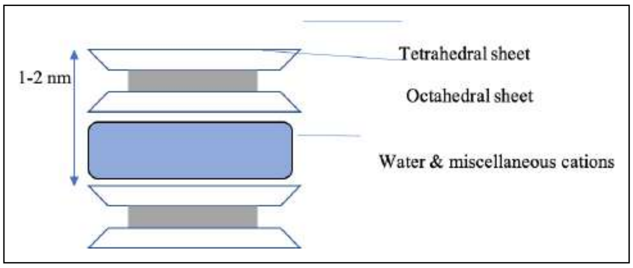

Figure 1. Montmorillonite chemical structure [21].

2. EXPANSIVE SOILS

An expansive soil is a type of soil that takes up water, expands, and then shrinks as it dries out. The unique swelling and shrinking of the soil is the primary engineering problem with expansive soils. The pressure from the volume change causes cracks on floors, pavements and roads, and wall movement as well as deformations in engineering constructions. This has a detrimental effect on serviceability and reduces the service life of structures constructed on expansive soil [12]. Shi et al. [14] state that cracking can either be vertical, where the crack continues to extend downward until a balance is achieved, or horizontal, produced by excessive water pressure from the exterior. Three primary traits of expansive soils include cracking, swelling, and over-consolidation [14].

The construction industry experience challenges working with expansive soils during construction as well as a structural failure after construction due to volume changes and low bearing capacity. According to Kerrane [15], the expansion in expansive clay soil can rise to about 10%. This volume change exerts pressure causing damages which include cracked floors, basement walls, and even damage to upper floors when there is a motion of the entire structure [16]. Therefore, expansive soils are one of the main concerns in the construction sector [17].

According to Osman [18], expansive soils contain up to 30% clay at a depth of 50 cm. They are composed of clay soil that contains expanding clay minerals, primarily the smectite group made of montmorillonite mineral, as shown in Figure 1 [19].

Montmorillonite belongs to the phyllosilicate class of minerals with a high SiO_2 to Al_2O_3 content in the ratio of 2:1 in the structure [20]. In the crystal structure, there are three sheets whereby one octahedral alumina sheet occurs between two tetrahedral sheets forming an interspace layer of about 0.96 nm wide [21]. The triple sheets are then connected by Van der Waals forces [22]. Krut & Yakushev [22] found out that between the layers there are several exchange monovalent cations especially Na+ trapped hence they suggested the formula of montmorillonite as $(Na, Ca)_{0.33}(Al, Mg)^2(Si_4O_{10})(OH)_2 \cdot nH_2O)$. The presence of the exchange cations especially sodium in the interlayers of montmorillonite, increases the distance between the layers hence allowing entry of water and this phenomenon makes clay with montmorillonite minerals expansive in nature [23].

According to Antoni [24], montmorillonite clay surface is negatively charged. Kumari & Mohan [19] stated that the negative charge is a result of the isomorphous substitution of Si^{4+} by Al^{3+} in the tetrahedral unit and substitution of Al^{3+} by Mg^{2+} in the octahedral unit, and further that the magnitude of negative charge depends on the number of substituted atoms/ions. The authors also stated that the number of cations required to balance the charge deficiency caused by the isomorphous substitution is known as the Cation Exchange Capacity (CEC). Kinoti et al. [21] reported that of all the clay minerals, montmorillonite has the highest CEC ranging from 80 to 150 milliequivalent per 100 grams.

Expansive soils are distributed throughout the globe, with a world coverage of about 20% of the total land area [13]. Legros [25] estimates that expansive soils cover 335 million hectares of the planet. Arid and semi-arid regions have the highest concentration of expansive soils, with the problematic soils being common throughout North America and parts of Asia, including India, Northern Thailand, China, and Japan [26]. Sudan, Kenya, Ethiopia, and South Africa are the African nations having the largest fraction of expansive soils [18]. Furthermore, expansive soils can be found in abundance throughout Europe in countries like the UK, Germany, Greece, Romania, Spain, Sweden, Norway, Cyprus, and the Netherlands.

According to Jones [12], damages incurred annually in the US as a result of expansive soils are worth over $15 billion. A prediction by the America Society of Civil Engineers (ASCE) shows that damages caused by expansive soil are experienced in one out of every four homes. According to Jones [12], the loss experienced by property owners due to expansive soil is more than that of earthquakes, hurricanes, tornadoes, and floods combined. There is, therefore, a need to stabilize this type of soil to make it tolerable in construction and minimize the damages associated with it during and after construction.

3. SOIL STABILIZATION

To enhance one or more qualities of natural soil, special soil, cement, or other chemical components are typically added to it. This process is known as soil stabilization [27]. According to Negi et al. [28], soil stabilization is necessary for soil that has a minimum passage of 25% through a 75 mm sieve, sulfate composition of greater than 0.3%, plasticity index of above 10, and organic materials greater than 1%. Expansive soil must be stabilized before it may be utilized as a sub-base, sub-grade, or base for the construction of roads, bridges, and structures. Soil stabilization is mostly done to increase the stiffness and firmness of natural soil, and decrease its flexibility, and shrinkage/swelling potential [29]. According to Firoozi et al. [29], stabilized expansive clay soil has a higher bearing capacity when a heavy load is placed on it, as compared to unstabilized expansive soil.

For expansive soils to have less of a chance of expanding, soil stability is essential [30]. Chemical stabilization aims to provide additives that result in a lower liquid limit and a higher plastic limit, which together reduce the plasticity index overall [13]. As a result, the stabilized soil becomes more compressible, which improves the workability of the soil, moisture content, and maximum dry density.

Permeability affects soil consolidation when a load is applied [31]. It also affects the volume changes in the soil during wet and dry conditions. The permeability of the soil mostly determines the rate at which pore water pressure dissipates. With the use of soil stabilization, soil particles can be more tightly packed together, which lowers the void ratio and consequently reduces the permeability coefficient. Shil [32] examined how fly ash affected the permeability of stabilized soil and discovered that permeability reduces as fly ash content rises [33]. Therefore, soil permeability can be reduced by the introduction of a stabilizing agent which acts as a binder hence flocculating the soil particles as well as application of mechanical compaction [34]. In order to stabilize kaolinite soil, Ghavami et al. [35] employed cement and cement kiln dust; they reported a reduction in the volume of void spaces and an improvement in the compressive strength of the soil. Other researchers have used lime [36], nanocomposite [37], and granulated blast furnace slag [38] in the successful stabilization of clay soils.

In most cases, there is a reduction in the cost of construction where the properties of substandard, readily available materials are improved through stabilization. There is also a reduction in the cost of maintenance and repair since the swell-shrink potential of the expansive soil is mitigated through stabilization. The material may remain a granular type caused by an increase in cohesion, especially where cementation takes place or the bond between the fines improves [39].

4. METHODS OF SOIL STABILIZATION

In order to make soil useful for building, soil stabilization entails enhancing its engineering qualities. According to Obianigwe & Ngene [27], soil stabilization is the process of enhancing the natural qualities of soil so that it is acceptable for use in construction projects by adding a cementing material, a unique kind of soil, or a chemical additive. Soil stabilization is broadly categorized into mechanical and chemical methods. These two methods can be done using different approaches which can further be categorized as in-situ methods, ex-situ methods, wet-mixing stabilization, dry-mixing stabilization, and deep-mixing stabilization.

Table 1. Mechanical stabilization

Type of soil	Stabilizer used	Stabilizer dosage	Major property tested	Value before sta.	Value after sta.	Author
Marginal base material	Gravel with natural sand	20%	CBR	68%	85%	[45]
Clay soil	Fines from construction & demolition waste	10%	CBR	23%	50%	[46]
Black cotton soil	Quarry dust	10%	PI	39%	35%	[44]
Low plasticity clay	Stone dust & coarse aggregates	30%	CBR	32.4%	194.7%	[47]
Black cotton soil	Quarry dust	20%	UCS	0.88 MPa	1.88 MPa	[48]
High plasticity clay	Quarry dust	25%	PI	64%	29%	[13]
Black cotton soil	Recycled concrete aggregates	30%	CBR	3%	27%	[49]

sta.: Stabilization; CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive.

4.1. Mechanical Stabilization

This entails altering the gradation of expansive soils to stabilize them. To create a composite with distinct qualities from any of the separate soil ingredients, two or more soil materials of different gradations are combined. It includes the use of rammers, rollers, vibrators, and other mechanical energy to compact and densify the soil. Mechanical stabilization mainly applies compaction to get rid of the air voids present in the soil which leads to soil densification and hence, improves the ability of the soil to support loads [40]. Ikeagwuani & Nwonu [41] indicated that during compaction, it is important to know the relationship between moisture and density by observing the optimum moisture content (OMC) against the maximum dry density (MDD) for the soil being compacted. According to research by Huang et al. [42], an improvement in dry density at the ideal moisture content boosts the capacity of the soil to support loads because fewer air gaps bring soil particles closer together and reduce swelling potential. Similarly, the liquid limit rises as the optimum moisture content rises, but an increase in MDD lowers the plasticity index [43]. Table 1 discusses a few studies on the application of mechanical stabilization. Quarry dust has been extensively used in mechanical soil stabilization, resulting to a decrease in plasticity index and increase in UCS. According to the study by Kumar [44], the dosage of quarry dust has to be above 10% for a significant reduction in plasticity index.

From Table 1, it is evident that application of more coarse materials like quarry dust and aggregates improves the plasticity index and strength behaviour of clay soils. This is attributed to the decrease in fine content, resulting to an increase in load bearing capacity. Introduction of quarry dust and aggregates changes the gradation of the high plasticity clay soils. This results to reduction in the amount of water that can be absorbed by the clay particles, since the pores between the fine particles are filled by the coarser particles.

4.2. Chemical Stabilization

This involves the addition of chemically active additives to react with the natural soil hence changing its properties like swelling behavior and load-bearing capacity. To enhance soil qualities including strength, compressibility, and permeability, stabilizing chemicals are added. The interactions between the soil surface and water are what it seeks to alter. The geotechnical characteristics of soil have been chemically improved by the use of several additives. Khemissa & Mahamedi [50] state that the strength, volume stability, bearing capacity, permeability, and durability of soil can all be enhanced by the use of additives. The kind of soil, the surroundings, and the intended use of the soil all influence the additive that is chosen. Adding substances either in- or ex-situ is possible.

4.2.1. In-situ Stabilization

This method of soil stabilization involves the addition of stabilizing agents to the soil on-site without removing the bulk soil. Using augers, a cementitious substance, such as cement or lime, is injected into the soil either wet or dry. The number of holes to be drilled by the auger depends on the size of the auger and the area of stabilization. Factors such as the construction design to be done, the effectiveness of the stabilizing agents, in-situ soil conditions and the in-situ moisture content determine whether to use wet mixing or dry mixing methods. This method can be considered deep mixing or mass stabilization depending on the depth of stabilization [51].

The stability of soils at great depths is accomplished through deep soil mixing (DSM). A wet or dry binder is injected into the ground and blended with in situ soils using a mechanical or rotary mixing tool [51]. It blends existing soils with a stabilizer which is pumped to a soil mixing rig outfitted with a rotary head. As the rotary head is withdrawn the paddles achieve further mixing. The aim of deep mixing is not to produce a stabilized soil mass that is stiffy, but to produce one which may interact with natural soil. Therefore, effective interaction between the stabilized soil and natural soil should be maintained for effective stabilization. Ikeagwuani & Nwonu [41] stated that the auger-made hole is filled with calcium oxide during lime stabilization in-situ without the use of displaced soil. The research also indicated that the mechanism of stabilization in lime treatment entails calcium ions diffusion into the soil and eventually modifies the physicochemical properties through the ionic exchange.

According to Madhyannapu & Puppala [52], the following factors are considered when choosing the design for DSM;

Table 2. Application of deep soil mixing soil stabilization method

Deep soil mixing method	Type of soil	Stabilizer used	Major test parameter	Initial performance	Final performance	Author
Dry soil mixing	Clay	15% lime	UCS	–	6.5 to 10 times improvement	[52]
Wet soil mixing	Clayey silt soil	12% OPC	UCS	0.17 MPa	1.78 MPa	[58]
Dry soil mixing	Silty sand (SM)	6% OPC	CBR	5.07%	10.15%	[59]
Wet soil mixing	Clayey silt soil	250 kg/m^3 cement	UCS	1.2 MPa	7.0 MPa	[56]
Dry soil mixing	Peat soil (CH)	12% calcium carbide + 8% rice husks ash	Bearing capacity	5.274 kPa	32.44 kPa	[60]
Dry soil mixing	Organic soil	250 kg/m^3 cement	UCS	0.1 MPa	1.2 MPa	[53]
Dry soil mixing	Clayey-sand	120 kg/m^3	UCS	0.4 MPa	2.9 MPa	[61]

CBR: California Bearing Ratio; UCS: Unconfined compressive strength.

1. The best binder dose levels and stabilizer kind. Following laboratory mix design and further examination, this is carried out.
2. The water-to-binder ratio at which DSM columns work at their best.
3. The length, diameter, and spacing of DSM columns depend on the characteristics of treated and untreated soils discovered by laboratory research.

Deep soil mixing is further classified as either dry or wet mixing, as discussed and summarized in Table 2.

In dry mixing soil stabilization, dry stabilizing materials are injected into the soil and thoroughly mixed with wet soil. Dry powdered binder ingredient is injected into the soil using compressed air through perforations in a mixing tool positioned on a rotating Kelly bar. The inherent water content of the soil causes chemical changes that increase its shear strength by making the soil less compressible and porous [53]. According to Timoney et al. [53], in common European usage, columns have diameters ranging from 0.5 to 1.0 m, whereas they can reach 1.5 m in Japan. The soil is premixed as it descends using a specialized tool until the necessary depth is reached. The dry stabilizers are then injected and blended with the premixed soil when the mixing instrument is removed, leaving behind a mixed column of moist soil.

The dry mixing method was used by Timoney et al. [53] to explore the application of cement and Ground Granulated Blast Furnace Slag (GGBS) in soil stabilization and found that the usage of cement-GGBS mixture resulted in higher UCS values of over 1000 kPa at 28 days compared to cement alone. Additionally, according to this study, samples stabilized using fly ash and lime binders exhibit weaker strength improvements than samples stabilized with cement and GGBS binders. Quality assessment tests carried out by Pan et al. [54] discovered that the depth of the Dry Soil Mixing (DSM) column was inversely correlated with the number of unqualified DSM columns and the difficulty of controlling the quality of DSM columns.

The wet mixing method, on the other hand, involves turning a binder into slurry form, then after that, injecting it into the soil using the nozzles on the end of the soil auger. Transverse beams, a drilling rod, and a drill end with a head make up the mixing tool [55]. Grout is injected into the soil at high pressure while mixing continues. During penetration, 80–100% of the slurry is transferred to the ground, and the homogeneity of the soil-binder mixture depends on the soil properties, the type of rotating auger, and the time of mixing [56]. Wet soil mixing is the most common in-situ soil stabilization method in the world [57]. This is because it is easy and cost-effective for use in soil strengthening for diaphragm walls and deep foundation for buildings.

Table 2 shows the results for some of the research works that have applied deep soil mixing in soil stabilization.

From the table, a conclusion can be made that the application of DSM has successfully improved both index and mechanical soil properties in the past.

Another method of in-situ soil stabilization other than DSM is Mass Stabilization. It is used for both shallow and deep stabilization of expansive soils with a lot of moisture, as well as silty organic soils. Mass stabilization is a practical method for stabilizing soil, particularly in sites with a lot of water. The soil and stabilizing agents are mixed using excavators mounted with a mixing tool. The mixer rotates while simultaneously moving both vertically and horizontally to mix the soil. About 200 kg/m^3 of Portland cement is the ideal amount needed for mass stabilization using cement [62]. Table 3 displays some of the research projects that have been done on the applications of mass soil stabilization.

4.2.2. Ex-situ Stabilization

This method involves dislodging a soil material from its original site and treating it for use at a different construction site. It is most common where the depth of the expansive soil is shallow and hence, the excavation process is not complicated. The excavated soil is normally mixed with the stabilizers using backhoes or pug mills [66]. Factors to consider when choosing this method include removal method, cost of transportation, availability of the disposal location, and the treatment site. Table 4 shows some of the studies on soil stabilization that have been carried out in-situ.

According to Federal Remediation Technologies Roundtable [70], ex-situ stabilization achieves more uniform mixing compared to all methods of in-situ stabilization. The dis-

Table 3. Application of mass soil stabilization

Type of soil	Stabilizer	Test parameters	Initial performance	Performance after stabilization	Author
Soft peat & clay	200 kg/m^3 portland cement	Shear strength	30 kPa	500 kPa	[63]
High plasticity clay soil	Liquid ion soil stabilizer (LISS)	UCS	34.47 kPa	379.2 kPa	[64]
CH grey and CL red clayey soil	Lime	Plasticity index	52%	19.9%	[65]
Clayey soil (CH)	150 kg/m^3 OPC	UCS	20 kPa	600 kPa	[62]
Soft clay soil	6% OPC	UCS	20 kPa	160 kPa	[10]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Table 4. Application of ex-situ soil stabilization

Soil type	Test parameter	Stabilizer used	Stabilizer dosage	Initial per.	Final per.	Ref.
Soils with inorganic contaminants	UCS	Phosphate-based binder, KMP	6%	20 kPa	110 kPa	[67]
Pb-Zn contaminated soil	DCP Strength	Superphosphate	8%	1.55 kN	11.11 kN	[68]
Red mud	UCS	Fly ash	30%	300 kPa	2250 kPa	[69]

per.: Ref.: Reference; Performance; UCS: Unconfined compressive strength; DCP: Dynamic cone penetrometer.

advantages of in-situ stabilization over ex-situ stabilization include difficulties in ensuring uniform chemical reagent or additive dosages throughout the sediments to be treated, a lack of process control because of reliance on monitoring site conditions both before and after treatment, and a lack of process control [71]. On the other hand, in-situ soil stabilization is cheaper compared to ex-situ stabilization since it makes use of the natural existing soil material instead of the excavation process. Table 4 shows recent studies on the use of the ex-situ soil stabilization method.

Figure 2 gives a summary of the methods of soil stabilization and how they relate to each other.

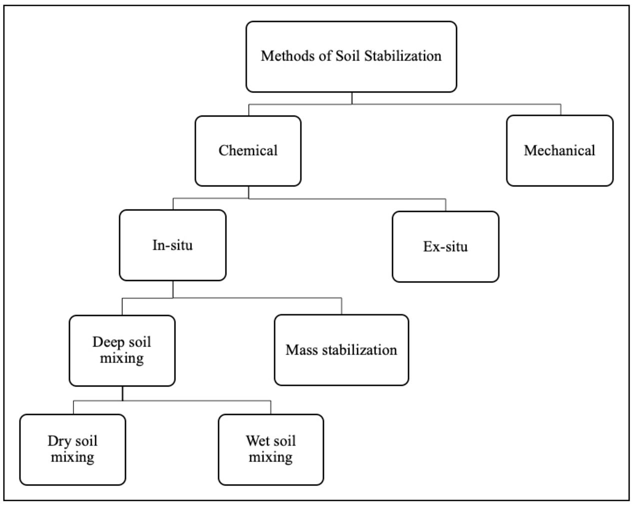

Figure 2. Methods of soil stabilization.

5. SOIL STABILIZERS

These are admixtures that are applied to stabilize soil both shallowly and deeply, enhancing the natural qualities of soil including strength and swelling behavior [72]. According to He [64], there are three different types of chemical stabilizers: traditional stabilizers (which include cement, lime, and fly ash), by-product stabilizers (which include coffee husk ash, blast furnace slag, lime kiln dust, cement kiln dust, and steel slag), and non-traditional stabilizers (which include ionic salts, enzymes, and geopolymers).

Geotechnical characteristics of expansive soils are improved by calcium-based additions like lime and cement. Their mechanism of stabilization depends on cation exchange between Ca^{2+} and other elements in the clay mineral like K^+ and Na^+ [73]. Jerod et al. [74] reported that the cement stabilization mechanism is divided into four; cation exchange, particle restructuring, cementitious hydration, and pozzolanic reactions.

In cation exchange, Ca^{2+} replaces the monovalent ions in the clay soil particles which leads to shrinkage of the water layer between the lay particles causing a reduction in soil plasticity. The introduction of Ca^{2+} decreases the distance between the layers as one divalent cation replaces two monovalent cations. Particle restructuring is the modification of soil also known as agglomeration and flocculation. It involves changing the texture of soil from plastic and fine to granular soil [74]. The production of calcium-aluminate-hydrate (CAH) and calcium-silicate-hydrate (CSH) as a result of cementitious hydration makes the soil more compact. Pozzolanic reactions, which increase the tensile strength of the soil, occur when calcium hydroxide $Ca(OH)_2$ reacts with the silica and alumina on the clay surface. Because the reactions can take months to complete, the soil must be continually strengthened [75].

5.1. Stabilization Using Lime

When quicklime is used, it reacts with the water in the expansive soil or added water and the process produces a lot of heat. The heat produced leads to the drying of the soil due to the evaporation of the moisture content, as illustrated in equation 1 [11].

Table 5. Soil stabilization using lime

Type of soil	Lime dosage	Properties studied	Initial performance	Performance after stabilization	Author (s)
Black cotton clay	6%	UCS	0.27 MPa	1.7 MPa	[76]
Low plasticity clay (CL)	15%	UCS	0.54Pa	2.54 MPa	[77]
High plasticity clay (CH)	4%	Swelling index	7%	0%	[17]
Clay soil	4%	CBR	1.17%	8.52%	[78]
Clay soil	6%	Swelling index	20%	1%	[79]

CBR: California Bearing Ratio; UCS: Unconfined compressive strength.

$$CaO + H_2O \rightarrow Ca(OH)_2 + Heat\ (65\ kJ/mol) \quad (1)$$

It is called the short-term treatment of the soil and usually takes place within the first few hours or days. The lime becomes hydrated after a reaction with water and forms Ca^{2+} and OH^{-}. The positively charged Ca^{2+} move to the surface of the negatively charged clay particles.

Additionally, calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) cementitious byproducts, are created when calcium hydroxide combines with the soluble silica and alumina in the clay [29]. These reactions are summarized in Equations 2 and 3.

$$CH + S \rightarrow CSH \quad (2)$$

$$CH + A \rightarrow CAH \quad (3)$$

A force of attraction develops and therefore there is a decrease in the repulsion forces within the clay particles. The force of attraction strengthens the bond between soil particles changing the texture of the soil, a process known as agglomeration and flocculation [75]. The phenomenon produces friable and granular soil that is easy to compact [28].

According to Negi et al. [28], the reaction of lime with the expansive soil takes place immediately and an increase in carrying capacity, CBR, resistance to shrinkage, and reduction in plasticity index was observed within a few hours after the reaction started. However, when the soil goes through cycles of soaking and drying, using lime is ineffective because the cohesiveness between the soil grains and the lime weakens, finally increasing soil volume. When soil goes through cycles of soaking and drying, using lime is ineffective because the cohesiveness between the soil grains and the lime weakens, hence increasing soil volume [29]. Table 5 below shows a discussion of the application of lime in soil stabilization.

From Table 5, a conclusion can be made that lime has shown positive performance in increasing soil strength and workability, and also decreasing swelling characteristics. However, a study by He [64], demonstrates one of the major negative effects of lime-stabilized soils is the formation of ettringite which cause heaving in the stabilized soil according to equation 4.

$$2C_3A + C_3A.3C\bar{S}.32H \rightarrow 3[C_3A.3C\bar{S}.32H] \quad (4)$$

According to Equation 5, another problem with lime-stabilized soils is the production of calcium carbonate from the reaction of calcium hydroxide with atmospheric carbon (IV) oxide [80]. In this reaction, calcium ions are used up and negatively affect the pozzolanic reaction. In addition, the calcium carbonate formed is soluble and pulverizes with time leading to strength deterioration.

$$CH + \bar{C} \rightarrow C\bar{C} + H \quad (5)$$

Jawad et al. [75], proposed the replacement of lime with magnesium oxide or magnesium hydroxide as they pose similar chemical characteristics, and magnesium oxide or magnesium hydroxide do not undergo carbonation.

5.2. Stabilization Using Cement

Firoozi et al. [29] discussed the reactions in cement stabilization by use of chemical equations 6, 7, and 8. The belite (dicalcium silicates) and elite (tricalcium silicate) from the cement hydrate into cementitious calcium silicate and hydrated lime, as determined by equations 6 and 7, when it comes into contact with the water in the soil.

$$2C_2S + 6H \rightarrow C_3S_2H_3 + 3CH \quad (6)$$

$$2C_3S + 4H \rightarrow C_3S_2H_3 + 3CH \quad (7)$$

Tricalcium silicate hydrates and hardens very quickly causing early setting and strengthening of the stabilized soil. The early strengthening of stabilized soils increases as tricalcium silicate concentration increases. Contrarily, C_2S hydrates and hardens slowly; as a result, it is to blame for the increased strength of stabilized soil at later ages than 7 days.

The tricalcium aluminate phase undergoes hydration to form tricalcium aluminate hydrate according to Equation 8.

$$2C_3A + 4H \rightarrow C_3S_2H_3 + 3CH \quad (8)$$

Hydration of C_3A produces a lot of heat which results in rapid hardening. This reduces the workability of the soil being stabilized. The rapid hydration of C_3A is slowed down by gypsum which is normally added during the final grinding of cement. Cement that has C_3A would set rapidly if gypsum was not present. Low percentages of C_3A in cement make the cement resistant to waters and soils that contain sulfates (external sulfate attack).

In addition, calcium hydroxide produced in equations 6, 7, and 8 reacts with the alumina and silica present in the soil through a pozzolanic reaction according to equations 2 and 3. This result in bond formation between soil particles causing agglomeration and flocculation of the soil particles. Research by Solihu [59] concluded that Portland cement acts as an effective stabilizer by improving the Atterberg limits, unconfined compressive strength, and reducing the changes in volume. Use of cement has recently been the most common soil stabilization method and its mechanism is similar to lime addition. Both cement and lime help in reducing the plasticity of the soil by providing a strong matrix to the soil. A study by Abdelkrim & Mohamed [81] found out that increase in cement content decreases the pressure swelling as

Table 6. Soil stabilization using cement

Type of soil	Cement dosage	Properties studied	Initial performance	Performance after stabilization	References
High plasticity soil (CH)	8%	PI	57.8%	27.6%	[83]
		UCS	0.27 MPa	1.19 MPa	
–	5%	UCS	0.8 MPa	1.01 MPa	[85]
Medium plasticity soil	10%	PI	46.6%	26.6%	[86]
		UCS	1 MPa	6 MPa	
High plasticity clay	10%	UCS	1.5 MPa	3.8 MPa	[87]
Soft soil	6%	UCS	20 kPa	160 kPa	[10]
Clay soil	8%	CBR	7%	48%	[81]

CBR: California Bearing Ratio; PI: Plasticity index; UCS: Unconfined compressive strength.

well as the free swelling of expansive soil. In addition, both soaked and unsoaked California Bearing Ratio (CBR) increases linearly with increase in the cement content.

Cement-treated soils have enhanced shear strength and decreased liquid limit, plasticity index, and swelling potential [82]. Stabilizing granular soils with cement has proven to be more economical and efficient since a small cement dosage is required. Research has proven that soils with Plasticity Index, PI>30 are difficult to treat with cement hence lime is added before mixing to keep the soils workable [83]. This research also established that increased cement content leads to improvement in unconfined compressive strength (UCS) and a reduction in the plasticity of the soil from 57.81% to 27.57% when cement content was increased from 0% to 12%. In agreement with these findings, Khemissa & Mahamedi [50] found that the swell pressure of treated samples decreases with an increase in stabilizer dosage. They also concluded that hydration in cement occurs faster than in lime which allows an immediate gain of strength. Cement-stabilized soils continue to gain strength over time as curing continues. Table 6 shows some of the recent studies in soil-cement stabilization. In both studies, the performance of the stabilized soil satisfies the strength requirements, that the minimum CBR should be 15% and UCS should increase by at least 80% for cement stabilized soil [84].

From Table 6 above, all studies agree that cement stabilization provides an increase in the bearing capacity of the stabilized soil. This is due to the formation of CSH and CAH bonds. However, the durability of cement-stabilized soil is not long enough due to sulfate reactions which result to heave formation according to Equation 1. In addition, the cement production process emits a lot of CO_2 which is a chief greenhouse gas that is majorly responsible for climate change and global warming [88]. About 5–6% of global CO_2 emission is due to the manufacture of OPC [89]. The use of OPC in soil stabilization contribute greatly to CO_2 emission since a significant amount of cement is needed for effective soil stabilization [90].

5.3. Stabilization Using Chemicals

Calcium chloride is used as an additive for water retention in soil bases stabilized mechanically because it is hygroscopic and deliquescent. This lowers the vapor pressure and rate of evaporation as well as increases surface tension. There is also a lowering of the freezing point of pure water which causes a reduction of frost heave in the stabilized soil. The freezing point of pure water is lowered, preventing or reducing frost heave. For the salt to work, the relative humidity of the air must be greater than 30%. Calcium chloride facilitates compaction because it also causes soil flocculation. Sodium chloride can also be used in place of calcium chloride and it has similar stabilizing action to calcium chloride. Some of the studies on the application of calcium chloride and sodium chloride in soil stabilization are shown in Table 7. The CBR values after chemical stabilization did not meet the minimum requirements of 15% in the studies discussed. This can be attributed to the poor performance of the original soil samples, since the increase in CBR in all the studies was more than 100% after stabilization. The studies carried out indicates the potential of calcium chloride and sodium chloride in stabilization of clay soils.

It is clear from Table 7 that when salt concentration and soil strength increased, the plastic limit, liquid limit, and plasticity index decreased. Jafer [91] explained the decline in plasticity is caused by a decrease in the thickness of the diffused double layer with an increase in salt content. More flocculates were formed, which was also thought to be the cause of the rise in MDD, CBR, and UCS of unstabilized soil. While working with calcium chloride and sodium chloride, the fundamental difficulty is that regular application is required to replace the chemical loss caused by leaching.

5.4. Stabilization Using Fly Ash

In presence of water, the use of fly ash in the soil provides exchangeable cations of Al^{3+}, Ca^{2+}, and Fe^{3+}, which results in the flocculation of the soil particles [64]. Fly ash also serves as a source of silica that in an environment with a high pH, reacts with lime to form cementitious products according to equations 2 & 3. This is a pozzolanic reaction that occurs slower compared to cement hydration. According to Afrin [11], fly ash addition in the soil leads to a reduction in plasticity, and permeability and an increase in durability, strength, and stiffness. This conclusion was corroborated by

Table 7. Soil stabilization using sodium chloride and calcium chloride

Type of soil	Type of binder	Binder dosage	Properties studied	Initial performance	Performance after stabilization	References
High plasticity clay (CH)	$CaCl_2$	8%	PI	25%	18%	[91]
High plasticity clay (CH)	NaCl	8%	PI	23%	18.5%	[92]
			CBR	1.8%	3.1%	
Black cotton soil (CH)	NaCl	8%	PI	23%	16%	[93]
			CBR	1.82%	6.1%	
Clayey soil	NaCl	2%	CBR	4.75%	9.22%	[94]
High plasticity clay (CH)	$CaCl_2$	1 N	PI	46%	22%	[95]
			CBR	2.11%	8.32%	
High plasticity clay (CH)	$CaCl_2$	15%	PI	36%	14%	[96]
		5%	UCS	0.5 MPa	0.75 MPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Table 8. Use of fly ash in soil stabilization

Type of soil	Fly ash dosage	Properties studied	Initial performance	Performance after stabilization	References
Organic soil	15%	PI	22%	7%	[99]
Black cotton soil	6%	PI	28.32%	13.72%	[97]
		CBR	4.7%	8.05%	
Black cotton soil	6%	CBR	3.12%	4.82%	[100]
Black cotton soil	20%	PI	29.8%	22.9%	[101]
		CBR	6%	16.8%	
High plasticity clay	25%	PI	64%	31%	[13]
		UCS	10 kPa	43 kPa	
Low plasticity clay	20%	CBR	5%	45%	[102]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Kumar & Harika [97], who discovered that the maximum dry density and unconfined compressive strength of black cotton soil were both improved by the addition of fly ash. Afrin [11] however, noted the following as limitations of using fly ash in soil stabilization;

(a) It is effective in soil with less moisture content, which therefore may require dewatering of the soil to be stabilized.
(b) Slaking and strength loss may occur in a soil-fly ash mixture that has been cured below zero and subsequently submerged in water.
(c) It contains a lot of sulfur, which might cause expansive reactions in the soil-fly ash mixture and lower its strength and durability.

Some recent research on the use of fly ash in soil stabilization is shown in Table 8. From the studies on the table, it can be observed that the amount of Fly ash used determines the extent of soil stabilization. The recommendation by AASHTO for soil stabilization using Fly ash is that the dosage should be between 20 to 30 percent [98]. It is evident from the table, that only those studies that used Fly ash content above 20% recorded strength performance suitable for use as subgrade.

5.5. Stabilization Using Zeolites

In soil stabilization, zeolites act as aqueous aluminum silicate pozzolans containing alkali and alkaline earth metals. Their structures consist of frameworks of SiO_4 and AlO_4 tetrahedrons that are interconnected using oxygen atoms in such a way as to form pores of specific sizes and shapes [103]. The Si^{4+} is substituted by Al^{3+} in the tetrahedral structures which results in a structural negative charge and consequent high cation exchange capacity [104]. Silica and/or alumina interact with cement in zeolitic pozzolanic reactions, which are time- and lime-dependent, to produce cementitious compounds that stabilize soil [105]. Typically, the high specific surface area and porosity in zeolites, act as a bonus in the pozzolanic reaction when mixed with materials like cement to form CSH and CAH [106]. In addition, zeolites portray high ion exchange due to the exchangeable cations in the structural pores, providing sites for Ca^{2+}, Mg^{2+}, Na^+, and K^+ catalysts [107].

In a study aimed to stabilize high-plasticity clayey soil, Yilmaz et al. [108] utilized a waste zeolite-lime mixture and reported a decrease in the swelling pressure exerted by the soil. Additionally, it was claimed that one-dimensional swelling of soil had boosted durability and unre-

Table 9. Soil stabilization using zeolites table

Type of soil	Zeolite used	Zeolite activator used	Zeolite dosage	Property studied	Initial performance	Performance after stabilization	References
Natural expansive clay	Natural clinoptilolite	Cement	30%	UCS	0.5 MPa	3.75 MPa	[111]
Clayey soil (with illite and smectite)	Natural phillipsite	Cement kiln dust	15%	UCS PI	250 kPa 66.5%	1200 kPa 31.9%	[112]
				CBR	1.73%	15.9%	
Gravel sand	–	Portland cement	10%	UCS	1.28 MPa	7.65 MPa	[113]
Expansive sand-Na-bentonite	Clinoptilolite zeolite	Cement	30%	UCS Swell potential	290 kPa 4.95%	394 kPa 0.35%	[114]
High plasticity clay	Zeolitic tuff (phillipsite and chabazite)	Lime	30% 25%	CBR UCS	1.6% 250 kPa	11% 500 kPa	[115]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

stricted compressive strength on a small scale. Rajabi et al. [107] reported that increasing the content of zeolites in the stabilizer mixtures had a consequent increase in plastic and liquid limits and corresponding plasticity index. In the study, the problematic soil was mainly made up of illite clay mineral, which contained free lime that led to cation reactants diminishing the interlayer thickness of the soil structure, thus enhancing the water retaining capacity of the soil [109].

In some instances, cement on its own does not produce desired properties when utilized in soil stabilization. Shahriar Kian et al. [110] utilized zeolites in such a case to improve the qualities of soil that has been stabilized by cement. The authors reported improved mechanical properties for soils stabilized with cement-zeolite mixtures compared to cement-only stabilization. In addition, the soils showed improved freeze-thaw durability when zeolite was used. In agreement with this study, Muhiddin & Tangkeallo [109] reported improved unconfined compressive strength in the stabilization of laterite soils rich in brownish-red iron oxides. Table 9 displays some of the most recent research on the use of zeolites for soil stabilization. For all the cited studies, the strength performance met the set standards that the increase in UCS should be more than 50 psi (0.33 MPa) compared to the original soil material [98].

5.6. Stabilization Using Geopolymers

Geopolymers are amorphous inorganic polymers based on aluminosilicates that are cured under ambient temperatures, and synthesized from liquid precursors [116]. They are structurally nanoporous and nanoparticulate, exhibiting good mechanical properties, thermal resistivity, and ceramic-like brittle failure properties [117]. In their synthesis, compounds rich in Al^{3+} and Si^{4+} such as feldspar, industrial wastes, and kaolinite are utilized as precursors, activated by alkaline bases such as NaOH, KOH, Na_2SiO_3, and K_2SiO_3 under ambient temperatures [118]. Owing to their cementitious properties, geopolymers are seen to replace OPC with advantages such as over 80% carbon dioxide emission reduction, resistance to relatively high temperatures, and an aggressive environment [119]. They are therefore used to replace cement in soil stabilization to reduce the environmental toll of soil stabilization on the environment.

In a study by Ghadir & Ranjbar [120] comparing the effectiveness of clayey soil stabilization using volcanic ash-based geopolymer and OPC, it was found that with a 15% replacement of binder, the compressive strength of soil increased from 0.2–4 MPa in wet conditions to 2–12 MPa in dry conditions. It was observed that geopolymer treatment was most efficient under dry conditions due to the role of pH and water in the kinetics of geopolymerization. It was also observed that an increase in the molarity of the activating agent had a consequent improvement in the compressive strength of the geopolymer-treated soil. In a study examining the viability of using anhydrous sodium metasilicate as a geopolymer activator for soil stabilization, Yu et al. [121] reported a similar effect. To stabilize expansive soil, Baldovino et al. [122] employed a geopolymer based on recycled glass powder and reported that increasing the volume of glass content improved the microstructural and mechanical qualities of the soil. This was because an increased content of glass powder led to a higher Si/Al ratio and therefore a higher yield of cementitious gel. Table 10 shows recent studies in soil stabilization using geopolymers. Except for the study by Samuel et al. [123], all other studies cited on the table met the standard requirements, that the UCS of the stabilized soil should be more than 0.8 MPa for use as sub-grade [85].

5.7. Stabilization Using Nanomaterials

Nanomaterials are compounds with at least one dimension within the nanoscale. In soil stabilization, particles in the form of nanofibers, nanofilms, or nanopowders are dispersed in the soil matrix to form composites that exhibit improved structural properties for geotechnical applications [127]. Common nanomaterials utilized in soil stabilization include nanoclay, carbon nanorods, graphene oxides, SiO_2, TiO_2, and Al_2O_3.

Table 10. Soil stabilization using geopolymers

Type of soil	Precursors	Activators	Geopolymer dosage	Parameters studied	Performance before stabilization	Performance after stabilization	Ref.
High plasticity clay	Metakaolin and class C fly ash	Sodium hydroxide and sodium silicate with lime and gypsum modifiers	6%	Swell potential	16.2%	3.2%	[124]
Low plasticity clay	Metakaolin	Potassium hydroxide and amorphous silica fume	4% 15%	UCS Free swell Linear	103 kPa 15% 15.5% shrinkage	310 kPa 7.8% 4%	[123]
Coarse aggregate	Fly ash	High alkaline red mud	20%	UCS	10 MPa	16 MPa	[125]
High plasticity clay	Fly ash	Sodium thiosulphate and sodium hydroxide	20%	UCS	0.22 MPa	6.4 MPa	[126]

Ref.: Reference; UCS: Unconfined compressive strength.

Table 11. Soil stabilization using nanomaterials

Type of soil	Nanomaterial used	Dosage	Parameters studied	Performance before stabilization	Performance after stabilization	References
Kaolinite clay	Nano MgO		PI	38.06%	6.44%	[132]
	Nano Al_2O_3				9.14%	
	Nano MgO		Swelling	15.51%	0.2%	
	Nano Al_2O_3				0.47%	
Expansive clayey soil	Nano SiO_2	1.5%	UCS	235.2 kPa	333.2 kPa	[133]
	Nano Al_2O_3	1.2%		227.5 kPa	309.7 kPa	
Low plasticity clay soil	Nano $CaCO_3$ with carpet waste fibers as reinforcers	1.2%	UCS	250 kPa	450 kPa	[134]
Expansive clayey soil	Nano Al^2O_3 as an auxiliary additive to lime	2%	UCS	100 kPa	450 kPa	[135]
Clayey sand	Carbon nanotubes and nanofibers	1%	UCS	143 kPa	237.5 kPa	[136]
Soft clay	Nano SiO_2	2%	CBR	15%	31%	[34]
		7%	UCS	56 kPa	294.5 kPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

In a study by Torabi-Kaveh & Heidari [128] nanoclay was comparatively used with lime in the stabilization of expansive marly soil. It was found that increasing the amount of nanoclay up to 4 percent improved the compressive strength of soil as a result of the nanocomposite particles filling the pore spaces of soil. Volumes of nanoclay beyond 4% exhibited increasing strength due to the flocculation of the particles. Similar findings were reported by Abisha & Jose [129] using nanoscales of clay, copper, and magnesium in the stabilization of soil, reporting improvement of dry density, linear shrinkage, and compressive strength with 1% nanomaterials.

In a study investigating the utilization of carbon nanomaterials in soil stabilization, Taha & Alsharef [130] used carbon nanotubes and nanofibers. Both were reported to improve dry density, specific gravity, and pH values slightly with maximum amounts of 0.2% dry weight of soil. The carbon nanotubes showed decreased hydraulic conductivity in comparison to the nanofibers. In a distinct study, nano-silica, lime, and vinyl acetate homopolymer coating were utilized to evaluate the mechanical behavior and physical features of soils in actual application in structural layers of rural roads [131]. The CBR and compressive strength were reported to considerably increase and thereby a possibility of reducing quicklime and mechanical means of preparing of sub-base layer was drawn. Table 11 lists some current studies on the application of nanomaterials to soil stabilization. However, the strength improvement in all the studies cited did not meet the minimum requirement. This can be attributed to the low dosages of nanoparticles used in the studies, which are below the recommended dosage of 4% for significant improvement in strength [128].

6. MICROSTRUCTURAL CHARACTERIZATION

Changes in the microparticles and micropores in a stabilized soil help to determine the overall changes in the stabilized soil. Chegenizadeh [137] indicated that SEM-EDS and XRD are important tools in the determination of microstructural development in stabilized soils. The physical properties of the microparticles are examined in SEM analysis, and their chemical composition is identified in XRD analysis. EDS is coupled with SEM to give details on the elements present in the soil material. Therefore, XRD and SEM-EDS are utilized to examine the chemical and physical properties of the soils, respectively.

6.1. X-Ray Diffraction

To determine the chemical composition of a material, XRD is used to analyze crystalline materials to pinpoint the crystalline phases that are present in a given substance [138]. The majority of soil particles are crystalline, and the crystals in those particles have distinctive geometries that can be used to identify the minerals that are present in soil material. A specific diffraction pattern is produced when an X-ray interacts with a crystallized specimen and is exclusive to the particular mineral and crystal structure it is found in. The diffraction pattern of the soil sample is analyzed for the qualitative and quantitative evaluation of minerals using powder diffraction or polycrystalline diffraction.

Due to the small size of soil particle sizes, it is not possible to investigate single crystals in soils; instead, powdered specimens are employed. The intensity of the diffracted beam as a function of range 2 Theta (2θ) is displayed on a chart after a small specimen containing particles in all possible orientations is placed in a collimated beam of parallel X-rays. Diffracted beams of various intensities are scanned and recorded automatically.

Horpibulsuk et al. [139] investigated the usage of cement for soil stabilization and reported that with an increase in cement dosage, soil particles and cement particles form clusters which decrease the number of voids in the soils and hence, increase the strength of the stabilized soil. Sekhar & Nayak [138] carried out a microstructural analysis on clay soil stabilized with Portland cement and BFS cement and reported that stabilization is due to the hydration process which leads to a reduction in the number of soil pores and voids that the hydration products fill. The XRD result also showed that the increase in strength was due to the formation of the CSH phase. According to Akula [140], XRD analysis can be used to quantitatively determine the reduction in the amount of quartz at different stabilizer dosages and different curing times, as well as an increase in CSH and CAH phases. This helps to account for the decrease in plasticity index, and an increase in maximum dry density and CBR at different stabilizer dosages and curing days. For instance, Sekhar & Nayak [138] carried out an XRD analysis for clay soil stabilized using Granulated blast furnace slag (GBFS) and associated the increase in the strength of stabilized soil with the formation of cementitious products CSH and CAH. Similarly, Mutaz & Dafalla [141] used XRD to account for higher strength in cement-stabilized clay soil in comparison to the one stabilized by lime. The authors observed higher amounts of CSH and CAH in cement-stabilized clay soil than when similar soil was stabilized using lime.

6.2. Scanning Electron Microscope with Energy Dispersive X-ray Spectroscopy

In the SEM examination, morphological changes are highlighted while interactions between the soil and stabilizing chemicals are visually displayed. Results from SEM and Energy-dispersive X-ray spectroscopy (EDS) are both semi-quantitative and qualitative. In SEM, the sample surface is scanned by an electron beam to provide a picture that depicts changes in the surface morphology of the material. The interactions between the stabilizing chemicals and the soil are displayed visually, and morphological changes are underlined. Additionally, SEM examinations are utilized to assess microstructural alterations in the examined specimens and examine the results of stabilizing soil additives. EDS is a commonly used elemental microanalysis technique that can identify and measure any element in the periodic table, except light elements up to Newbury & Ritchie [142]. Therefore, a combination of SEM coupled with an EDS detector helps to obtain information on the surface morphology of stabilized soil as well as the chemical composition of the products formed.

SEM studies carried out by Indiramma & Sudharani [143] indicated that the addition of fly ash causes the soil to assume a flocculated structure, which is responsible for the decrease in plasticity index and increase in strength of the stabilized soil.

According to Philip & Singh [144], sample preparation involves drying the soil sample for 1 hour at 50˚C–80˚C in an oven to remove any moisture present and then grinding the sample between two glass slides. The ground samples are then oven-dried again for one hour at the same oven temperature and then mounted in small amounts onto stubs. The sample is then fed into a scanning electron microscope machine for scanning and detection using EDS detector which gives a spectrum for all the elemental composition of the soil sample.

SEM-EDS shows reaction products and variations on stabilized soil microstructures due to pozzolanic reactions which result in the formation of CSH and CAH cementitious products. A study by Sekhar & Nayak [138], found that the natural clay soil SEM images show a smooth texture and larger void spaces as shown in Figure 3. After stabilization with cement and GBFS, the soil produced agglomerations; hence the particles were flocculated into friable granules and the pore or air spaces were reduced, causing strength gain to mixtures as shown in Figure 4.

The research also indicated that cement generates hydration products at higher curing periods, which helps to increase the strength of the stabilized soil with an increase in the curing period. In a study by Moretti et al. [145], EDS validated the XRD results on the chemical composition of the stabilized soil by showing a reduction in peak intensity of Al, Si, and K at 5% lime addition. According to Odeh & Rkaby [126], while geopolymer stabilized soil pores were filled with cementitious materials to generate a dense matrix

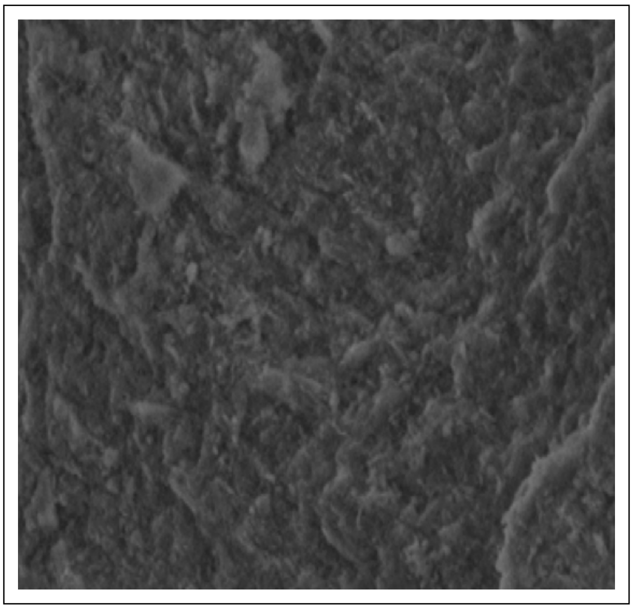

Figure 3. SEM image for neat clay soil [138].

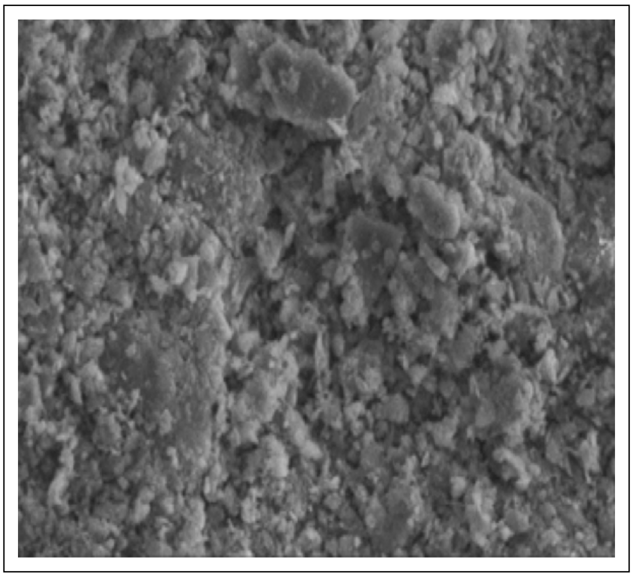

Figure 4. SEM image for GBFS & cement stabilized clay soil [138].

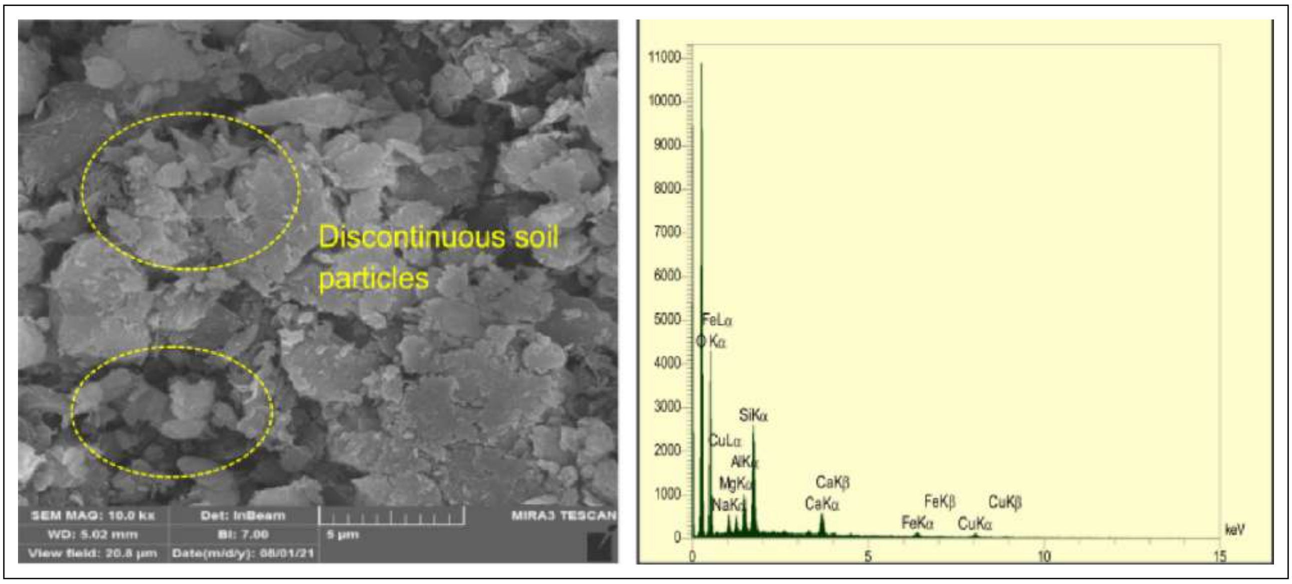

Figure 4. SEM-EDS analysis of untreated clay soil [126].

as seen in Figures 5 and 6, neat soil SEM pictures showed isolated soil particles with a weak, flaky structure and some arrangement between them. The geopolymer-treated samples EDS analysis revealed higher peaks and a higher fraction of O, Si, Al, Fe, and Na than in the clay that wasn't treated. It was clear that N-A-S-H, the main cementing element responsible for increasing strength, was at work.

6.3. Thermogravimetric Analysis and Differential Scanning Calorimetry

Thermogravimetric analysis (TGA) is performed in soil stabilization to ascertain the production of hydration products like CSH and CAH. With a rise in temperature, Weight loss for the samples with the temperature rise is measured by thermogravimetry [20]. TGA data is often converted to mass loss or gain peaks through differentiation in a technique known as Differential Thermogravimetric (DTG) Analysis, as an overlay over TGA data to ease interpretation. The amount of calcium consumed during hydration and pozzolanic reactions can be calculated using TGA in conjunction with Differential Scanning Calorimetry (DSC) [61]. According to Bandipally et al. [146], TGA can be used in soil stabilization using cement, to evaluate strength development during curing. The weight loss corresponds to decomposition of chemical phases formed during stabilization.

According to Scrivener et al. [147], the temperature range between 0 °C and 400 °C is where weight loss of water from smectite and other hydration products happens. Additionally, decarboxylation-related weight loss occurs above 700 °C. If the soil-cement sample TGA findings reveal little calcium consumption, there has been significant calcium

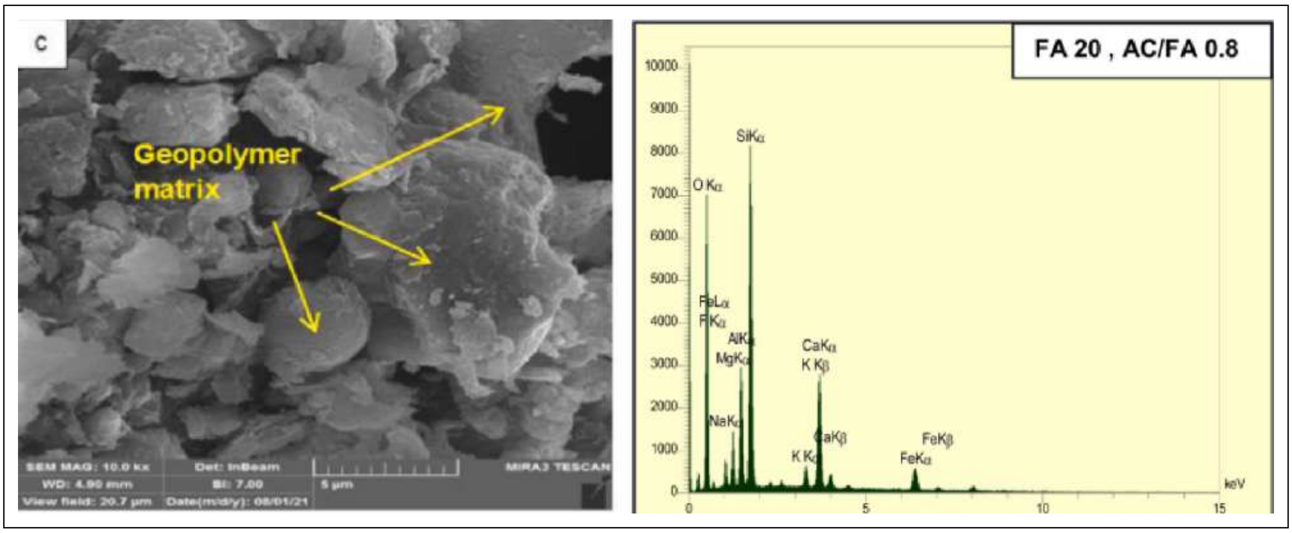

Figure 6. SEM-EDS analysis for geopolymer-treated clay soil [126].

leaching and a high level of degradation [148]. Pham et al. [61] observed degradation of portlandite at 400 ˚C 500 ˚C for cement-stabilized clay soil, which the authors attributed to the pozzolanic reaction to form CSH and CAH. A TGA analysis by Akula et al. [20] reported that lime-stabilized soil had a lower dehydration peak at 100 °C than virgin clay soil. This meant that there was less interlayer water for the treated soil sample compared to untreated soil.

6.4. Isothermal Calorimetry

Isothermal calorimetry can be used in soil stabilization to analyze the variations in reactivity between the employed binders to stabilize soil [149]. Thermal power displays the heat produced in real-time by a stabilized soil sample at a specific moment, whereas total heat displays the heat that has accumulated since the soil and binder were mixed at that specific moment. Thermal power displays the heat produced in real-time by a stabilized soil sample at a specific moment, whereas total heat displays the heat that has accumulated since the soil and binder were mixed at that specific moment [150].

Tran et al. [151] used Isothermal calorimetry to compare the heat of hydration at different water-binder ratios (w/b) and they found that a higher w/b ratio produces more heat compared to a lower w/b ratio. In addition, Wattez et al. [149] compared total heat flow when Portland cement, steel furnace slag, and alkali-activated slag were separately used to stabilize clay soil. They found that the total heat flow by pure Portland-treated soil was more than twice as when stabilized with BFS or with the sodium hydroxide-activated slag binder. This shows a higher reactivity of Portland cement binder in soil stabilization. Hu et al. [125] used isothermal calorimetry to investigate the effect of temperature on the stabilization of pavement base using geopolymer. When the temperature was elevated from 20 °C to 38 °C, both geopolymer base samples gained strength more quickly. This finding was in tandem with the study by Narmluk & Nawa [152] which reported an increase in pozzolanic activity with an increase in temperature.

7. FACTORS INFLUENCING SOIL STABILIZATION

7.1. Organic Matter

High organic content in soils results to lower gaining of strength [153]. This is explained by the fact that soil organic content prevents the formation of the hydration products by slowing down the pozzolanic reaction that leads to a gain of strength in stabilized soils. Firoozi et al. [29] stated that the amount of clay minerals are low in soils that have high organic content. They further added that organic contents have high water withholding capacity which results in less available water for the hydration process. Organic matter in soil also lowers the soil pH to about 9 because of the presence of humic acid which slows down the cementing reaction during cement stabilization [154].

Ling et al. [153] suggested the addition of kaolinite and zeolite to soils with organic matter that reacts with calcium hydroxide to form humic acid. This provides enough silica that is required for the pozzolanic reaction to occur in the soil. Also, the addition of bentonite to the soil during lime stabilization was found to reduce the negative effect of organic matter in the soil. Bentonite serves as a pozzolana material and also has a high water-retention capacity, which facilitates the hydration of cement and lime. Bentonite serves as a pozzolana material and also has a high water-retention capacity, which facilitates the hydration of cement and lime.

The presence of organic matter in soil increases its porosity thereby lowering the soil's strength as well as increasing its plasticity [155]. According to Pradeep & Vinu [156], the presence of organic matter in the soil increases the ability of the soil to hold onto water, raises the void ratio, and lowers the specific gravity of the soil because organic matter has a lower specific gravity. As a result, the maximum dry density of the soil decreases, increasing soil flexibility, and lowering CBR. Additionally, when the amount of organic material rises, the unconfined compressive strength decreases parabolically.

According to a study by Gui et al. [157], when the organic matter content of clay soils is above 7.5%, clay soils exhibit free organic matter properties. This increases the water adsorption capacity of the clay soil. In a clay sample containing 1.5 percent humic acid, cracks were noted by Wanatowski [158]. For clay containing 3% humic acid, the fissures were considerably more noticeable. This is due to the humic acid obstruction which retards particle flocculation when lime is added making the stabilization or modification process more difficult later. XRD analysis for lime-stabilized specimens with various humic acid contents indicated that the amount of silica and alumina decreases with increasing humic acid. This resulted in a decrease in the amount of CAH and CSH due to less pozzolanic reaction. Also, humic acid coats clay minerals (silica and alumina) making it difficult for them to be detected by EDX.

7.2. Sulphates

Sulphate ions in soil may originate from the presence of sulphate salts in soils or sulphides. Sulphides may be present in industrial by-products in form of Iron (II) sulphide (FeS_2). Once these industrial by-products are used in soil stabilization, FeS_2 may undergo oxidation to form sulphuric acid which then reacts with any calcium carbonate to form gypsum as shown in equations 11 and 12. In presence of excess moisture in the soil, the gypsum formed will lead to a degradation effect similar to sulphates [51].

$$FeS_2 + H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (11)$$

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \quad (12)$$

The presence of high sulphate content in the soil causes an expansive reaction when calcium-based stabilizers are used. This is because of the formation of ettringite according to equation 4, which is an expansive mineral that occupies a larger volume than the hydration products. Verástegui-Flores & Di Emidio [159] stated that degradation caused by sulphate attack affects parameters such as hydraulic conductivity, strength, and stiffness of calcium-based stabilized soils. According to Jha [160], sulphate increases the liquid limit of stabilized soil hence increasing its plasticity index. It also results in a decrease in maximum dry density and an increase in optimum moisture content due to the formation of ettringite which increases the pore size of stabilized soil. In addition, the presence of sulphate in large quantities decreases the strength of stabilized soil with longer curing time due to heave formation resulting from the ettringite compound. The type and amount of additives, the type of soil, the concentration and type of cation linked with the sulphate anion, and the extent of damage caused by ettringite are all factors that determine the durability of sulphate-rich stabilized soils [161].

7.3. Moisture Content

Calcium-based stabilizers and the reactive soil compounds (especially silica and alumina) dissolve in water and result in a soil-water-stabilizer reaction system which is a precipitation reaction according to equations 13 and 14 [162].

$$Ca^{2+} + SiO_2 + H_2O \rightarrow CaO.SiO_2.H_2O \quad (13)$$

$$Ca^{2+} + Al_2O_3 + H_2O \rightarrow CaO.Al_2O_3.H_2O \quad (14)$$

The reaction product precipitates on the surface of the soil and fills its micropores, strengthening the soil as a result. It is important, therefore, to have enough moisture content during stabilization for the hydration process as well as to enhance compaction. According to Afrin [11], cement takes 20% of its weight in water and is taken up by the environment, with quicklime absorbing roughly 32% of its weight in water. If the moisture content is not sufficient, the soil will compete for water with the stabilizing agent and if the soil has a high affinity for water like clay soil, the amount of moisture available for hydration will be less. This will result in a lower strength of the stabilized soil. Dahunsi [163] stated that when the natural moisture content of soil is higher than its optimum moisture content, the soil becomes saturated since the moisture content has moved to the wet side of the compaction curve. This reduces the density index of the soil hence, lowering the dry density of that soil. Similarly, Backiam [164] observed that strength of stabilized soil decreases with increase in moisture content.

According to a microstructural study conducted by Yin & Zhang [162] using SEM-EDS, the soil becomes finer and has few big aggregates and agglomerations as the NMC rises. Additionally, the hydration products were only discovered after 7 days of curing and are too little to be readily found in 1 day or 3 days. Because more free water converts into structural water during the hydration process, it was discovered by elemental analysis using EDS that at greater NMC, the percentage of oxygen element is a little higher.

7.4. Temperature

The pozzolanic reaction is sensitive to temperature changes and is favored by high temperatures. When temperatures are low the reaction is slow and this will lower the strength of the stabilized soil. Afrin [11] indicated that it is important to carry out calcium-based soil stabilization when the season is warm. According to [165], both liquid limit, plastic limit, and plasticity index decrease at high temperatures. This is because the kinetics of pozzolanic reaction involved in calcium-based stabilizers is slow at low temperatures [166]. With an increase in temperature, unconfined compressive strength also rises.

A study by Attah & Etim [167] reported that an increase in temperature results in a corresponding increase in the soaked CBR. In this study, SEM analysis was carried out and the soil at ambient temperature was found to have a different morphology from the one subjected to higher temperatures. This morphological change with temperature variation was due to the deformation or breakdown of soil fabrics, change in basic mineral composition as well as variations in the physicochemical and chemical processes that took place during heating.

7.5. Wet-dry Cycles

Cement-stabilized soils are prone to dry-wet cycles, which are typically brought up by daily temperature fluctuations and may generate stress inside a stabilized soil. Therefore, wet-dry cycles in soils stabilized by cement should be avoided. Wet-dry circumstances have a disorienting effect on lime-stabilized clayey soils [168]. A research by Consoli et al. [169] found that the strength of soil stabilized by Portland cement reduced after each wet-dry cycle. Each drying phase cycle causes the CBR to rise while the wetting phase causes it to fall. This outcome was in line with a study by Li et al. [170], which discovered that as the number of freeze-thaw cycles increased, the volume of mesopores grew and the volume of micropores dropped, lowering the CBR value. According to an SEM investigation, the porosity of the stabilized soil dramatically improved as the number of wet-dry cycles increased. Contrarily, Moayed et al. [171] found that after 5 wet-dry cycles, silty soil stabilized with lime-micro silica did not affect CBR. The majority of studies concur that a rise in wet-dry cycles reduces the stability of stabilized soil. According to James & Pandia [172], lime-stabilized soil is less effective under extreme wet-dry cycles. This finding was in tandem with the study by Kampala et al. [173] which found a significant decrease in the strength of clay soil stabilized using calcium carbide residue with increase in the number of wet-dry cycles.

7.6. Freeze-Thaw Cycles

Construction materials are frequently damaged by the freeze-thaw cycle. When water fills the spaces in a hard, porous material, it causes damage when it freezes and expands into a volume that is 9% larger than liquid water [174]. When surrounding material is under pressure from freezing water, cracks will appear because the pressure is greater than the tensile strength of the material [175]. The gaps are made larger during this process, allowing for the storage of more water during the subsequent thaw, which causes more cracking during the subsequent freeze. Camuffo [175] stated that the greater the pore size, the greater the force, so a material with high total porosity will be more exposed to risk. Duration and temperature range for the freeze-thaw cycle are the key determinants of the extent of damage to the physical and mechanical properties of a material [176]. The strength of stabilized soil decreases after cycles of freezing and thawing due to formation of microcracks on the stabilized soil particles, as was noted by de Jesús Arrieta Baldovino et al. [177]. Similarly, a research by Nguyen et al. [178] noted a significant decrease in the mechanical strength of lime-stabilized soil with increase in number of freeze-thaw cycles. This was attributed to the formation of ice lenses in the stabilized soil during freezing.

7.7. Curing Time

When calcium-based stabilizers especially lime and cementitious materials are used in soil stabilization, the strength of the stabilized soil increases with increased time. This can be attributed to the fact that the pozzolanic reaction is a slow reaction and therefore strength development is expected to continue for a long period [179]. According to Amadi & Osu [180], the pozzolanic reaction is time-dependent and cementitious products continue to form long after soil stabilization was carried out, causing a continuous increase in strength and maximum dry density of the stabilized soil. Horpibulsuk et al. [139] investigated the effect of curing time on the strength development in cement-stabilized soil and observed a decrease in pore volume with time. This was attributed to the continuous formation of hydration products which filled the pores between the soil particles. Athanasopoulou [181] observed a greater decrease in plasticity index for soil samples cured with lime and cement additives for 24 hours compared to those samples cured for half an hour. The author noted that an increase in curing time favors pozzolanic reaction, resulting in the formation of cementing compounds that bind the clay particles together to form large agglomerations.

7.8. Type of Soil and Minerals Present

Soil stabilization is greatly influenced by the type of soil and its mineralogical composition. This helps in choosing the most effective soil stabilizer for a given type of soil. According to James & Sivakumar [182], the effect of a given stabilizer on soil depends on the type of minerals present in the soil. Kaolinite is more effective in reducing plasticity and increasing strength using lime than illite and smectite [183]. Pedarla et al. [184] stated that soils with high content of montmorillonite failed in durability tests after stabilization with both cement and lime. The authors recommended that for effective stabilization, such soils should be stabilized with high dosages of lime and cement.

The difference in the effectiveness of soil stabilization for various types of soil is caused by the difference in cation exchange capacity and the type of cations present in the minerals [185]. For this reason, clay soil containing montmorillonite minerals is expected to have better improvement when stabilized with lime and cement than other clay minerals. This is because it has the highest CEC and a higher number of cations in the double-layer space [186].

7.9. Soil pH

Soil stabilization using lime and cement is influenced by changes in pH which determine the increase in strength of the stabilized soil. The pH value determines the extent of dissociation of silica and alumina in the soil during the pozzolanic reaction to form cementitious products (hydrates) of CAH and CSH [76]. Ghobadi et al. [187] stated that at low pH, alumina dissociates preferentially to form CAH, while at high pH, silica dissociates preferentially. However, the authors stated that for the dissociation of both alumina and silica, the pH value must be greater than 9.0. A study by Abdilor et al. [187] proposed the minimum pH value for soil stabilization using cement as 5.3. The study also stated that maximum soil stabilization using lime takes place at a pH value above 10.5.

Low pH value in soil consumes the alumina and silica content that should take place in the pozzolanic reaction. This causes a decrease in the strength of the stabilized soil from the expected value. Therefore, the pH value should be kept above 11 for the pozzolanic reaction to proceed effectively [182]. During lime stabilization, lime hydrates to produce calcium hydroxide which increases soil pH to above 12.4 and facilitates the pozzolanic reaction of Ca^{2+} with silica and alumina. Similarly, in soil stabilization using cement, pH increases as a result of calcium hydroxide which is produced as a by-product of the hydration of cement phases [188].

Table 12. Factors influencing soil stabilization

Factor	Soil stabilizer	Variation	Major geotechnical properties investigated	Initial value	Final value	Reference
Organic matter	Lime	15%	Shear strength	105.7 kPa	62.4 kPa	[157]
	–	1.5%	CBR	15.72%	4.75%	[155]
	5% lime	31%	CBR	12%	7.5%	[156]
Sulphate	10% OPC	20%	UCS	1.4 MPa	1 MPa	[191]
	6% lime	30,000 ppm	Shear strength	70 MPa	60.7 MPa	[192]
	15% OPC	1%	UCS	410 kPa	200 kPa	[193]
	4% lime	6%	PI	19%	60%	[161]
	5%	10,000 ppm	LS	5%	11%	[194]
Moisture content	4% OPC	15%–19%	UCS	2.9 MPa	2.4 MPa	[162]
Temperature	–	25 ˚C–100 ˚C	PI	44%	29%	[165]
	8% lime	23 ˚C–65 ˚C	Axial strain resistance	450%	950%	[195]
	–	25 ˚C–150 ˚C	CBR	6%	20%	[167]
	9% OPC	15 cycles	UCS	4.3 MPa	7.2 MPa	[196]
Wet-dry cycles	9% OPC	15 cycles	UCS	4.3 MPa	7.2 MPa	[196]
	4% lime	6 cycles	UCS	1.06 MPa	0 MPa	[197]
Freeze-Thaw cycles	6% lime	3 cycles	UCS	4 MPa	3.4 MPa	[198]
	12% OPC	10 cycles	UCS	1.05 MPa	0.5 MPa	[199]
Curing time	9% lime	7 days–28 days	UCS	0.8 MPa	2.3 MPa	[181]
	12% OPC	7 days–28 days	UCS	2 MPa	6 MPa	[180]
Quality of pulverization	6% lime	60% finer than 4.75 mm	UCS	0.06 MPa	0.65 MPa	[189]
		100% finer than 4.75 mm	UCS	0.06 MPa	1.43 MPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

7.10. Quality of Pulverization

Pulverization of soil before stabilization is one of the key factors that affects the extent of soil stabilization. It provides a surface for the reaction between the soil particles and the soil stabilizers. Good quality of pulverization ensures there is an increased surface area for uniform pozzolanic reaction throughout the soil particles. Bozbey et al. [189] observed that the most effective soil stabilization using lime is achieved for soil particles finer than 4.75 mm. Similarly, a study by Esan et al. [190] on soil stabilization using cement, noted a continuous increase in the strength of stabilized soil with a decrease in particle sizes for similar cement dosage. Therefore, it is important to ensure that the soil to be stabilized by cement or lime should be well graded with a higher percentage of fine particles after pulverization. According to James & Sivakumar [182], poor quality of pulverization results to slow rate of pozzolanic reaction, which leads to increased curing time to achieve the required strength of lime stabilized soil.

Quality of pulverization causes a difference between the laboratory performance of stabilized soil and performance in field application. This is because it is difficult to ensure similar pulverization in field application as in laboratory application. Researchers have recommended that large soil lamps should be broken and pulverized in the field to increase the performance of stabilized soils. This will also help in saving on the dosage of cement or lime needed to achieve the desired field performance. According to Bozbey et al. [189], higher fineness can be achieved in ex-situ soil stabilization than when soil stabilization is done in situ.

Table 12 summarizes some of the case studies on the parameters which influence soil stabilization.

8. CONCLUSIONS

The paper is a comprehensive review of the state of knowledge regarding expansive soils, and the different methods and agents (the traditional ones as well as the emerging techniques) that are used to stabilize expansive soils. From the review, the following conclusions were drawn.

1. Different stabilization methods can result in a comparable improvement on a given property of stabilized soil. Thus, it can be inferred that, the advantage of one stabilization method/ chemical over the other is highly dependent on the site's specific conditions.
2. Evaluation of the performance of the stabilized soil can be done majorly by comparing its PI, CBR and UCS with that of the original material before stabilization. The performance should also be compared with the set standards to determine the suitability of the stabilized material for field application.
3. Moisture content below or above the "optimum" amount is one of the main influential factors that affect soil stabilization using mechanical as well as

other stabilization methods. In relation to that, the moisture content of a given soil mass can be affected by the presence or absence of organic matter (because of their high water-holding capacity). Therefore, it can be understood that solely a single factor may not be the only influencing factor for the soil stabilization process. Multiple and interrelated factors can coexist together and affect the choice of stabilizers, stabilization methods, and the result.

4. Soil stabilization using cement is the most common among all the other methods of soil stabilization. However, it is deemed to contribute to about 6–8% of global CO2 emissions and bring a toll on the environment. On the contrary, the use of industrial wastes like fly ash is a sustainable and environmentally friendly solution for soil stabilization as well as waste management.
5. Methods such as SEM-EDS and XRD that are employed to study microstructural properties of materials are being used to examine microparticles and micropores of stabilized soils and it is helping to determine the overall changes in the stabilized soil.

8.1. Potential Areas For Future Research

1. Many studies have focused on the stabilization of expansive soil for application in roads, pavements, and highways. Soil stabilizers discussed in this review should be investigated for the stabilization of expansive soils to make them effective as construction materials in earthen construction.
2. Expansive soils stabilized with calcium-based stabilizers especially Portland cement and lime face problems of ettringite-based heaving which reduces durability. More studies should focus on suitable soil stabilizers which control the ettringite formation and offer similar performance as lime and cement.
3. Several chemical stabilizers have been used in improving the properties of expansive soils. More studies that focus on thermodynamic modeling of various reactions and/or processes between stabilizers and soil minerals to understand the reaction mechanism and/or solution chemistry are essential.
4. Studies show that an increase in temperature improves the properties of calcium-based stabilized soil, as it increases the rate of pozzolanic reaction. However, the optimum temperature for stabilization when different calcium-based soil stabilizers are used needs to be established. Further, more studies on the engineering performance of different stabilized soils should be conducted for different climatic conditions such as tropical and temperate climates.
5. The amount of stabilizer needed for optimum performance in soil stabilization depends on the type of soil. Further research should be carried out to determine the stabilizer dosage range for each type of soil according to different soil classification systems.
6. The strength of stabilized soil declines exponentially as soil organic content increases. Humic acid present in organic soils reduces soil pH and consumes calcium ions hence inhibiting stabilization. More research should, therefore, address stabilizers like bio-enzymes that can reduce the concentration of humic acid in organic soils and make stabilization effective.
7. OPC has been widely used in cement stabilization. However, its production process contributes to about 6–8% of global CO_2. Studies should focus on the applicability of new low-carbon cement for soil stabilization and any other environmentally friendly and sustainable solution. Also, sustainability studies on the use of OPC vis-à-vis other alternative soil stabilizers like zeolites, geopolymers, and nano-materials are required with the use of techniques such as Life Cycle Assessment and Cost Benefit Analysis.
8. A combination of different stabilization methods such as chemical and mechanical have been found to work in some case studies. However, a cost-benefit analysis should be conducted to evaluate the most feasible options for different applications and operating standards.
9. The durability of stabilized soil is affected by many factors like wet-dry cycles, chemical composition, and other external factors like temperature. Service life prediction models should be developed for the performance of stabilized expansive soils exposed to different conditions of temperature, moisture content, sulfates, and organic matter.
10. The effectiveness of soil stabilization using cement is determined by the hydration products of different types of cement. More studies on the hydration kinetics for OPC and blended cement when used as soil stabilizers should be conducted to predict strength development in cement-stabilized expansive soils.
11. Most of the common soil stabilizers reviewed are costly and unaffordable in most developing countries. There is, therefore, a need to explore on utilization of locally available raw materials such as bio-enzymes and geotextiles in soil stabilization.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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Review Article

Review on advances in bio-based admixtures for concrete

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ABSTRACT

Bio-based admixtures (BBAs) are emerging as a promising class of additives for concrete, offering a more sustainable and environmentally friendly alternative to conventional chemical admixtures. Derived from various natural or biological sources, including plants, animals, and microorganisms, BBAs have shown potential in enhancing the performance characteristics of concrete in several key areas. This review article provides an in-depth exploration of BBAs, beginning with a detailed classification of the different types of BBAs based on their source material and production methods. It then delves into the various characterization techniques used to assess the properties and performance of BBAs, providing insights into their impact on the workability, strength, durability, and rheology of concrete. The article also discusses the diverse application areas of BBAs, highlighting their versatility and potential for wide-ranging use in the construction industry. It further identifies and discusses the challenges associated with the use of BBAs, such as issues related to compatibility with different types of cement and concrete, storage and shelf-life considerations, quality control and standardization concerns, and cost-effectiveness. In conclusion, the review emphasizes that while BBAs hold great promise as an alternative to conventional chemical admixtures for concrete, there is a need for more interdisciplinary collaboration and research to overcome the identified challenges and fully realize their potential. The paper calls for further studies focusing on optimizing the production and application processes of BBAs, as well as developing standardized testing and quality control procedures.

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1. INTRODUCTION

Currently, over 50% of the global population lives in urban areas, according to The World Bank [1]. The report estimates that by 2045, there will be 6 billion more people living in cities worldwide. This population growth demands for the basic services, infrastructure, and affordable housing. As a result, the construction sector will need to expand rapidly in order to meet the demand. On the other hand, environmental concerns are increasing as the population grows and the built environment expands. One sector with a significant adverse impact on the environment is the construction industry [2]. Environmental challenges such as global warming, natural resource depletion and ecosystem destruction which are caused by the construction industry, have put the construction sector under a spotlight [3]. Manufacturing of construction materials, transportation, on-site erection, use, maintenance, and demolition of the built structure at the end of its service life, in general from cradle to grave, the construction industry poses environmental repercussions.

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The main environmental effects of the construction of concrete structures are the carbon footprint of concrete and the massive consumption of natural resources. Out of the concrete-making materials, admixtures make up the smallest proportion when compared to the other ingredients (aggregates, cement, and water). However, these chemicals or minerals (admixtures) have a significant role in getting the desired fresh and hardened concrete properties. In addition, admixtures have an unwanted environmental impact that mainly arises from their production process and the feedstock materials that are used in the manufacturing processes. For instance, condensation products of formaldehyde such as naphthalene sulfonated formaldehyde condensates, sulfonated melamine formaldehyde polymers, and aminosulfonic acid series are used in the production of several conventional water-reducing admixtures [4]. Furthermore, it is known that these items produce formaldehyde, a chemical that is extremely hazardous to living things, into the environment. Additionally, because the raw materials used to make polycarboxylates, which are used to make water-retarding admixtures, are obtained from petroleum, there would be a potential shortage of these materials [4, 5]. Superplasticizers contribute between 0.4 and 10.4% of dthe total environmental effect of concrete, according to Sabbagh & Esmatloo [6].

Academic and industrial research on admixture is concentrating on creating novel, environmentally friendly, and biodegradable products that are made from renewable natural resources as environmental concerns increase. This review paper thoroughly summarizes and presents the state of knowledge concerning bio-admixtures which are based on natural or biological sources which are non-petrochemicals. Detailed systematic review was conducted on potential bio-admixture making materials, their production process, and application areas. Additionally, gaps that have not been covered in the literature are noted and suggested for additional research. This study also provides a brief overview of the chemical admixtures currently used in the building sector.

2. ADMIXTURES

Occurring naturally or in manufacture, admixtures can be defined as additives or chemicals that are often added when the concrete is mixed, with an aim to enhance specific properties of the concrete, either in plastic or hardened form, such as durability, workability, early or final strength [7]. They offer several benefits to concrete including increased workability, reduced water requirement, better durability, improved strength, volume changes and desired coloration, among others.

However, due to limitations in understanding their mechanism of interaction with concrete, admixtures are often utilized on trial-and-error basis. In this regard, studies have often focused on understanding the interaction between admixtures and the hydrating components of cement [8]. Out of this, it has been observed that the admixtures can occur freely in the concrete matrix as solids or solutions, achieve surface interactions or combine chemically with cement components or the cement paste itself. The consequence of the interaction is therefore the influence on the mechanical and physico-chemical properties of the concrete as durability, strength, setting time, microstructure, kinetics of hydration, water demand and products composition [9].

2.1. Classification of Admixtures

Admixtures are majorly classified into mineral and chemical. Mineral admixtures are also known as Secondary Cementitious Materials (SCMs). SCMs include, fly ash, limestone, shale, calcined clay, pozzolana and many others. These are often added in large amounts to the concrete with the aim to improve the workability conditions of fresh concrete; improve its resistance to sulfates attack, alkali-aggregate expansion and thermal cracking; and reducing the cement content in the mixture [10]. Chemical admixtures are often applied in very small amounts to improve the quality of concrete during transportation, mixing, curing or placement [11]. More specifically, they are tasked with air entraining, plasticizing concrete mixtures, reducing water requirements and in control of the setting time. Some special admixtures are designed to control shrinkage, inhibit alkali-silica reaction or corrosion [12]. According to ASTM C494 and AASHTO M194, chemical admixtures fall into 8 types according to their physical and general requirement; water reducing (Type A), retarding (Type B), accelerating (Type C), water reducing and retarding (Type D), water reducing and accelerating (Type E), water reducing, high range (Type F), water reducing, high range, and retarding admixture (Type G), and specific performance admixtures (Type S) [13].

In practical use, chemical admixtures will be incorporated often in the range of less than 1–2%, and rarely up to 5% against the weight of cement [10]. The normal water reducing or plasticizing admixtures are designed to increase workability of concrete while decreasing water content consistently up to 10%. Ready mix companies use this type of admixtures for performance optimization of normal concretes.

The sole purpose of retarding admixture is to slow down the hydration process of the cement, thereby preventing setting before placement and compaction. This is usually a necessary method in places characterized by hot climatic conditions, when extensive concrete pours are required. Retarding admixtures are known to cause a retardation effect on concrete by either of these ways: (i) through adsorption of the retarding compound on the surface of the particles of cement, thereby forming a protective skin that prevents further reaction, thus slowing down hydration, (ii) through the adsorption of the retarding compound onto the nuclei of calcium hydroxide, thereby poisoning their growth, (iii) forming complexes with calcium ions that exist in solution thus increasing their solubility and consequently discouraging formation of calcium hydroxide nuclei, or (iv) by precipitation around cement particles of insoluble derivatives of the retarding compounds formed by reaction with the highly alkaline aqueous solution, thereby forming a protective skin [14].

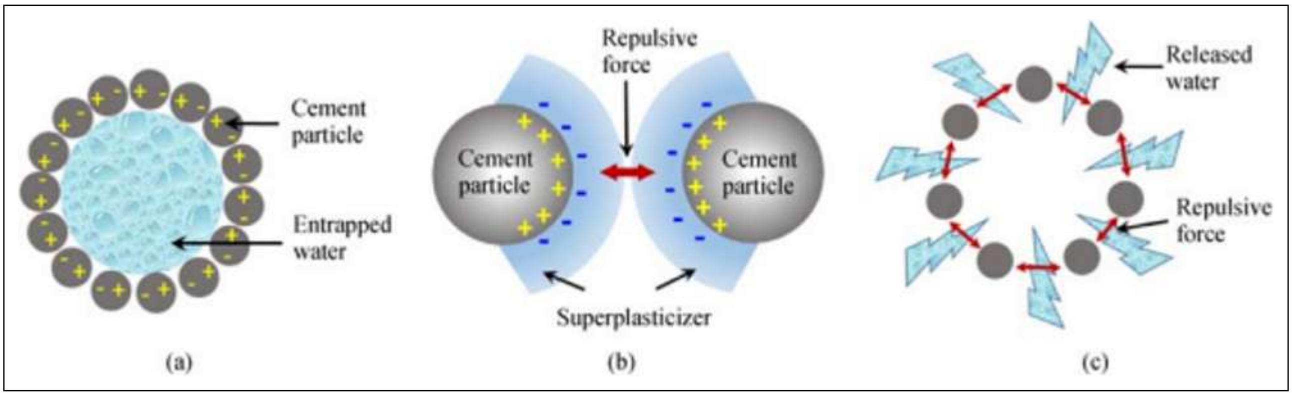

Figure 1. Effect of superplasticizer on cement particles [15]. **(a)** entrapment of water by cement particles, **(b)** repulsion of superplasticizer coated cement particles, **(c)** release of entrapped water.

High range water reducing superplasticizers are used when high water reduction with high workability is required, up to 30%, from about 12%. Such use cases include projects involving steel fiber reinforcement, precast and self-compacting concretes. When a superplasticizer is added to cement mortar, negative charges due to the superplastizer cause dispersion of cement particles through repellence, thereby improving the flow characteristics [15]. This is illustrated in Figure 1. Previous X-ray Diffraction and Scanning Electron Microscopy analysis have shown that superplasticizers affect the crystallinity of the cement hydrates, instead of altering the types of hydration products [16].

Air entraining admixtures are used especially in frost prone areas to improve the concrete by introducing stable air bubbles of less than 0.3 mm in diameter in the concrete, that reduce scaling and cracking due to frost action. The advantage of this type of admixture is that beyond the aforementioned application, the entrapped air improves cohesion in concrete mix, which improves segregation and bleeding of water before rest. Common agents of air entraining admixtures include sulfonated compounds, polymers of polyethylene oxide, resins of natural wood and neutralized vinsol resins [11]. The mechanism of air entrainment is characterized by critical requirements for air development and stability is concrete; introduction of air, surface tension reduction at water/air interface, shell strength and elasticity at water/air interface, and development of matrix viscosity [17]. Mixing action introduces air into the concrete. Without the air entraining admixture, the volume of air in concrete ranges approximately 1–3% with voids greater than 0.5 mm. The admixture is necessary for fine air bubbles distributed evenly throughout the concrete. 0.5 seconds of exposure to a hydrating mixture of cement with air entraining admixtures, the bubbles will be covered in particulates, leading to formation of a shell characterized by sufficient strength and density as to withstand coalescence forces, rupture and gas exchange [18]. The bubbles will remain spread throughout the cement matrix if the paste has enough viscosity. According to Stoke's law, however, if the viscosity of the admixture is too low, air bubbles will escape from the paste as a result of the force of buoyancy [19].

Accelerating admixtures are aimed at increasing early hydration rate in the cement. These admixtures are often used in cold conditions, where they accelerate the early strength development or setting or the concrete. It has been noted that both inorganic and organic additives can quicken the hydration of Portland cements. The compounds can be conveniently separated into two categories: soluble inorganic salts and compounds, and soluble organic salts and compounds, with the first category being the larger [20]. Compounds from both classes are combined to create many commercial accelerators. Insoluble solid substances, such as silicate minerals, cementitious materials, and finely ground magnesium and calcium carbonates, have been employed as accelerators to a considerably lesser extent [21]. Soluble inorganic salts based on alkali or alkali earth metals as hydroxides, chlorides, nitrites and nitrates, carbonates, among others, are often employed in the accelerated setting of Portland cement. Both anion and cationic salts of alkali and alkali earth metals partake in the acceleration reaction on tri-calcium silicate (C_3A) hydration [21]. Calcium chloride for instance, is a known accelerator of the aluminate phases-gypsum system hydration. The Cl^- enhance ettringite formation until consumption of gypsum. If there is free C_3A remaining, calcium monochloroaluminate ($C_3A.CaCl_2.10H_2O$) is formed [22].

Water resisting admixtures, also referred to as waterproofing admixtures, expel, impede or block natural flow of water in hardened concrete capillaries. This is applicable and indispensable for structures below the water table for water retaining structures.

The classification of admixtures is summarized in Figure 2.

2.2. Base Materials for Admixture Production

There are multitude of admixtures which are classified based on benefit-orientated classification. Some of these admixtures are water-reducers, superplasticizers, Air-entrainers, and accelerators. A variety of chemicals are used for the production of those admixtures and the chemicals that are basis for the production are summarized in Table 1.

Lignosulphonates (LS) as water reducers are mostly applied in ready mix concrete. These chemicals are usually biproducts of bisulphite pulping of wood during the separa-

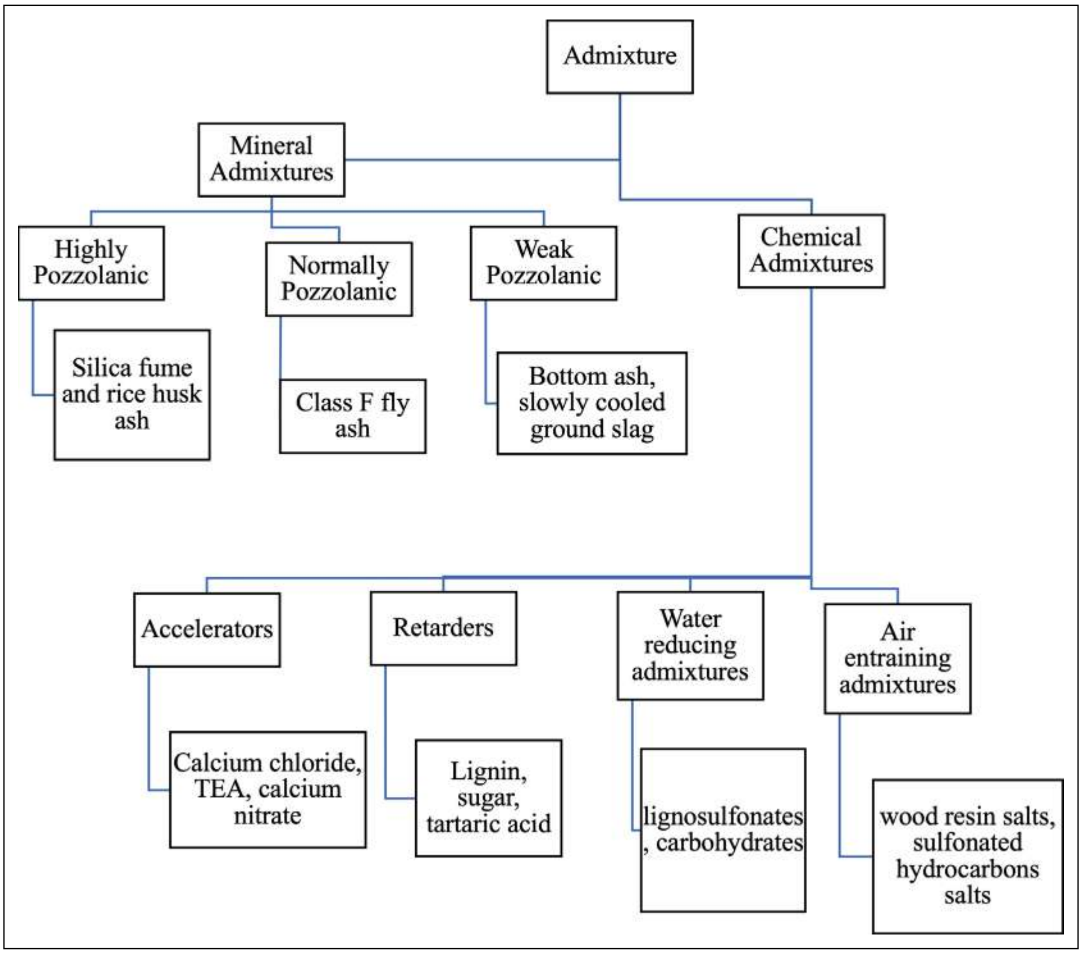

Figure 2. Classification of admixtures [7].

tion of lignin from cellulose fibres. Natively, lignin is insoluble in water, presenting a complex three-dimensional network of randomly crosslinked monolignos like conyferil, coumaryl and synapyl alcohols. Sulphate based delignification involves use of bisulphites and sulphites of magnesium, sodium, calcium or ammonium at elevated temperatures [24]. Hereby, low molecular weight lignin is achieved due to molecules fragmentation occurring over breaking of ester bonds. In addition to this, the sulphonic groups attached to the aliphatic chains are added, making the molecule water soluble. Through this, the LS is separated from the insoluble cellulose through filtration. However, for application to concrete, the lignosulphonate produced through this method needs further modification [25]. This is because about 25% of its total solid's composition is made up of sugars with strong concrete setting retardation. It therefore undergoes precipitation, which removes the sugars, then alkaline heat treatment, amine extraction or ultrafiltration as necessary. Despite their large application in ready mix concrete, LS show minimal water reduction capability of approximately 8–10%, at an average dose of 0.1–0.3% the weight of cement. It is due to this reason that LS is not applied in high-performance concrete [26]. Lignosulfonates are made up of various functional groups as carboxylic acids, phenolic hydroxyls, methoxyl, cathechol, sulphonicacids and various combinations of these, as shown in Figure 3. The dispersing effect of lignosulfonate on cementitious materials has been observed to be a function of its degree of adsorption on the surface of cement grains and hydrates. Thereby, the two main dispersing mechanisms are steric hindrance, and electrostatic repulsion, both portrayed by lignosulfonates [27]. During electrostatic repulsion, the LS, through its functional groups, renders the surface of the cement particle negatively charged. Such particles, on approaching each other, are repelled electrostatically, thus formation of agglomerates is prevented [28]. LS has also been observed to have an adsorption preference to aluminate and ferrite over silicate phases [28]. In a study by Danner [29], the authors discuss that the hydration of aluminate phases C_3A and C_4AF, and silicate phases, C_3S and C_2S, are observed to be retarded by Ca-lignosulfonate. This was observed to occur through retardation of the transformation of hexagonal C_2AH_{13} and $C4AH_{14}$ to the cubic hydrogarnet phase C_3AH_6 [29].

Monosaccharides are other components regarded as an important aspect in retardation, due to the effect of sugars stereochemistry on the ability of the chemical to complex with metal ions on solutions and surfaces on which such cations have an affinity. This complexation, although not a sufficient condition, is necessary for concrete retardation to occur. Thereby, to increase the complexation activity of aldehyde sugars, partially oxidizing them to carboxylic acids

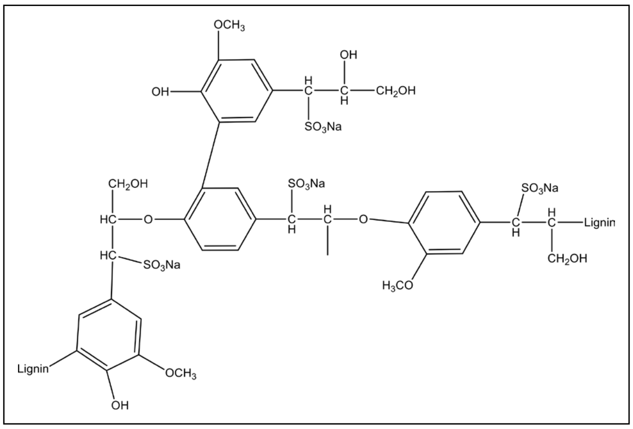

Figure 3. Chemical structure of lignosulfonate [24].

Table 1. Basis of chemical admixtures [23]

Type of admixture	Chemical materials forming the basis for the admixture
Water-reducing	Lignosulphonate
	Hydroxycarboxylic acid
	Hydroxylated polymers
Superplasticizers	Sulfonated naphthalene formaldehyde
	Sulfonated melamine formaldehyde
	Polyacrylates
Air-entraining	Neutralized wood resins
	Fatty-acid salts
	Alkyl-aryl sulfonates
	Alkyl sulfates
	Phenol ethoxylates
Accelerators	Calcium chloride
	Calcium formate
	Triethanolamine

can be done. This is usually a spontaneous reaction, which can be slow, but the alkaline nature of cementitious systems has been seen to catalyze the process. This leads to many different degradation products, that carry carboxylate function. A glucosidic bond between two monosaccharides can influence redox reactivity of sugars, and their reactivity in alkaline conditions as those in cementitious products [24].

Polysaccharides are often utilized as viscosity-modifying admixtures (VMA) in concrete. Through microbial fermentation, high molecular weight welan and diutan polysaccharides (Fig. 4) are produced, for use as VMAs [30]. With a molecular weight of about 10^6 g/mol, welan gum is made of tetrasaccharide backbone chain made up of L-rhamnose, L-mannos, D-glucurinic acid and D-glucose. The backbone of welan gum hosts side chains with either L-mannose or L-rhumnose single units substituting third carbon of every 1, 4 linked glucose. Diutan only differs from welan gum with two units of L-rhamnose and a higher

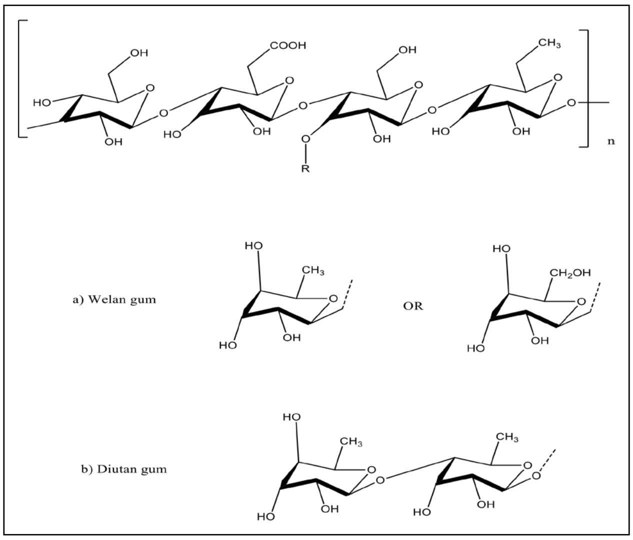

Figure 4. Structure of welan and diutan gum polysaccharides.

molecular weight of 3–5 x 10^6 g/mol. These gums are seen to have high stability even under elevated temperatures and pH up to 11 [31]. When used in cement, they adopt double helical conformation, whereby side chains screen the backbone thus preventing cross-linking of the carboxylate groups on the backbone by calcium ions in concrete. Therefore, high Ca^{2+} concentrations do not destabilize them, making them the ideal VMAs [32].

3. BIO-BASED ADMIXTURES

In general biomaterials are defined as processed or engineered products that are used in different application areas and obtained partially or fully from renewable biobased resources [33]. Bio-admixtures, in that sense, are admixtures that are derived from renewable biobased resources. Others define bio-admixtures as molecules that contain natural or modified biopolymers and biotechnological and biodegradable products [31]. Plank [34] defines bio admixtures as a functional molecule used in building products to optimize material properties.

3.1. Bio-Based Sources for Bio-Admixture

Natural polymers such as lignosulfonate, starch, chitosan, and protein hydrolysates can be found in bio-admixtures that are used for concrete application. For different reasons, bacteria or fungi can also be used in combination with those natural polymers [35]. From this, it can be inferred that bio-admixture can be sourced from plants, animals or microorganisms.

Several plant and plant derivatives have been used as a bio-admixture. Even in the ancient times, during the Roman Empire, vegetable fat used to be added in lime mortar [35]. Many studies have been done recently on the usage of various plant kinds and plant derivatives as admixtures in concrete. Some of the plants/plant derivatives which have been investigated for their pertinence for concrete application are:- Acacia Karro gum [36], starch from cassava and maize [37], arrowroot [5], corn [4], molasses from sugar

Table 2. Microbial-based admixtures and their production process [60]

Admixture	Biotechnological process	Function/application	Application	Dosage	References
Sodium gluconate	Biooxidation of glucose by bacteria Gluconobacter oxydans, filamentous fungi Aspergillus niger, or yeastlike fungi Aureobasidium pullulans	Superplasticizer, retarder, corrosion inhibitor, water reducer	Gypsum plaster, mortars, grouts, concrete mix	0.1–04%	[34, 61]
Xanthan gum	Biosynthesis by bacteria Xanthmonas campestris	Thickener, retarder in self-consolidating concrete	Paints, floor screeds	0.2–0.5%	[62]
Welan gum	Biosynthesis by bacteria Alcaligenes sp.	Thickener, retarder in self-consolidating concrete	Paints, floor screeds	0.1–0.5%	[63, 64]
Scleroglucan	Biosynthesis by fungi from genera Sclerotium, Corticium, Sclerotinia, Stromatinia	Thermostable viscosifier	Paints, floor screeds	0.2–0.5%	[63]
Succinoglycan	Biosynthesis by bacteria Alcaligenes sp.	High-shear thinning, temperature induced viscosity breakback	Soil stabilization	1–15 g/L of water	[63]
Curdlan gum	Biosynthesis by bacteria from genera Agrobacterium or Alcaligenes	Set retarder, viscosifier	Self-consolidating concrete	Up to 10 g/L of water	[32, 65]
Polyaspartic acid	Chemical synthesis	Dispersant, corrosion inhibitor, air-entraining agent	Set retarder in gypsum	–	[60]
Dextran	Biosynthesis by lactic acid bacteria	Rheology modifier	Portland cement, grouts (self-leveling)	–	
Pullulan	Biosynthesis by yeastlike fungi Aureobasidium pullulans	Viscosifier, set retarder	Self-consolidating concrete	–	
Sewage sludge	Waste biomass of municipal wastewater treatment plants	Viscosifier, set retarder	Sintered light-weight aggregate for nonstructural concrete	1:1–1:3 ratio of clay to sewage sludge ratio	[66]
Bacterial cell walls	Aerobic cultivation of bacteria	Microstructural filler	Concrete production	0.03–3.3%	[60]

production [38], aqueous extract from okra [39], grape and mulberry extracts [40], gram-flour and triphala [41], gum of triumfetta pendrata [42], guar gum [43], palm liquor [44], seaweed [45], Black tea extract [46], cypress tree extract [47], pine tree bark extract [48], vegetable cooking oil [49–52].

Animal products have been utilized for a very long time as an admixture in the construction of buildings and other structures, much as plants and their derivatives. For instance, the Romans used dried blood as an air-entraining agent and biopolymers such as proteins as set retarders for gypsum [53]. Similarly, the Chinese have used egg white, fish oil, and blood-based mortars when constructing the Great Wall [35]. Recent studies have looked at concretes that feature natural admixtures made from animal products. Such animal products include: ghee [41], broiler hen egg [54] and animal protein [55].

Microorganisms can improve the properties of concrete [56]. The addition of microbial biopolymers to concrete and dry-mix mortars is one of their main uses in the building sector. The examples of microbial admixtures that are used in concrete are protein hydrolysates and welan gum; and in case of dry-mix mortar these admixtures are succinoglycan and xanthan gum [57]. In addition, sodium gluconate, xanthan gum, curdlan, or gellan gum are also such kind of admixtures [35]. The other is, a consortium of certain species of beneficial microorganisms which are known as effective microorganisms (EM). These include lactic acid bacteria (LAB), yeast, photosynthetic bacteria (PSB), and Actinomyces which are more effective than only one type of microorganism because their coexistence allows their metabolites to be used as food, hence extending their life span [56].

4. BIO-ADMIXTURE PRODUCTION PROCESS

4.1. Plant-Based Admixture Production

With the use of portable water, plant parts are properly cleansed of dust and other contaminants. To obtain a gel, the stem or leaves are filleted. Other chemical extracts are obtained from dissolving pulverized powder such as gum in water and filtered to obtain liquid extracts such as aloe vera gel.

Mbugua et al. [36] produced a bio-admixture from Acacia Karroo Gum by collecting the tears (exudates) from the tree bark and dried it at room temperature. Following the removal of bark bits and other foreign objects, the cleaned ooze was crushed, sieved through a 200 μm sieve, and then stored in a cold, dry area until it was needed. On the other hand, Schmidt et al. [42] prepared bio-admixtures from acacia gums and gum of the *triumfetta pendrata* A. Rich. The gums were initially dissolved in tap water at room temperatures, then the solution was filtered to separate the coarse impurities, and finally, the filtrate was dried and ground. The same researchers have also prepared cassava starch-based admixture by dissolving the cassava starch in a tap water at a temperature of 70 °C. Then the residue of coarse particles was sieved off, and the remainder was dried and ground to obtain the admixture [42].

Another study utilized four litters of water to boil one kilogram of cypress bark, which was chopped into tiny pieces and heated under pressure for two hours. Another investigation involved boiling a kilogram of cypress bark, which was broken up into tiny pieces, for two hours while under pressure. After 24 hours it was shaken vigorously for 5 minutes and the admixture was collected [58]. Similar to this, in a study on a bio-admixture composed of okra extract, the seed and pod of the okra were broken up into small pieces and added to tap water in a predetermined ratio (weight of okra to volume of water), then swirled for five minutes, and left undisturbed for an hour. The viscous extract was then filtered using a 300 μm sieve. The okra bits were further crushed by hand for more extraction before being passed through a 150 μm sieve. The extracted material was subsequently used within a day of storage [39].

Water hyacinth plant extract was made by Okwadha & Makomele [51] after they harvested and cleaned the plant under flowing water. Once the muddy debris and impurities had been removed, it was spread out on a clean, absorbent piece of cloth and dried in the shade. The dry plant was then finely cut into small pieces of about 5 mm, and then ground into fine powder. Followed by a moistening of 500 g of the powder with a liter of tap water, and soaked in 30 ml of ethanol for 24 hr. Then the filtered extract was stored for use.

In relation to the preparation of starches used in construction materials Schmidt et al. [59] suggested that the starch needs to be cold water soluble. And when it is used in cementitious materials where the pH environment is high, the starches have to be stabilized by ether or ester bond in the hydroxyl groups. As the stabilization typically reduce the tendency for retrogradation and to minimize intermolecular interactions.

4.2. Microbial-Based Admixture Production

Microbial based admixtures can be made by using bacteria or fungi, by employing biotechnological processes. These types of admixtures are getting attention because of their high biosynthesis rate as compared to plant-based products. And these admixtures can be produced in biotechnological factories, in industrial level [57]. Some of the microbial-based admixtures with their production processes are summarized in Table 2.

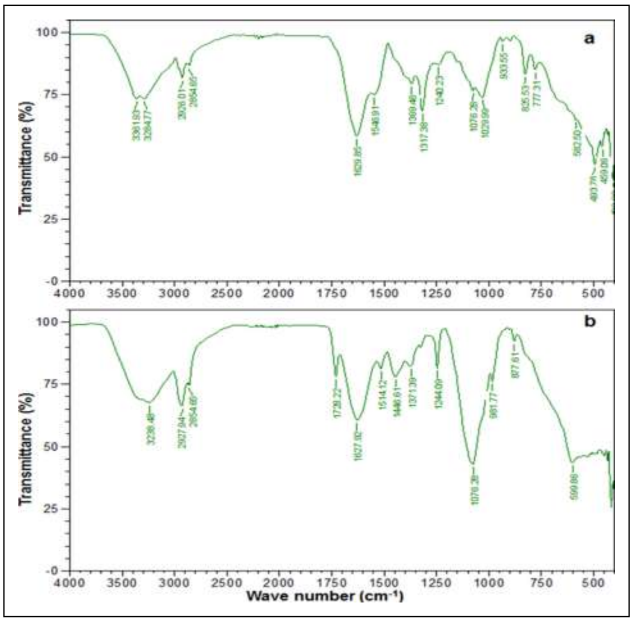

Figure 5. FTIR studies of: **(a)** Spincea oleracea and **(b)** Calatropis gigantea [69].

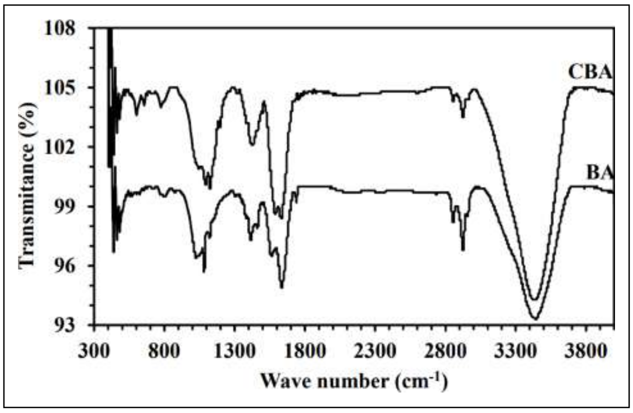

Figure 6. FTIR Spectra of aqueous bio-admixture (BA) and cement treated bio-admixture (CBA) [39].

5. CHARACTERIZATION OF BIO-ADMIXTURES

Chemical and ionic composition, type of organic functional groups, structure of the polymer and distribution of molecular weight of different polymers affect the behavior of admixtures. These property-defining parameters can be examined using different techniques or methods of characterizations [67]. Some of the methods are; Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Fourier transform Raman spectroscopy (FT-Raman), ionic chromatography, ultraviolet-visible spectroscopy (UV-VIS), nuclear magnetic resonance spectroscopy (H-RMN and C-RMN), gel permeation chromatography (GPC) [40, 67].

5.1. Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR was used to characterize a starch-based chemical admixture used to reduce heat of hydration. The spectra analysis mainly showed the presence of is starch-based –OH hydrophilic, functional group [68]. Malathy et al. [69], have conducted FTIR on a dried plant extracts produced from

Table 3. Summary of FTIR studies in bio-admixture characterization

Admixture	Active chemical	Property	Application	Dosage	FTIR observations	References
Aqueous okra extract	Acidic hetero polysaccharide (pectin)	Viscosity enhancement	White cement paste	15 ml of 10% cement paste blended with 100 ml plant extract	Broad bands in 1500–1700 cm^{-1} and two absorption minimums near 1634 cm^{-1} and 1565 cm^{-1} suggested presence of pectin and proteins as major chemical constituents in admixture 1640–1660 cm^{-1} – amide I present in protein of plant extract. 1550 cm^{-1} – amide II due to protein.	[39]
Egg albumen	Protein (hydrophilic and hydrophobic aminoacids)	Improve workability	Natural hydraulic lime mortar	0.1–0.3% by weight of water	3293 cm^{-1} – OH stretch due to proteins, illustrating the hydrophilic character of egg albumen, thus could generate more bond moisture 1031 cm^{-1} – carboxyl groups corresponding to cell wall pectin	[71]
Natural sugars (molasses/ palm jaggery/ honey) and Terminalia chebula	Polysaccharides	Rheology alteration and retarding	Fly ash and ground granulated blast furnace slag-based mortars	0.8% by weight of aluminosilicate materials.	881 cm^{-1} – presence of beta-glucosidic linkages between monosaccharides. 1390 (R-NH_2), 1270 (–C–O–H bending) and 1120 (Ph–NH_2) due to chebulagic acid, chebulinic acid and hydrolyzable tannoids in terminalia chebula.	[72]
Spinacea oleracea and Calatropis gigantea plant extracts	Polyphenols	Self-curing agent (water retention)	Fly ash-based concrete	0.6% (S. oleracea) and 0.24% (C. gigantea) by binder weight	3435.12 cm^{-1} - –OH stretch vibrations due to adsorbed water molecules. 875.63 (C–O bending) and 1421 (C–O stretching) attributed to CO_3^{2-}	[69]

Spincea oleracea (*S. oleracea*) and *Calatropis gigantea* (*S. oleracea*), to test the existence of hydroxyl (–OH) and ether (–O–) functional groups in a bio admixture used as internal curing agent The peaks as observed are illustrated in Figure 5.

According to Figure 5, the peaks observed at wavenumbers 3361.93 and 3284.71 cm^{-1} confirmed the presence of -OH groups as in the *S. Oleracea* and 3238.48 cm^{-1} as in *C. Gigantea*. This feature indicated the water retention capability of the plant extract and thus qualified them as concrete bioadmixtures.

Hazarika et al. [39], prepared the test sample of okra aqueous extract which is treated (CBA) and untreated (BA) with filtrate of cement water suspension. The FTIR spectra, as observed, are shown in Figure 6.

The results of the FTIR spectrum indicated the chemical composition of bio-admixtures. Some of the functional groups that were found from the observation are O-H, CH_2, C=O groups. According to Silverstein et al. [70], the presence of these functional groups is an indication for the presence of galactose, rhamnose and galacturonic acid of pectin. In the study, it was also observed that some peaks shifted to higher frequency, while others increased in intensity, when the bio-admixture was applied to cement matrix. This indicates that FTIR technique, in addition to fingerprinting the chemical composition of the bio-admixture, can also give an insight on the interaction of the admixture and the cement phases.

Abd El-Rehim et al. [4], performed FTIR to confirm the starch modification by chlorosulfonic acid and interpret the structure of sulfonated starch which was proposed to be used as water-retarding agent in cement industry. Other studies whereby FTIR has been applied in bio-admixture characterization are summarized in Table 3.

5.2. X-ray Diffraction (XRD)

X-ray powder diffraction (XRD) is a technique widely used in material science to investigate crystalline materials in finely divided or powder form, it can also be applied to non-crystalline solids. On the contrary, studies have shown that structural information about liquid crystalline phases can be obtained from XRD. Qualitative or quantitative analysis can be used to characterize the material properties. Each crystalline phase is individually characterized by the specific distribution and intensity of diffraction peaks, which is similar to a fingerprint. On this basis, qualitative analysis is founded. On the other hand, because the diffraction intensities are directly related to crystal structure and the amounts of each phase, quantitative analysis, which is the determination of the amounts of more than one phase in a mixture, is possible.

Table 4. Summary of XRD characterization

Admixture	Type/feature	Application	Dosage	XRD observations	References
Cactus (Opuntia ficus indica) mucilage	Water repellent	Hydraulic lime mortar + sand mixture	25–100% of lime-sand mixture	High intensity peaks of CH in hydraulic lime, decreasing in reference mortar to medium intensity and trace amounts in cactus-based mortar. Medium intensity peaks peaks of CSH and geh Medium intensity peaks peaks of CSH and gehlenite identified in both reference and cactus modified mortars indicating hydraulic nature of lime used.	[73]
Bilwa (Aegle marmelos) fruit extract	Water retention and air entraining agent	Hydraulic lime mortar	1–3% by weight of water	Portlandite peaks were observed at higher intensity, along with moderate brucite and calcite peaks	[74]
Cactus extract	Water retention	OPC 53 grade cement-based concrete	2–10% by weight of water	Portlandite was observed to reduce in cactus modified samples indicating early consumption of portlandite to form CSH phases Higher intense peaks of C_2S and C_3S phases were observed in 10% cactus concrete compared to reference, which supported observed enhanced mechanical properties	[75]
Black tea extract	Dispersant/ workability enhancement	Metakaolin blended cement mortar	0.5–2% by weight of water.	Content of CH Content of CH significantly higher when black tea extract is used, indicating potential facilitation of hydration of cement in production pf CH, suppression of pozzolanic reaction of metakaolin thus consume less CH at 7 days curing	[46]

Using XRD Mahmood et al. [40] directly examined grape and mulberry extracts which were used as natural admixtures. Others have studied cement paste, mortar or concrete that contain a variety of bio admixtures to infer the effects of a given bio-admixture on mineralogy of the mix. This implicitly gives some idea about the characteristics of the admixture. Table 4 summarizes some studies that used XRD in characterization of bio-admixtures.

5.3. Nuclear Magnetic Resonance (NMR)

Nuclear magnetic resonance (NMR) is the response of atomic nuclei to magnetic fields. Many nuclei have a magnetic moment and behave like a spinning bar magnet. These spinning magnetic nuclei can interact with external magnetic fields, producing a detectable signal [50].

Although the most common application of NMR is the structural determination of molecules, the technique has the advantage of direct mixture analysis, and thus, NMR has demonstrated a unique potential to be used for metabolic mixture analysis. This technique has also been used for easy and quick recognition of microorganisms, antimicrobial susceptibility tests, and other applications [76]. NMR can also be utilized to study the degree of hydration, the reactivity of pozzolanic materials, clinker composition, interaction of organic admixtures with cement minerals, the different states of water in concrete, among others [77].

Mota et al. [78], have used ^1H NMR to study the impact of sodium gluconate on white cement-slag systems with Na_2SO_4. The authors stated that ^1H NMR is highly advantageous to analyses the distribution of water in the sample among the different pore sizes. A summary of studies that characterized admixtures with NMR is given in Table 5.

5.4. Gas Chromatography–Mass Spectrometry (GC-MS)

When gas chromatograph (GC) and mass spectrometer (MS) are combined into one GC-MS system, the resulting capabilities of the system are not simply the sum of the two instruments however it increases the analytical capabilities exponentially [83]. One of the common applications of GC-MS is for identification of key small molecules such as fatty acids, amino acids, and organic acids in biofluids [84]. For instance, Okwadha & Makomele, [51] conducted GC-MS to identify the components of water hyacinth extract. From the analysis, minute fragments of dissolved lignocelluloses, fatty acid groups, alcohols, aldehydes, and ketones were observed. Similarly, Sathya et al. [52], examined water hyacinth using GC-MS, and reported similar findings as saturated and unsaturated fatty acids, in addition to lignocellulose, which had the admixture classified as a retardant. More studies are summarized in Table 6.

5.5. Rheology

The study on how concrete paste or slurry deform or behave under a given water/powder ratio is rheology. The study of rheology is known as rheometry. Many fluids depict simplest form of linear deformation referred as Newtonian flow [88]. However, complex fluids such as mortar and concrete show plastic behavior explained by Bingham model [89]. In the Bingham model, flow initiates on some level of stress (yield stress) following a linear relationship of stress and strain [90]. Concrete as a material demonstrates yield stress properties to obtain a specific level of viscosity. Although, flow depends on other factors such as concentrations, temperature and many more. The concrete or mortar parameters like workability include mobility, stability and compatibility [88]. The fresh concrete workability

Table 5. Summary of NMR characterization in bio admixture studies

Admixture	Dosage	Application	Analysis conditions	NMR observations	References
Latex admixture	0.1–0.5%	Tile mortar	^{13}C, ^{27}Al and ^{29}Si NMR spectra were acquired at Magnetic field of 7.05 and 11.74 T, Spinning speeds of 8 kHz and Temperatures of 233 – 243 K	Only minor differences in ^{13}C spectra at slightly heightened admixture concentrations before and after 14 days of hydration. After hardening, signal ratios of CHO and CH_2 to the CO and CH_3 groups were observed to change, indicating polymer decomposition due to partial hydrolysis.	[79]
Chitosan based admixture	5–20% the weight of water	OPC mortar	^{1}H NMR spectroscopy	Approximately 27% and 7% of the total amino groups were transformed into amides attached with 3,4 – dihydroxyhydrocinnamic acid groups	[80]
Basalt fiber	1.3% of the cementitious material	Recycled aggregate concrete	Porosity was measured with NMR of magnetic field of 0.3 T, resonance frequency of 50–60 Hz and coil diameter of 60 mm	It was observed that internal pores of the specimens were mainly micropores.	[81]
Organic corrosion inhibitors (OCI) (easter-, alcoholamine-, and carboxylic acid- based)		OCI-modified concrete		OCIs used were observed not to affect the hydration product species. Easter-based OCIs significantly decreased the proportion of larger pores, thereby enhanced compressive and reduced capillary absorption rate. Concrete frost resistance was observed to improve on addition of alcoholamine-, and carboxylic acid based OCIs.	

Table 6. Summary of researches utilizing GC-MS in admixture characterization

Admixture	Active chemical	Property	Application	Dosage	GC-MS cbservations	References
Olive oil and milk	Fatty acids	Hydrophobic admixture	Standard CEM I mix	–	The total fatty acid value measured was appreciably higher for the olive oil, due to the significantly lower fatty acid content of milk.	[85]
Kadukkai (Terminalia chebula) and jaggery	Fatty acids	Antimicrobial activity	Air Lime mortar	1–5% the weight of water	Peaks of 2-piperidinone (antimicrobial quality), ethybenzene (formation of styrene), and cyclobutenes(antioxidant) were observed.	[86]
Water hyacinth (Eichornia crassipes) extract	Lignin	Water reduction	Portland cement concrete	0.25–0.75% hyacinth extract the weight of concrete	Lignocellulose, saturated and unsaturated fatty acids were observed in the extracts, which were concluded to play a role in the improvement of cement workability.	[87]
Water hyacinth (Eichornia crassipes) extract	Fatty acids and lignin	Retarder	Self-compacting concrete	0–25% partial replacement to commercial superplasticizer	Concentrations of octanoic acid, hexadecenoic acid, heptane, phycol, 1-ethyl-2-pyrrolidinone, among other compounds were observed in GC-MS peaks	[51]

is measured by flowing ability, passing ability, segregation and bleeding resistance and viscosity [91]. Special concrete rheology is evaluated through slump tests ranging from Abram's cone slump test, slump table flow test, V-funnel, U-box test, J-ring test and L-box test [92]. Introducing bio-admixtures into fresh mixes interfere with thixotropy and viscoelasticity of the slurry particles with the aim of improving pumpability and shooting flow [93].

Table 7. Water Hyacinth utilization as a bio-admixture

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
A mix of 1:2:4 (Class M15) with water/ cement ratio 0.45 under OPC	The water hyacinth was replaced at 0%, 10%, 15%, 20% and 25% by volume of commercial admixture, Auramix 40	The increase in the percentage of Water Hyacinth increased workability. WH extract retained SCC slump flow of 2–5 seconds and a diameter of 500–700 mm on T_{500} slump flow test	The compressive strength was checked on the 7th, 14th and 28th days. At 20% of WH, the highest compressive strength on the 28th day.	On the 7th day, there was an optimum 2.8% water absorption rate with 25% WH extract dosage. On the 28th day, the water absorption rate significantly increased to 6.3%	[51]
A mix of 1:2:4 (M class M15)	The water hyacinth was replaced at 0%, 0.5% and 1%.	The addition of 0.5% WH decreased the initial setting time to 172.2 from 187.2 minutes. However, the final time increased from 255 minutes to 270 minutes. Further addition of WH to 1% reduced both the initial and final setting times significantly. The results recommended for further percentage increase to ascertain the yielding point of WH as an admixture	Compared with the standard concrete increasing WH from 0.5% to 1% increased the compressive strength from 21.4 to 21.7 on the 28th day.	–	[99]
A design of 1:1.78:2.77 (cement: sand: coarse aggregate) and Water/ cement ratio of 0.45	A powder form of WH on percentage replacement was done at 1%, 2%, 5% and 10% on cement. Solution form of WH was done at 0.25%, 0.5%, 0.75% and 1% on cement	Increasing the WH extract in percentage dosing, increase workability. This was attributed to fragments of lignocellulose dissolved in the extract. On the 7th day cubes with 5% and 10%, WH had not set. Similarly, they noted that WH solution retained slump flow and recommended it for a superplasticizer.	The compressive strength increases from 0 to 0.25% but further dosing was reduced and was assimilated to the uneven fineness of WH powder and cement.	–	[98]
Normal concrete	0%, 0.5%, 1%, 1.5% & 2% by mass of aggregate	–	Compressive strength (IS 516-1959) and Tensile strength	Water absorption	[101]
Mortar at 1:3	0.38 w/c at 0%, 10, 15 and 20% mass replacement of cement	Increased workability with retard effect	Increased compressive strength with% increase of WH	Decreased water absoption with% increase	[52]

5.6. Mechanical Properties

Special concrete (SP) is a modern concrete for wide applications in the laboratory and practical world. Selecting SP components and ratios depends on the physical and mechanical properties required in the project [94]. The mechanical characteristics include compressive strength, split tensile strength, flexural strength and modulus of elasticity [95]. There are many types of biological agents used to retard, accelerate, or remove air in mortar and/or concrete improving workability, curing and hardened properties [52]. The study on mechanical properties of bio-concrete enhances awareness on optimal use of available biological agents for sustainable concrete production.

5.7. Microstructure Analysis

Concrete is categorized into three heterogeneous components, cement paste, pore structure and interfacial transition zone that enhance mechanical strength and durability [96]. Microstructure study seeks to interpret the behavior of concrete in exposure conditions during the serviceability period [97]. Introducing bio-admixtures to fresh mix of concrete and mortars enhance packing ability. The hardened property of the enhanced mortar can be porous of impervious to chemical and water ingression (SLO). Microstructure study establishes the behavior of bio-concrete when exposed to various environmental aspects. This is discussed further in the section of Bio-Admixtures.

6. BIO-ADMIXTURES

6.1. Plant-Based Bio-Admixtures (Pb2A)

6.1.1. Water Hyacinth

Water hyacinth (WH) is an aquatic plant classified under weeds from its high regenerative rate of 2 tons per acre [51]. Its scientific name is *Eichhornia crassipes*. The weed is highly invasive, which makes it difficult for aquatic species to survive. Physical extraction is the only method to physically stop its spread [98]. Utilizing the weed for additional purposes, such as the manufacturing of concrete, aids in sustainable waste management as shown in Table 7. The utilization of water hyacinth in concrete is attractive in relation to its composition. The use of the plant's extracts as a concrete retarder has been made possible by the presence of cellulose, saturated fatty acids, and unsaturated fatty acids, according to Gas Chromatography analysis [51]. According to a second study using biomass from pulverized water hyacinths, the effect on concrete varied depending on the replacement ratio of the additive, with 0.5 percent replacement causing an acceleration effect and 1 percent replacement causing a retardation effect [99]. According to a different study, water hyacinth liquid extract, which according to Gas Chromatography analysis was found to include lignin, improved water reduction in the concrete created [100].

6.1.2. Gum Arabic

Gum Arabic is a yellow exudate from acacia trees, such as Acacia Senegal, also known as chaar gund, acacia gum, or meska [102]. The discharge is produced by a wounded bark. Water can dissolve the gum [103]. It is composed of polysaccharides and glycoproteins with adhesive or binder characteristics [104]. Some applications of Gum Arabic are discussed in Table 8.

6.1.3. Starch

Starch is a natural biopolymer classified as a homo-polysaccharide. It forms a basic unit of glucose constituting amylopectin and amylose, given in Figure 7 [111]. Starch is hydrolyzed in presence of water components that delay the hydration process in cement. The formation of nanocrystals is influenced by the presence of amylopectin [112]. Starch applications in enhancing concrete properties are discussed in Table 9.

6.1.4. Aloe Vera Gel

Aloe vera plant is a tropical climate plant believed to originate from the Arabian Peninsula. It grows to a height of between 60–100 cm [119]. The plant is collected from the field, thoroughly cleaned under moving water. The green layer is peeled off and the white part grained to a gel. The chemical constituents of aloe vera gel are given in Figure 8. The gel is added to concrete during fresh mixing at the percentage weight of cement. In concrete, the major application of aloe vera gel is to act as a plasticizer, since it contains above 95% water content [120]. Studies based on aloe vera utilization are summarized in Table 10.

6.2. Microbial Based Bio-Admixtures

The effects of three microbial based bio-admixtures are summarized in Table 7. These are Sodium gluconate (SG), Welan gum (WG) and Xanthan gum (XG). SG, given in Figure 9, is a crystalline powder that can be produced under properly controlled conditions [124]. And it is one kind of typical hydroxycarboxylic acid salt [125].

Both WG and XG, given previously in Figure 4, are industrially produced microbial polysaccharides [60]. Xanthan gum (XG) is obtained by aerobic fermentation by Xanthmonas campestris [126]. Whereas WG is high molecular microbial polysaccharides produced by the fermentation of Alcaligenes species [68]. Further studies are summarized in Table 11.

7. APPLICATIONS OF BIO-BASED ADMIXTURES

Chemical admixtures have a plethora of applications in the construction sector. Similarly, bio-admixtures are expected to have such a broad application with even more sustainable manner. However, there are limited number of researches which examine the applicability of bio-based admixtures in different types of concretes. The two types of concretes which were found in literatures and use bio-admixtures are self-compacting (SCC) and self-healing concrete (SHC). SCC is a special type of concrete obtained by adding plasticizers and superplasticizers to the normal concrete. SCC flows under its self-weight to fill congested reinforcement in sophisticated formwork. Scholars and interested companies have carried research on alternative organic admixtures for producing SCC [51]. have used water hyacinth extract as a bio-admixture and improve the rheological property of SCC. And Xanthan Gum was used by [126].

The other is self-healing concrete, a type of concrete which has the ability to repair its cracks automatically. Among the various methods of self-healing, biological self-healing is the most common one. Biological self-healing works by adding bacteria to the concrete. In self-healing concrete, bacteria are used along with calcium nutrients known as calcium lactate. This product is added in the concrete mix in wet condition. The bacteria that are introduced in the concrete can be in inactive stages for up to 200 years and become active as soon as it comes in contact with water seeping through the cracks in concrete. Then germination of bacterial spores will be initiated, which feeds on the calcium lactate consuming oxygen. This process transforms the soluble calcium lactate into insoluble limestone. When this limestone gets hardened, the crack is being filled up [131].

Different microbials are used to produce self-healing concrete. Provided that appropriate conditions, sufficient nutrients and a calcium source are available, several strains of bacteria can induce the precipitation of calcium carbonate. And this precipitation has been known for its ability to improve the mechanical properties and durability of construction materials. In this regard, encapsulated bacterial spores have shown the ability to self-heal cracks in concrete. These days self-healing concrete based on mi-

Table 8. Gum Arabic studies on producing bioconcrete

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
SCC mix design according to EFNARC guidelines at 2% air content and water-powder ratio (w-p) from 0.65–0.8	GA at 2%, 4%, 6%, 8% 10% and 12%	The spread flow ranges from 660-750 mm falling under the SF2 flow class. Spread flow increased with an increase in dosage where the optimum spread flow at 1.8% wt% of 680 mm. At 1.1 w-p, spread-flow reduce due to an increase in yield stress. The lowest yield stress 2%	–	–	[105]
The control mix design had a water/ cement ratio of a controls 0.5 and 0.45 of SCC. under Dangote OPC cement	Gum Arabic as a superplasticizer	In dosing of Gum Arabic, the initial time increased from 1.8 hours to 5.3 hours while the final setting time increased from 3.6 hours to 8.36 hours for control and SCC respectively.	The compressive strength increased over the age from 7 days to 90 days. At the 28-day normal concrete obtained higher compressive strength but SCC gradually gained strength to the 90 days and obtained a higher value of 32.34 N/mm^2	–	[104]
		The slump retention for the control was 25 mm. The flowability of SCC confirmed to Class 1 at 582 mm. the L-box achieved 7.2 seconds,			
		Viscosity through V-funnel was recorded as 5.48 sec which is less than 8 seconds.			
SCC design mix as per the European Guidelines for Self-Compacting Concrete (EFNARC) in the provision of BS-EN 12350-1 and BS-EN 12350-2.	0.9% and 1.5%	SCC1 records a slump flow of 560 mm thus Class SF_1. The V-funnel is 8 sec adequate for SCC. L-box, U-box and Fill-box have low values hence low passing ability but no segregation.	–	–	[106]
–	–	SCC2 had a V-funnel value of 7s good flowability with 590 mm. L-box, U-box and Fill-box have low values hence low passing ability but no segregation	–	–	
–	–	SCC3 V funnel the flow of 5.5 s with a flowability diameter of 660 mm. L-box, U-box and Fill-box have good values recommended passing ability. Thus SCC class SF_1	–	–	
–	–	SCC4 has a slump value of 680 mm Class SF_1. V-funnel flowability value of 5s thus Class VF_1 of satisfying viscosity of SCC. L-box, U-box and Fill-box	–	–	

Table 8 (cont). Gum Arabic studies on producing bioconcrete

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
		have good values recommended passing ability			
OPC grade 52.5 is used at a Water/cement ratio of 0.5	Gum Arabic Karoo at 0%, 0.3%, 0.4% 0.5%, 0.7%, 0.8%, 0.9%, 1% and 1.1% of cement	The setting times are according to EN-03 2005. The highest initial setting time for Gum Arabic Karoo is 0.5% dosage. It was higher than 3.18 hours to control but reduced at 0.9% dosage. The final setting time higher at 0.6% dosage	The value of compressive strength decreases with an increase in gum Arabic Karoo dosage across 2 days, 7 days and 28 days.	Thermogravimetric analysis was done at 7 days curing	[36]
–	–	The flow test according to ASTM C-330:2003 and water/cement ratio 0.7. Flowability increased by 19% between 0.4% and 0.7% dosage but beyond 0.8% flowing increased by 70.3%.			
–	–	Bleeding was controlled at 0.8% dosage. But excess dosage caused bleeding			
OPC used with ASTM C 14737 and ACI-211.1	Gum Arabic dosage at 0.0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.7%.	There significant increase in initial setting time from 0.4% to 0.7%. The final setting times increased in the same manner	There is an average increase of compressive strength over age (7 days, 28 days and 90 days) with a maximum value at 0.7% dosing which is attributed to prolonged curing.		[103]
–	–	The slump increased by 205.7% and 500% with a dosage of Gum Arabic.			
A concrete mix ratio of 1:1.7:2.5 and water ratio of 0.5 with characteristic strength of 20 KN/m^3	GA at 0.00%, 0.25%, 0.5%, 0.75% to 1.00% wt% by cement Cured between 3 days to 90 days	The slump ranged between 30 to 180 mm. Under OPC, GA reduced apparent viscosity and shear rate thus high fluidity.	According to ASTM C192/C192M the compressive strength increases with increasing GA% dosage with optimum value at 0.5% wt% dosing.	The density and water absorption according to ASTM C 642-13. Density values are normal at 2537 kg/m^3 to 2842 kg/m^3	[107]
–	–	–	–	Water absorption increases with increased GA% dosage hence increase in porosity with curing age.	
Normal concrete	GA powder and liquid 0.1%, 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, and 1.2% of cement content	In presence of GA powder slump values remain constant across percentage dosage (wt%). Optimum at 0.2% of GA-Powder	Compressive strength decreases with an increase in percentage dosage of GA powder	–	[108]
		In presence of GA liquid slump values increase with the increase in GA liquid.	Compressive strength decreases with an increase in percentage dosage of GA powder	–	
SCC mix design as according	0.2% while varying cement kg/m^3	Reducing cement from 400 kg/GA to 370 kg/Ga and 350 kg	–	–	[109]

Table 8 (cont). Gum Arabic studies on producing bioconcrete

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
to BS EN 480		slump flow increase satisfying BS EN 206-9-201 -Flow rate for SCC increases in presence of 0.2% GA.			
–	–	0.2% GA enhances SCC resist bleeding, segregation and surface settlement	–	–	
–	–	GA in reducing cement weight per meter cubic increases air content	–	–	
Standard mix of 1:2:4 and cured at 7 days, 14 days, 21 days and 28days	GA at 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0% by weight of cement	-Initial setting time increase with the increase in% dosage of GA (from 88 min at 0% to 387 min at 1% GA) -Workability through slump test as per BS 8110: 1970. Slump reduces with increase in% GA. Workability reduces from high to medium thus improving	The compressive strength increases with age at a particular GA content but reduces with increasing dosage.	Shrinkage increase with the increase in dosage of GA. Weight reduces with an increase in GA content.	[110]

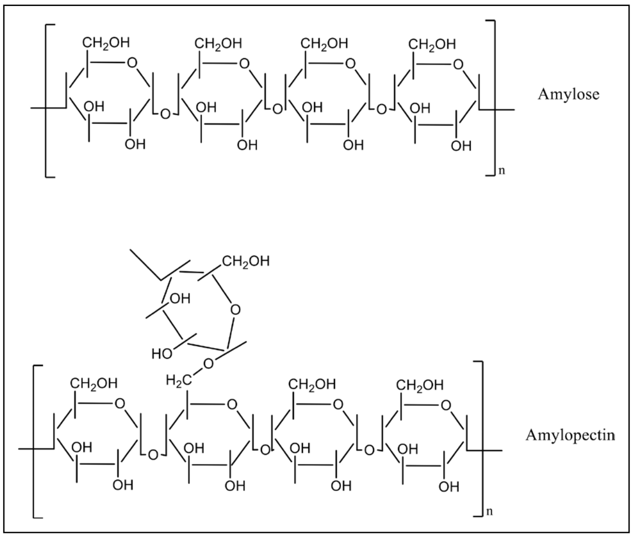

Figure 7. Chemical structure of starch.

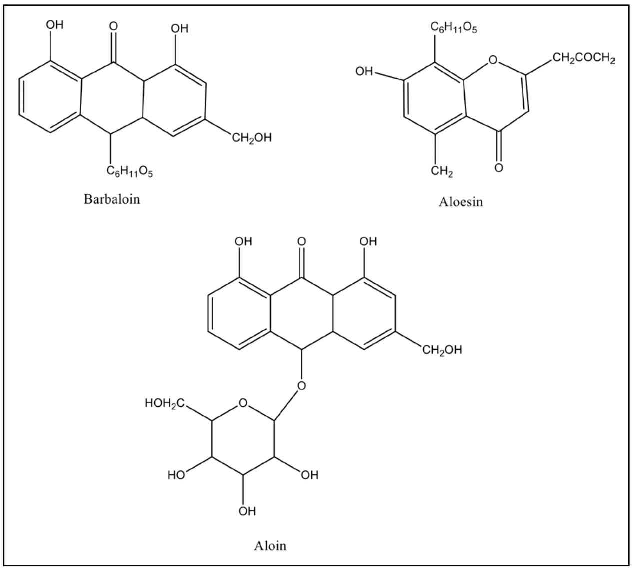

Figure 8. Chemical constituents in aloe vera gel [121].

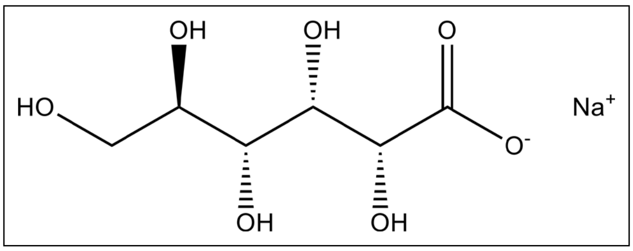

Figure 9. Chemical structure of sodium gluconate.

crobial mineralization has become a promising technology to enhance the durability of concrete structures.

8. OPPORTUNITIES AND CHALLENGES IN USING BIO-BASED ADMIXTURES

8.1. Sustainability Studies

Environmental aspects or potential impacts result from material inputs and environmental releases associated with the manufacturing, transportation, construction and demolition of concrete. Out of the total environmental load of concrete, the contribution of admixtures or superplasticizers is minimal. However, in the production of superplasticizers crude oil and natural gas are used both as raw material and as fuel. Thus, to reduce the environmental impact of superplasticizers in the concrete the raw materials as well as the way of production have to change [6].

Table 9. Starch applications in bioconcrete

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
SCC mix design under OPC	0%, 0.25% and 0.5%	Allows slump retention	–	–	[112]
		Low slump retention with an increase in dosage	–	–	
Normal concrete (BS EN 8500-2)	0.4, 0.8, 1.2, 1.6 and 2.0%	Slump test according to (BS EN 12350-2) and reduced with addition of Cassava starch	–	Water absorption (BS 1881-122), sorptivity, resistance to sulphates, sodium and chloride penetration	[113]
Mortar w/c of 0.5 under OPC	0%, 0.5%, 1.5%, 2.0% and 2.5%	Initial and final setting times as per ASTM C187 and ASTM C191	–	Absorption test as per ASTM C1403	[114]
–	–	Flowing ability as per ASTM C1437	–	–	
–	–	Normal consistency	–	–	
Mix proportion of 1.5:3:4	0%, 0.5%, 1% and 1.5% maize starch and cassava starch	Deteriorate slump with increase starch	Compressive strength	Durability increased	[115–117]
Mix design was at ratio of 1:2:3 at 0.47 w/c	Percent weight of cement at 0%, 1%, 3% and 5%	Corn starch improves workability at optimum 1%	Corn starch improves workability, increase compressive strength and density up to the optimum 1% dosage	–	[118]

Table 10. Aloe vera gel studies on producing bioconcrete

Mix design	Bio-admix/ superplasticizer replacement%	Rheology	Mechanical properties	Micro-structure analysis	References
M30 at 0.45 w/c	1%, 1.5%, 2%, 2.5%	Workability increased with percentage dosage of admixture	Compressive strength reduced with increase dosage	–	[122]
	–	–	Flexural strength as per IS 516-1959 increased by 7.9% and optimum at dosage of 1%	–	
M25	0%, 10%, 20% ad 30%	–	Compressive and flexural strength increased by 30% over conventional concrete	Aloe is a good corrosion inhibitor	[119]
	–	–	Split tensile does not change with pc. dosage		
	0.5%, 0.7% and 1% of cement weight	2% workability of Aloe Juice was comparable to Rheobuild chemical admixture	% Dosage increase, reduced compressive strength. But compressive strength was at par by the 28 days with the normal concrete.		
M25 as per IS 10262-2009	0.5%, 1%, 1.5%, 2% and 2.5%		In presence of jute fiber, both the tensile, compressive and flexural strength increase in all ages (3, 7, 14 and 28 days)		[123]

Regarding raw materials usage bio-admixtures use renewable natural resources which can easily be cultivated and grow. And this makes bio-admixtures environmentally friendly solution. In relation to the production process, plant-based bio-admixtures have almost a net zero environmental impact. These days the question of sustainability is an alarming issue. Thus, uses of bio-admixtures have to go beyond laboratory application or research and should be made widely available for the construction industry.

Table 11. Summary of three microbial based bio-admixtures and their effect on concrete property

Bio-admixture	Bio-admixture dosage	Tested physical/ mechanical properties	Conclusions drawn on the resulting cement paste/ mortar / concrete properties	References
Sodium gluconate (SG)	0.00–0.05% with the increment of 0.01% by weight of cement	Compressive strength, Normal consistency and setting time, Fluidity of cement mortars, Hydration kinetics and hydration products, Microstructural analysis	At 3 and 10 days, 10% and 6% of compressive strength increase observed as compared to the blank cement mortar Initial and final setting time were prolonged and the difference between the two decreased with the increase in SG. For fluidity, the "saturation dosage" of SG was 0.01% SG prolongs the induction period and delays the reaction of C_3S.	[124]
	0.02 wt.%, 0.06 wt.%, 0.10 wt.%, and 0.15 wt.% by cement mass	Setting time at 20 °C and 35 °C curing temperature, Compressive strength, Fluidity, Zeta potential Hydration behavior using isothermal calorimetry measurements, X-ray diffraction (XRD), and thermogravimetric analysis (TGA)	For the dosage of SG in the range of 0.02%–0.15%, setting time has a linear relationship with that of the amount of SG used (at 20 °C). At a higher temperature (>35 °C) is difficult to maintain significant retarding effect using SG SG reduce the cement cumulative heat of hydration and delay the occurrence time of heat evolution peak at some degrees, but with a little impact on reducing the cement evolution rate peak. Mechanical and dispersion properties of cement pastes added with SG are depending on their additions. At the dosage less than 0.15%, SG has positive effects on the compressive strength, and the negative effects occur if the dosages exceed 0.15% Compressive strength is highest when the SG addition dosage is 0.06%	[125]
Welan gum (WG)	0, 0.03, 0.05, 0.075 and 0.10 percent by mass of cement WG and 0.4, 0.8, 1 1.5, 2, and 2.5% of naphthalene-based HRWR	Fluidity, rheological properties, washout mass loss bleeding setting time	Losses in fluidity due to the use of WG can be regained without significant effect on the resistance to washout and forced bleeding, by using adequate dosage of HRWR, increase in WG content and the reduction in the HRWR dosage increase the degree of pseudo-plasticity of cement grout washout resistance is enhanced by the increase in WG dosage and reduction in HRWR content. However, with a proper use of WG-HRWR, highly flowable, yet washout resistant mixtures can be secured Combinations of WG and HRWR can secure high resistance to forced bleeding since The coupled effect of WG-HRWR delays the onset of initial setting of cement grout. Such delay seems to be more affected by the dosage of WG	[127]
	0.00 (blank), 0.025, 0.05, 0.075, 0.10 and 0.25% (the mass ratios to water).	Setting time at normal consistency Compressive strength Hydration characterization Microstructural analysis (XRD, TG-DSC, SEM)	WG slightly increases the water demand for normal consistency With the increase in concentration of WG, time period from initial to final setting also slightly increases 0.05% WG solution promotes the compressive strength development at longer ages and reduces the pore size of the cement paste. The induction period and the second reaction of the aluminate phase have delayed due to the WG, but has very limited influence on the total heat release of cement paste. The hydration of C_3S was also a little retarded at early hydration time; meanwhile, WG affects the formation of $Ca(OH)_2$ but not AFt.	[68]

Table 11 (cont). Summary of three microbial based bio-admixtures and their effect on concrete property

Bio-admixture	Bio-admixture dosage	Tested physical/ mechanical properties	Conclusions drawn on the resulting cement paste/ mortar / concrete properties	References
			From SEM analysis, WG does not affect the morphologies of hydration products, but there are many gel-like particles stick on the surface of the hydration product, which can be a reason for the higher porosity in hardened cement pastes with high dose of WG.	
	0.01, 0.03, 0.05, 0.075, 0.1% by weight of cement	Compressive- flexural strength tests mini-slump, and mini-V funnel tests	WG caused an increase in compressive strength up to 0.05%. Beyond this dosage it caused a decrease on the mechanical strength and negatively affect flexural strength	[128]
Xanthan gum (XG)	Welan gum and superplasticizers β-FDN (naphthalene) or PCE (polycarboxylate) were set to 0.1 wt%, 1 wt% and 0.2 wt%	Bleeding rate Rheological properties of cement slurry, Fluidity Mechanical properties Hydration heat Zeta potential	A good anti- segregation and anti-bleeding properties was obtained because of WG Cement slurries containing WG with superplasticizer show non-Newtonian fluid behavior, For WG combined with β-FDN, no significant differences observed on the workability, mechanical properties, hydration heat and zeta potential of the slurries For WG combined with PCE, the workability, rheological properties and zeta potential are significantly affected by the two mixing methods, implying significant competitive adsorption of WG and PCE.	[129]
	0.0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% of cement	On the fresh concrete, slump flow, V-funnel, U-box, L-box, J-ring tests On the hardened concrete, compressive, tensile and flexure tests	Using XG 1% of cement binder, improved fresh properties like as Slump- flow, V-funnel, L-box, U-box and J-ring compared to conventional SCC. Optimum dosage of XG for M-25 and M-40 grade concrete was1%. With the addition of optimum dosage in SCC maximum values of fresh properties were achieved The compressive strength of SCC M-25 decreases by 17% on addition of 3% of XG. While for M-40 it decreases by 14%. The flexure strength of SCC M-25 and M-40 decreases by 24% on addition of 3% of Xanthan gum. The Tensile strength of SCC M-25 and M-40 decreases by 18% on addition of 3% of Xanthan gum.	[126]
	XG was used in seven different proportions from 0.0–1.2% with 0.2% increment in combination with 0.5% and 1% of Sulphonated Naphthalene superplasticizer	Slump flow, flow time, L-box tests on the fresh Self Compacting concrete Compressive strength, Split tensile strength and, Flexural strength	To increase flowability Super plasticizers are required with XG. Workability results shows that T50 time is increasing with increasing dosage of XG along with superplasticizer. However, slump flow decreases with increasing dosage of XG. At 7- and 28-Days Compressive strength, split tensile strength and flexural strength increased up to 0.6% of XG along with super plasticizer. After adding more than 0.6% of XG along with superplasticizer compressive strength and split tensile strength decreased. At 7 and 28 days (0.6% XG and 0.5% SP) and (0.6% XG and 1.0% SP) gives higher compressive strength, split tensile strength and flexural strength	[130]
	0.01, 0.03, 0.05, 0.075, 0.1% by weight of cement	Compressive and flexural strength mini-slump, and mini-V funnel tests	XG reduced the compressive strength in all ratios Negatively affect flexural strength XG was effective in terms of fresh state behavior activity.	[128]

8.2. Codes and Standards

For the traditional chemical admixtures there exist standard specifications which cover the materials, the test methods and other requirements in relation to the use of chemical admixtures to be added to hydraulic-cement concretes. Some of these standards are ASTM C494/C494M-17, ACI 212.3R-10, IS:9103 and IS:2645. However, to the authors acknowledgement, such kind of specifications are lacking for the case of bio-based admixtures especially for Plant-based bio-admixtures. And this a challenge which hinders a large-scale production and application of bio-admixtures and it has to be addressed. To assure the quality of the product and wide range applicability of bio-based admixtures especially plant-based bio-admixtures, codes and standards need to be developed. In addition, codes and standards help to standardize the production process, handling and storage mechanisms of the bio-admixtures.

9. CONCLUSION

1. Bio-based admixtures are promising alternatives to conventional chemical admixtures for concrete, as they can improve the rheological, mechanical, and durability properties of concrete while reducing the environmental impact of the construction industry. However, there is a lack of comprehensive and systematic studies on the sources, production, performance, and compatibility of bio-based admixtures with different types of cement and concrete. More research is needed to optimize the bio-admixture production processes, standardize the characterization methods, and evaluate the long-term effects of bio-admixtures on concrete structures
2. Bio-based admixtures can be derived from various renewable sources, such as plants, animals, or microorganisms, and can be produced by different biotechnological processes, such as biosynthesis, bio-oxidation, or bio-fermentation. For the manufacture of admixtures, there are, however, only a limited number of bio-based sources that are available and diverse, particularly in some areas where natural resources are in short supply or in danger of becoming endangered. More research is needed to explore new and sustainable bio-based sources, such as agricultural or industrial wastes, that can be used for admixture production.
3. Bio-based admixtures can be characterized by various techniques, such as FTIR, XRD, NMR, GC-MS, and rheology, to determine their chemical composition, functional groups, molecular structure, interaction with cementitious materials. Standardization and harmonization of characterization methods for bio-admixtures across different studies and applications has not been identified. More research is needed to develop and validate reliable and comparable characterization methods for bio-admixtures that can provide consistent and accurate results.
4. Bio-based admixtures have been reported to provide various functions and benefits to concrete, such as water reduction, rheology modification, retardation, acceleration, air entrainment, self-curing, self-healing, corrosion inhibition, and antimicrobial activity. However, there is a need for more research on the mechanisms and effects of bio-based admixtures on the hydration, microstructure, and properties of concrete.
5. Although, the fresh and hardened concrete property that results from the usage of plant-based bio-admixtures is of acceptable quality, there are a number of bottlenecks that hinder industrial application of Pb2A. Some of the reasons are lack of standard manufacturing, handling, and storage mechanisms.

10. AREAS FOR FURTHER RESEARCH

1. Concerning plant-based bio-admixtures (PB2A), the majority of studies identified fail to specify or denote the age of the source plant. However, it is imperative to recognize that the age of the plant constitutes a potential factor influencing the properties and performance of the derived bio-admixture. Thus, dedicated research efforts are warranted to systematically investigate the impact of plant age on the quality and characteristics of bio-admixtures.
2. Furthermore, for PB2A, it is essential to acknowledge that the handling and storage mechanisms are expected to exert a significant influence on their properties. Therefore, comprehensive evaluations of PB2A under diverse environmental exposure conditions are imperative. For instance, inquiries should explore the consequences of storing bio-admixtures in temperate zones, arid regions, or cold environments. Additionally, research should address how direct sunlight exposure affects the properties and performance of these bio-admixtures.
3. A notable observation is that the majority of studies pertaining to PB2A employ the produced bio-admixture for its intended purpose within a relatively short timeframe post-production. To ensure the longevity of bio-admixtures when extended storage is necessary, proactive measures must be considered. Consequently, investigations into the potential use of preservative chemicals to maintain the functionality of the product over an extended period are warranted.
4. It is noteworthy that the studies conducted on bio-admixtures predominantly employ Ordinary Portland Cement (OPC). Consequently, there is a pressing need to examine the compatibility and applicability of bio-admixtures with various types of cement, including blended cements, cement composites, and low-carbon cements.
5. In addition, the applicability of bio-admixtures in various types of concrete has not received adequate attention in current research endeavors. Therefore, it is imperative to conduct comprehensive investigations into the suitability of bio-admixtures for different concrete types, encompassing high-performance concrete, lightweight concrete, air-entrained concrete, prestressed concrete, reinforced concrete, precast concrete, polymer concrete, and digital fabrication techniques employing bio-admixtures.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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