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Research Article

Effects of bamboo leaf ash on alkali-silica reaction in concrete

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ABSTRACT

The construction industry is generally faced with so many challenges of which deterioration in concrete structures caused by Alkali-silica reaction (ASR) is one of the pressing challenges. This reaction induces expansion in concrete, resulting in its eventual cracking and subsequent failure. Research direction is being geared towards obtaining properties of pozzolanic concrete of recently discovered different biogenic pozzolans such as bamboo leaf ash (BLA). BLA has been proven to be acceptable in terms of compressive strength and some other properties but few researches have been performed on the impacts of ASR on BLA concrete structures. This research work focuses on investigating the properties of BLA through X-ray diffraction and fluorescence analyses, and its effectiveness in resisting or eliminating ASR that may be present in concrete. Tests were performed on concrete bars soaked in NaOH at a temperature of 80 °C to determine the possible reactivity of aggregates to ASR. In addition, workability and the compressive strengths of BLA concrete at different percentage levels were determined after curing for 7, 28 and 56 days. The findings of the research show that BLA improves the workability of fresh concrete, however, it causes a decline in the compressive strength of concrete when compared with the strength of conventional concrete. Also, BLA has no detrimental effect on the linear expansion of concrete. This study recommends that a 5% partial replacement of cement with BLA will give effective performance when used in areas where strength is not the major priority.

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1. INTRODUCTION

Durability, high fire resistance, low cost, and low maintenance associated with concrete have contributed immensely to its wide acceptability worldwide [1]. However, concrete deterioration can occur when concrete is exposed to aggressive environmental conditions [2]. Alkali-silica reaction is one of the main causes of concrete deterioration due to its detrimental influence on the durability of concrete structures [3]. For instance, the deleterious features of the ASR in concrete are cracking, expansion and misalignment of structural elements, and spalling of concrete's surface [4].

Also referred to as concrete cancer, ASR occurs in concrete structures as a result of the availability of alkalis in concrete's pore solution, calcium hydroxide in a free state, high PH, reactive silica (amorphous) in aggregates and sufficient moisture to drive the reaction [5]. At high PH, the hydroxyl ions of sodium and potassium alkalis existing in concrete's pore solution react with and cause the reactive amorphous silica in aggregates to dissolve [6]. This dissolved silica reacts with free calcium (Ca^{2+}) ions from calcium hydroxide (obtained from the hydration process between cement and water) to form a gel-like material around the aggregates and within the concrete pores [7, 8]. Figure 1 shows a schematic diagram of the mechanisms involved in the Alkali-silica reaction in concrete.

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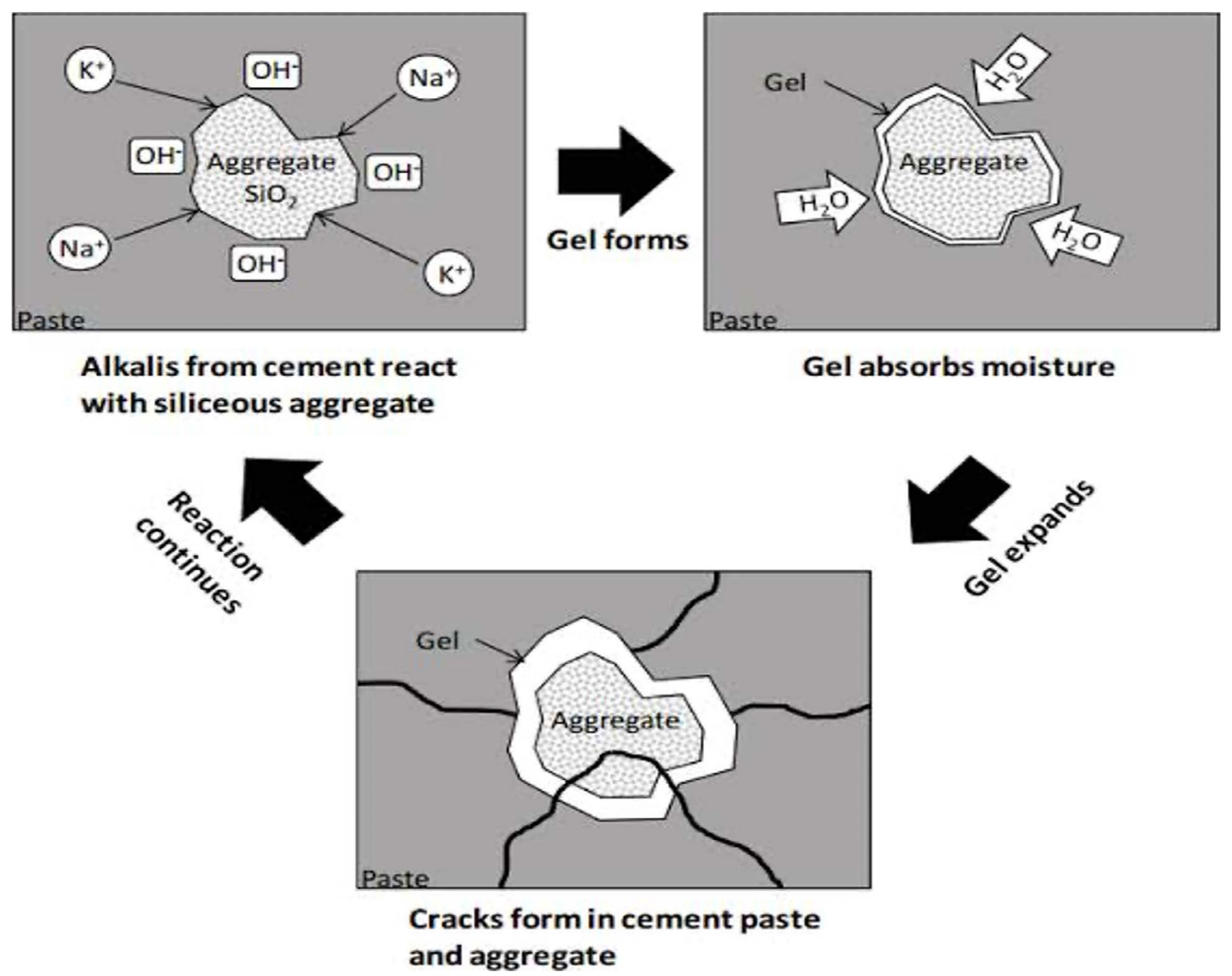

Figure 1. Diagram showing Alkali-silica reaction mechanism in concrete. Source: [10].

This gel, referred to as Alkali-silica gel, is rich in silica, alkalis and other ions. In addition, ASR gel is hygroscopic. Expansion occurs when this gel absorbs water and enlarges in size, then it exerts pressure in the concrete; when this pressure exceeds the tensile capacity of concrete, cracking occurs. The development of cracks in the concrete increases the inflow of moisture, causing an iterative process that exposes the concrete to more expansion. This ultimately causes spalling and strength loss in concrete [6, 9, 8]. If this reaction is not checked, it can further lead to the corrosion of reinforced steel and sulphate attacks [4] thereby reducing the serviceable life of the concrete [7].

ASR occurs in concrete in two major stages:

First stage:

Reactive silica+alkali+moisture→ASR gel

$SiO_2+2KOH+H_2O \rightarrow K_2SiO_3.2H_2O$

(2KOH can be replaced by 2NaOH)

Second stage:

ASR gel+moisture→Expansion

A lot of strategies have been put in place to lessen the development of ASR in concrete. Among such strategies include limiting concrete's alkali content using low alkali cement, applying chemical admixtures such as lithium compounds, using non-reactive aggregates and incorporating pozzolanic materials in concrete [11, 12]. This study, however, focuses on the use of pozzolans in curtailing ASR in concrete. This is because pozzolanic materials improve the concrete's resistance to ASR by reducing calcium hydroxide ($Ca(OH)_2$) and the spreading of ions in concrete [13].

Pozzolanic materials are artificially or naturally-occurring materials that contain reactive amorphous aluminosiliceous and siliceous materials [14]. They have the characteristics of reacting with alkali in the presence of moisture and in a fine form to form cementing compounds [15]. Silica, present in pozzolans reacts with calcium hydroxide, $Ca(OH)_2$ found in concrete's pore solution to form calcium silicate hydrate and other cementing compounds [16–18]. The production of calcium silicate hydrate in concrete is effective in binding alkalies and thus mitigating ASR in concrete.

The chemical representation of the pozzolanic reaction is given below:

$3Ca(OH)_2+2SiO_2=3CaO.2SiO_2.3H_2O$

$3Ca(OH)_2+Al_2O_3+3H_2O=3CaO.Al_2O_3.6H_2O$

Other properties discovered in the use of pozzolans are lower permeability and higher strength [19]; influence on the rate of bleeding and segregation, the heat of hydration and setting time, water demand and workability of concrete [20].

The reactivity of pozzolans, whether naturally obtained or artificially obtained, depends largely on their degree of fineness, the amorphousness of their structures and the content of their aluminum, iron and silicon oxides. While investigating the influence of fly ash on Alkali-silica reaction, [21] clarified that the effectiveness of fly ash in inhibiting ASR majorly depends on the replacement level than the degree of fineness. The study of [22] attributed the high pozzolanic reactivity of artificial pozzolans such as fly ash, metakaolin and silica fume to their high concentrations of soluble reactive SiO_2.

This finding was also similar to that of [23] when they assessed the effect of four kinds of pozzolans – blast-furnace slag, natural pozzolan, silica fume and siliceous coal fly ash – on Alkali-silica reaction elimination in concrete. Based on their findings, the mortars containing cement-pozzolan blends exhibited lower open porosities when compared with the control mortars. However, only coal fly ash and silica fume were more effective in curbing Alkali-silica reaction in concrete while blast-furnace slag and natural pozzolan require higher replacement level of at least 30% to effectively curb Alkali-silica expansion. The study of [24] clarified the higher efficiency of silica fume in mitigating Alkali-silica reaction over fly ash. They attributed silica fume's effectiveness to its porous surface which causes it to absorb more alkalis than fly ash. Concrete is more durable and resistant to Alkali-silica reaction when the replacement level of silica fume is within 7 to 10% [23–25].

The research findings of [26] proved that metakaolin significantly decreased the concentration of calcium hydroxide present in mortars. Due to its low calcium content, it reduces the calcium-to-silicon ratio, thereby increasing concrete's resistance to Alkali-silica reaction [27]. Further studies by [28] opined that the 20% of metakaolin present in concrete can effectively reduce about 89% of the expansion caused by Alkali-silica reaction. Metakaolin also improves the compressive strength of mortar. The findings of the research conducted by [29] revealed that there was an increase in the compressive strength of mortar with an increasing amount of metakaolin. However, the optimal strength was obtained when the replacement level of metakaolin is within the range of 5 and 10%.

Although industrial by-products such as silica fume and fly ash are often used as cementitious materials to replace cement partially in concrete, however, due to the possible decrease in their production in the future and limited availability in developing countries, researchers are now tilting towards investigating the potential of agricultural wastes such as bamboo leaf ash, rice hush ask, palm oil fuel ash, and sugarcane bagasse ash in influencing concrete's durability and mechanical properties [30].

Studied how bamboo leaf ash affects concrete's mechanical properties [31]. They found that the incorporation of bamboo leaf ash makes concrete more impermeable, thus reducing water absorption. However, an increase in the replacement level of bamboo leaf ash in concrete led to a decrease in the compressive and tensile splitting strengths of the concrete. Although the optimum replacement level of bamboo leaf ash in the concrete is 10% when compressive strength is considered while it is 20% for tensile splitting strength. Bamboo leaf ash also influences the setting time and heat development in concrete. The research findings of [32] pointed out that concrete containing cement-bamboo leaf ash blends have setting times higher than that of conventional concrete, thereby lowering heat development in mass concrete.

Likewise, studies have been made to investigate the ability of rice husk ash to act as a supplementary cementitious material. Obtained by burning rice husk at 800 ºC, its high silica content and specific surface area contribute to its high reactivity [30, 33]. Rice husk ash with finer particles have higher pozzolanic reactivity and are much more potent in preventing ASR in concrete than those with coarser particles [34–35]. The partial replacement of cement with fine rice husk ask makes the concrete mix more impermeable, thus reducing the percolation of alkalis in the concrete [36]. [2]'s review of literature on how Alkali-silica reaction can be mitigated in concrete revealed that rice husk ash is more effective when the replacement level is 40%.

To determine the effectiveness of these pozzolans to inhibit Alkali-silica reaction in concrete, it is imperative to determine the alkali silica reaction of these pozzolans as it will be of further help in knowing the expansion ability of each pozzolanic material. This research, therefore, investigated the effect of BLA on ASR.

2. MATERIALS AND METHODS

Materials used in this research are BLA, clean water for mixing and curing, Ordinary Portland Cement (Dangote type), granite and sand as coarse and fine aggregate respectively.

2.1. Raw Materials

Bamboo leaves were collected from the main bamboo trees and dried. BLA was obtained by burning the dried bamboo leaves at a temperature of about 600 °C for 1 h based on the optimum temperature from past researchers [37]. It was then sieved using a 75 μm sieve to increase the surface area needed for the reaction.

2.2. Mixing Ratio and Curing Conditions

A mix ratio of 1:2:4 of cement to sand and coarse aggregates respectively was used. The water-cement ratio used was 0.65. The concrete cubes were cured by immersing them in clean water at a temperature of 27 °C for a period of 7, 28 and 56 days.

2.3. Test Methods

Particle size distribution analysis, moisture content test and specific gravity test were carried out on the sand. The aggregate crushing value (ACV) test and aggregate impact value (AIV) test were carried out on granite. X-ray diffraction analysis and X-ray fluorescence analysis were performed to determine the chemical composition and pozzolanic reactivity of BLA. Compressive strength and accelerated mortar-bar tests were performed on concrete samples to determine the strength of concrete and the potential alkali-silica reactivity of aggregates respectively. Cement was partially replaced by BLA in levels of 0%, 5%, 10%, 15%, 20% and 25% respectively by weight. For each percentage replacement, three concrete cubic specimens were produced.

2.3.1. Test Methods Applied to Aggregates

Particle size distribution analysis: Sieve analysis to assess the distribution of the particle sizes of the soil sample was performed per [38]. A quantity of soil sample was weighed and dried in the oven at a temperature of about 110 °C. The dried sample was poured into a set of sieves. The sieve at the top has the largest mesh size and each lower sieve in the column has a smaller mesh size than the one above it. At the base of the column was a round pan used to collect particles with sizes lesser than 75 μm. This set of sieves was manually shaken for some minutes. The sample retained on each sieve was weighed after the shaking was completed. The percentage passing and the percentage retained on each sieve were calculated. The outcomes were presented as a graph of percentage passing against the sieve size on a semi-logarithmic graph.

Moisture content test: The moisture content test was carried out in accordance with [39] to determine the total amount of water present in the soil sample.

A container and its lid were clean, dried and weighed (M1). A portion of the test portion was placed in the container and then weighed (M2). This was heated at a steady temperature of about 110 °C in the oven for a duration of 16 to 24 h. The container was then taken out of the oven, allowed to cool, and weighed once more (M3). The moisture content of the sample was calculated as:

$$\text{Moisture content} = \frac{M2-M3}{M3-M1}\ x\ 100\%$$

Specific gravity test: Specific gravity gives the ratio of the mass of the soil to the mass of the standard reference, which is water.

Three density bottles with stoppers were cleaned, dried, and weighed. Their masses were recorded as W1. Small amounts of oven-dried soil samples were put into the bottles and their weights were taken and recorded as W2. The bottles were then completely filled with water and left for 24 h. After this, their weights were taken and recorded as W3. The bottles were emptied, thoroughly cleaned and filled with water. The weights were taken and recorded as W4.

The specific gravity of the soil sample was calculated as:

$$\text{The specific gravity of soil} = \frac{W2-W1}{(W4-W1)-(W3-W2)}$$

Aggregate crushing value test: To assess the aggregate's resistance to crushing under a gradually applied compressive load, the aggregate crushing value test was performed in accordance with [40].

12 mm aggregates were dried in an oven for about 4 h at a temperature of 110 °C. Three equal layers of the specimen were placed within the cylinder, and each layer received 25 tamping strokes from the tamping rod. The plunger was inserted so that it rested horizontally on the levelled surface of the aggregate. The apparatus was placed inside the universal testing machine along with the test specimen and plunger. The specimen was loaded at a uniform rate till the aggregates were crushed. The load was removed and the crushed material was poured on a clean tray of known mass. The weight of the tray and the aggregate were measured and recorded as M1. The whole specimen on the tray was sieved on the 2.36 mm test sieve and the weight of the fractions that passed through the sieve was recorded as M2. The aggregate crushing value was calculated as:

$$\text{ACV} = \frac{M2}{M1}\ x\ 100\%$$

Aggregate impact value test: The aggregate impact value test was carried out in accordance with [41] to determine the aggregate's resistance to sudden impact.

Aggregates of size 12 mm sieve were oven-dried at a temperature of about 110 °C for 4 h and cooled before testing. The aggregates were placed inside the steel cup and then compacted by applying twenty-five strokes of the tamping rod to it. The steel cup was fixed to the base of the impact testing machine and the hammer, which is at a position 380 mm above the upper surface of the cup, was made to fall freely on the aggregates 15 times. The crushed aggregate was poured on a clean tray of known mass. The weight of the tray and the aggregate were measured and recorded as M1. The whole specimen on the tray was sieved on the 2.36 mm test sieve and the weight of the fractions that passed through the sieve was recorded as M2.

The aggregate impact value was calculated as:

$$\text{AIV} = \frac{M2}{M1}\ x\ 100\%$$

2.1.2. Test Methods Applied to Bamboo Leaf Ash

X-ray diffraction analysis: The structural characterization of BLA was determined using an X-ray powder diffractometer. In a cathode ray tube, X-rays were produced, collimated, and directed at the sample. Every crystal has atoms that are arranged in a periodic arrangement, which allows them to diffract light. The arrangement of these atoms in the sample is revealed by the diffraction pattern that is created when X-rays are scattered from these atoms. The X-ray detector captured the reflected X-rays' strength. When the geometry of the incident X-rays colliding with the sample fulfils Bragg's equation, constructive interference and peak in intensity occur. This equation indicates the relationship between the diffraction angle, lattice spacing and wavelength of the electromagnetic radiation. The diffraction pattern produced by the diffractometer is compared with standard patterns to identify the crystalline form of BLA.

X-ray fluorescence analysis: The chemical and elemental composition of BLA was examined using an energy dispersive X-ray fluorescence spectrometer. BLA placed in an appropriate sample tray was exposed to high-energy X-rays from a controlled X-ray tube, which resulted in the emission of distinctive secondary X-rays. The detector selected these distinctive X-rays and produced a spectrum, which serves as a visual depiction of the sample's composition. This allowed for the determination of the sample's elemental analysis and oxide composition, which were then printed.

2.1.3. Test Methods Applied to Bamboo Leaf Ash-Based Concrete

Compressive strength test: Compressive strength of concrete is the ability of concrete to support loads on its surface without crack or deflection. It is dependent on the quality of concrete material, strength of Portland cement, water-cement ratio, etc. This test can either be carried out in a cube or a cylinder.

Concrete specimens of 150 mm x 150 mm x 150 mm sizes were produced by replacing cement partially with BLA at 5%, 10%, 15%, 20% and 25% levels. The specimens were cured for 7, 28 and 56 days' duration at a temperature of 27 °C. The compressive strength was carried out in conformity with [42].

It should be noted that three cubic specimens were prepared for the control specimens and specimens containing partial replacement of cement.

Potential alkali reactivity of aggregates: This test method provides a means of detecting the potential of an aggregate to undergo an ASR within 16 days. The test was carried out per [43].

Portland cement, sand and granite were mixed in a ratio of 1:2:4 to form mortar. Two test specimens were made for the control and each cement-BLA combination. Molds made according to [44] specifications were filled with mortar in two equal layers. After this, the molds were placed in a moist cabinet or room for the next 24 h. The specimens were removed from the molds, and the initial comparatory readings were made. The specimens were then immersed in tap water inside a storage container, and placed in an oven at a temperature of about 80 °C for 24 h. After this, the specimens were removed, dried and the zero readings were taken. Later, the specimens were immersed in Sodium Hydroxide inside the storage container. The container was sealed and placed in an oven at a temperature of 80 °C. Subsequent comparator readings of the specimens were taken at 7, 28 and 56 days to check for variations in the lengths of the concrete specimens. The difference between the zero reading of the specimen and the comparator reading at each period was calculated and recorded as the expansion of the specimen for that period.

3. RESULTS AND DISCUSSION

3.1. Properties of Aggregates

The particle size distribution analysis of the soil sample shown in Figure 2 indicates that the soil sample has a coefficient of uniformity of 3.33 and a coefficient of curvature of 0.83. This implies that the soil sample is uniformly graded [45]. Table 1 shows the overall moisture content of the soil sample to be 8.4%. Since the moisture content is less than 15%, the soil sample is dry soil. The specific gravity of the soil sample is 2.70 (Table 2) and this indicates that the soil sample is silt [46].

The aggregate crushing value of granite used as the coarse aggregate in concrete is 28.6% as shown in Table 3. Since this value is less than the maximum attainable value of 30%, it shows that coarse aggregate is a good material in the production of concrete [40]. Also, the aggregate impact value of granite shown in Table 4 is 19.4%, showing that the granite is strong and capable of resisting suddenly applied loads [41, 47].

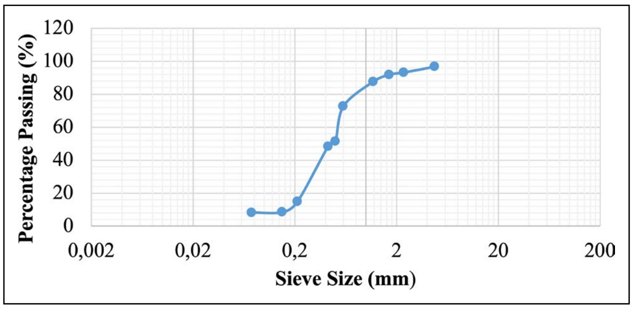

Figure 2. Particle size distribution curve for soil sample.

Table 1. Moisture content of soil sample

	Sample 1	Sample 2	Sample 3
Weight of container, M1 (g)	24.8	24.5	25.6
Weight of container+wet soil, M2 (g)	116.0	99.2	110.0
Weight of container+dry soil, M3 (g)	109.2	93.1	103.6
Moisture content (%)	8.1	8.9	8.2
Average moisture content (%)		8.4	

Table 2. Specific gravity of soil sample

	Sample 1	Sample 2	Sample 3
Weight of empty bottle, W1 (g)	284.3	292.4	322.3
Weight of bottle+dry soil, W2 (g)	299.2	307.1	337.8
Weight of bottle+soil+water, W3 (g)	576.8	571.6	586.7
Weight of bottle+water, W4 (g)	566.4	562.7	578.1
Specific gravity	3.31	2.53	2.25
Average specific gravity		2.70	

Table 3. Aggregate crushing value of granite

Aggregate	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average (%)
Granite	30.8	28.6	26.5	28.6

Table 4. Aggregate impact value of granite

Aggregate	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average
Granite	17.9	19.2	21.1	19.4

3.2. Properties of Bamboo Leaf Ash

The X-ray diffraction analysis of BLA shown in Figure 3 shows that the minerals in BLA are tridymite (a stable form of SiO_2), graphite, garnet (a silicate mineral), illite, lime (calcium oxide), periclase (magnesium mineral) and hanksite.

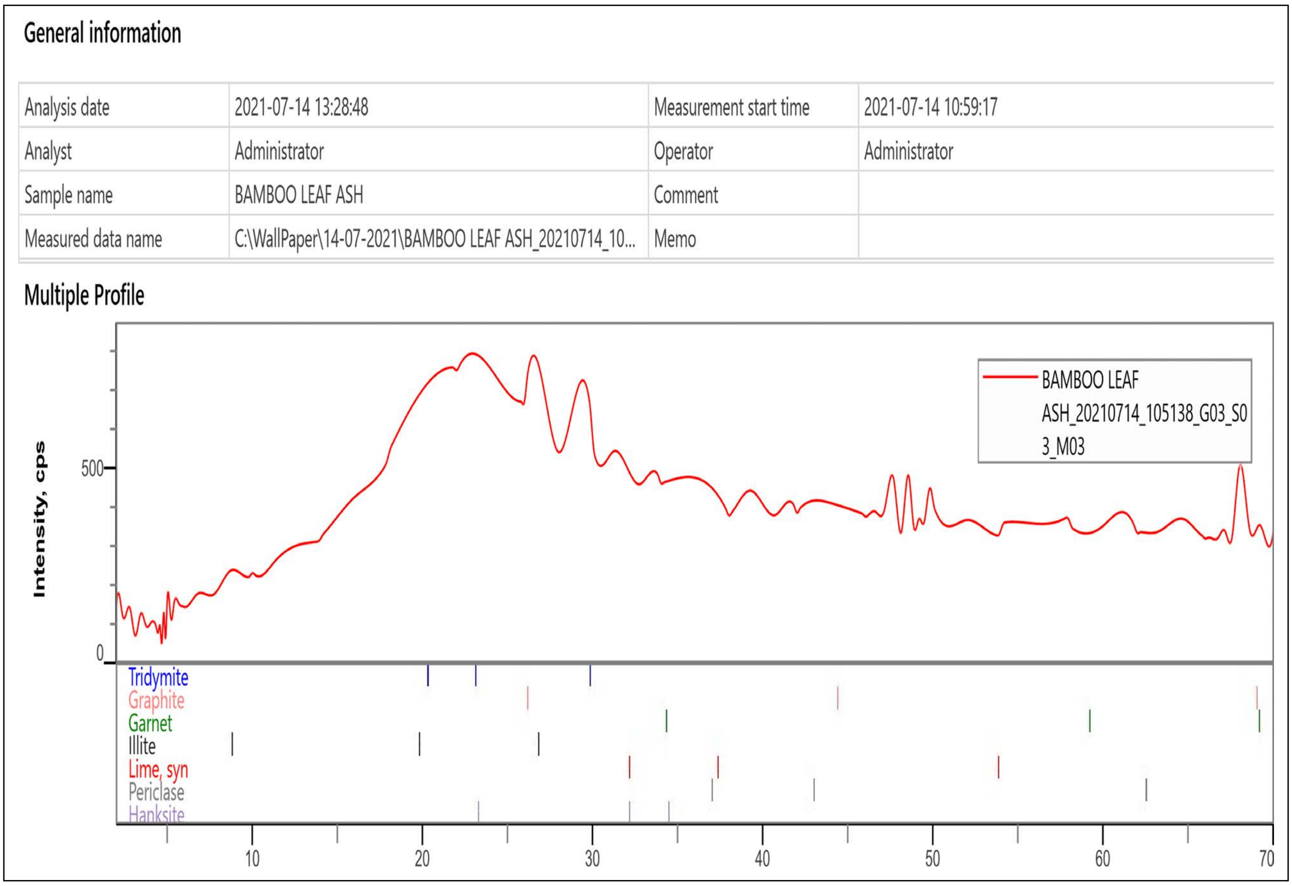

Figure 3. A pattern showing the compounds present in BLA and their intensities.

Table 5. Major required oxides of bamboo leaf ash

Constituent	Composition (%)
Aluminum oxide (Al_2O_3)	2.96
Calcium oxide (CaO)	16.26
Ferrous oxide (Fe_2O_3)	3.98
Magnesium oxide (MgO)	0.00
Potassium oxide (K_2O)	6.37
Silica (SiO_2)	64.81

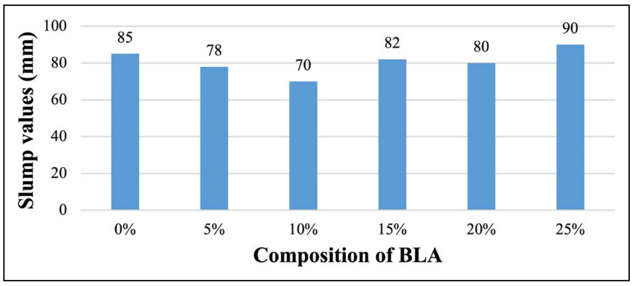

Figure 4. Effect of bamboo leaf ash (BLA) on the workability of fresh concrete.

The result of the X-ray fluorescence analysis of BLA shown in Table 5 reveals that the combination of Silica (SiO_2), Aluminum Oxide (Al_2O_3) and Iron Oxide (Fe_2O_3) present in the BLA is 71.75%. This is greater than 70%, the minimum required before a material can be considered a pozzolan. Therefore, BLA is a pozzolan of Class N [48].

3.3. Effects of Bamboo Leaf Ash on the Properties of Concrete

This section discusses the effect of BLA on the workability, compressive strength and linear expansion of concrete.

3.3.1 Workability of Fresh Concrete

The slump values of the concrete presented in Figure 4 show that the fresh concrete has medium workability which is typically used for normal reinforced concrete placed with vibration.

3.3.2. Compressive Strength of Concrete

The result in Figure 5 shows the variations in the compressive strengths of the control concrete and each bamboo leaf ash-based concrete. The strength of the control specimen has attained 59.5% of the 28-day expected concrete strength after 7 days of curing while that of 5% BLA-based concrete has attained 46.5% of the 28-day expected concrete strength. Reduction in strength was recorded as the percentage replacement of BLA increases. This is an indication of a lower hydration rate of BLA concrete samples. The same trend was recorded for 28-day and 56-day compressive strengths of the concrete.

In conclusion, the incorporation of BLA has a negative impact on the compressive strength of the concrete. The general overview shown in Figure 5, indicates that

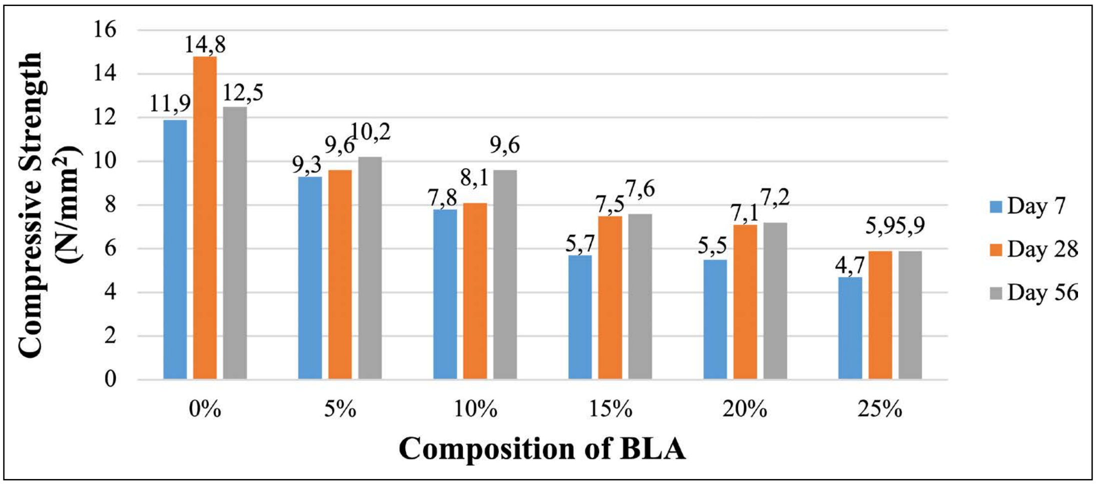

Figure 5. A graph showing the comparison of the average compressive strengths of concrete at 7, 28 and 56 days against the composition of BLA in cement.

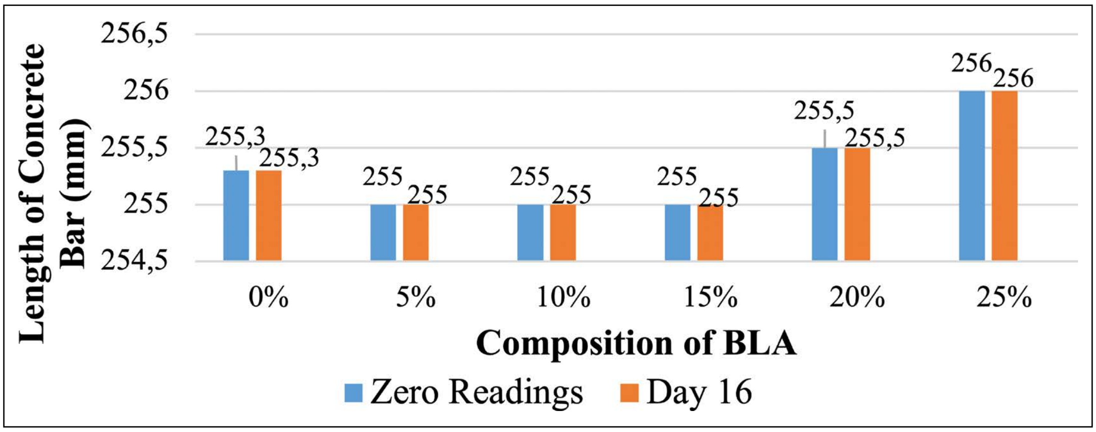

Figure 6. A graph showing the comparison of the zero readings and Length of concrete bars on day 16.

concrete specimens with cement-BLA combinations have lesser strengths when compared to the control specimens i.e. the conventional concrete. This corroborated the study of [49] which establishes that concretes containing natural pozzolans have lower strengths when compared with conventional concretes.

3.3.3. Linear Expansion of the Concrete Bar

The initial reading of each concrete bar is approximately 255 mm and Figure 6 shows a comparison between the zero readings and the length of concrete bars after being placed in Sodium Hydroxide solution at a temperature of 80 °C. There was no difference in the length of the bars after the zero readings were taken and after 16 days of being immersed in sodium hydroxide solution. From this, it can be deduced that the incorporation of BLA in concrete causes the concrete to be at low risk of deleterious expansion when used under field conditions [43].

3.4. Comparison of the Study with Previous Studies

The findings of this study, regarding the silica content, workability, and compressive strength of the concrete, including the optimal content value of bamboo leaf ash are compared with those obtained in previous studies shown in Table 6.

The silica content of the bamboo leaf ash used in this study was 64.8% and this value is less than the ones obtained in five studies. This difference can be attributed to possible inconsistencies in the temperature at which bamboo leaves were calcined. The study of [50] established a correlation between the suitability of calcining temperature of BLA and the silicon oxide content.

Based on past literatures, bamboo leaf ash causes a decrease in the workability of concrete. The increase in workability of BLA-cement blend concrete against the control concrete can be attributed to the high water-cement ratio used in the study. This is consistent with the research findings of [51] that proved that concrete's workability increases with increasing water-cement ratio.

In conclusion, based on the correlation between this research and previous research works, it can be deduced that the incorporation of bamboo leaf ash in concrete reduces the compressive strength of concrete. However, in construction works where durability and sustainability are the main focus, and not compressive strength, 5 to 10% of cement can be replaced with bamboo leaf ash.

Table 6. Effects of bamboo leaf ash on concrete in past literatures

Authors	Silica content (%)	Compressive strength (N/mm²)	Slump value (mm)	Optimal value (%)
[37]	53.00	Concrete with BLA-cement blend has higher strength than that of control.	–	8
[50]	72.81	There was a decrease in the strength of BLA-cement concrete as the proportion of BLA increases. However, the strength of BLA-cement concrete at optimum value for BLA was higher than that of the control concrete after 56 days of curing.	–	5
[52]	75.69	Reduction in compressive strength of BLA-cement blend concrete with increasing concentration of BLA.	Reduction of workability by 5.5%.	5
[53]	75.90	Reduction in compressive strength of BLA-cement blend concrete with increasing concentration of BLA.	Increase in the BLA content in concrete leads to decrease in workability.	10
[54]	65.66	An increase in the content of BLA led to a decrease of the compressive strength of BLA-cement blend concrete.	There was a decrease in concrete's workability as the proportion of BLA increased.	5–10
[55]	72.78	There was a decrease in the compressive strength of BLA-cement blend concrete with an increase in the concentration of BLA.	The higher the proportion of BLA in concrete, the lower the workability.	5
[56]	75.10	Reduction in compressive strength of BLA-cement blend concrete with increasing concentration of BLA, especially at early ages.	Increase in the concentration of BLA causes increase in workability.	10

4. CONCLUSION AND RECOMMENDATIONS

Based on the findings of this research, the following conclusions can be derived;

a. Bamboo leaf ash can be used in construction (especially weak concrete zones like German floors or blinding) where high concrete strength is not a priority.
b. The use of bamboo leaves in the production of bamboo leaf ash is a means to reduce waste in the environment.
c. Bamboo leaf ash has no detrimental effect on the linear expansion of concrete. Concretes containing BLA are at low risk of expansion caused by ASR if they are to be used in real construction.

This research recommends that to achieve optimum strength in concrete, a five per cent partial replacement of cement with BLA should be used. Also, the use of locally-available materials should be encouraged in the Nigerian construction industry to promote environmental sustainability.

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 author 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

Acoustic property of interlocking compressed stabilized earth blocks: A sustainable alternative for building materials

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ABSTRACT

This study uses a tested laterite soil composition to investigate the acoustic properties of interlocking compressive stabilized earth blocks (ICSEBs) produced by the Nigerian Building and Road Research Institute (NBRRI). The laterite samples comprised 40.75% fines (silt-clay), 48.65% fine/medium/coarse, and 10.6% fine gravel. The ICSEBs produced from this composition were evaluated for their sound absorption coefficient values at octave bands of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. The results demonstrate that the ICSEBs exhibit favorable acoustic insulation properties, with sound absorption coefficients ranging from 0.71 to 0.99 at the tested frequencies. Comparative analysis with commonly used materials, such as fiberglass insulation batts and acoustic plasterboard, highlights the competitive performance of the ICSEBs. This study emphasizes the need for further research to explore the influence of composition, thickness, and installation methods on the acoustic performance of ICSEBs, ensuring their suitability for specific applications. Meanwhile, the findings indicate that ICSEBs made from the laterite soil composition can be a cost-effective and durable solution for acoustic insulation in building construction. Therefore, this study provides valuable insight into the acoustic properties of ICSEB, which could be helpful for architects, engineers, and builders who seek to incorporate sustainable and cost-effective building materials in their projects.

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1. INTRODUCTION

The use of the earth as a building material dates back to the earliest times of human civilization, as evidenced by the histories of ancient Egypt and Mesopotamia [1]. Recent studies by Riza [2] suggest that this traditional building material has regained attention, particularly in developing countries struggling to provide adequate housing for their rapidly expanding populations. As a result, stabilized earth has become a topic of ongoing research and development, emphasizing its structural suitability, socio-economic considerations, and environmental sustainability as a modern construction material.

The 2006 National Building Code [3] stipulates that earth blocks should consist of appropriate soils stabilized by ordinary Portland cement, with a minimum of 5% by weight, and be compressed with a minimal pressure of 3N/mm^2. In line with this building code, the Nigerian Building and Road Research Institute (NBRRI) researchers have been working on developing an ICSEB that does not require mortar for bonding. Instead, lateral, and horizontal interlocking of alternate grooves and tongues joints form a wall. This development was reported by Didel et al. [4].

Interlocking compressed stabilized earth blocks (ICSEBs) have gained popularity in recent years as sustainable and affordable building materials. They are made from

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locally available materials, such as soil, sand, and stabilizers, and can be produced on-site using manual or mechanized methods [5]. The Nigerian Building and Road Research Institute (NBRRI) has developed a range of ICSEBs that have been tested for their structural properties, such as compressive strength and durability, and be comparable to or even better than conventional building material [6].

Using sustainable building materials is increasingly becoming a priority in the construction industry as the negative environmental impact of conventional building materials, such as cement and steel, is becoming more apparent [7]. ICSEBs have the potential to be a more sustainable and eco-friendly alternative to these materials, as they use locally available materials, require less energy for production, and have a lower carbon footprint [8]. Investigating the acoustic properties of ICSEBs can provide valuable insights into their potential for use in building applications. It can contribute to the development of more sustainable and cost-effective building materials. Sound insulation and noise reduction are important considerations in building design, particularly in urban areas where noise pollution can be a significant problem. While various building materials, such as concrete, wood, and gypsum board, are commonly used for sound insulation [9], the acoustic properties of ICSEBs are not investigated.

There are quite a few studies on the acoustic properties of ICSEBs. This particular research is believed to contribute to the existing body of literature on this subject matter. Among the literature consulted, Eires et al. [10] examined a new type of interlocking stabilized compressed earth blocks in Mawali. Using a manually operated compaction machine, they conducted acoustic insulation tests on stabilized and un-stabilized compressed blocks. They found that the sound absorption coefficient of their specimens was poor, measuring 0.5 at 3000 Hz. They concluded that this behavior may be attributed to the lower compaction pressure of the blocks. In another study, Leitao et al. [11] researched the thermal and acoustic performance of ICSEBs cured for 28 days, with an average density of 1800 kg/m^3. They used alkali-activated Class F fly ash, which had no commercial value, in the mixture to produce the ICSEBs. Class F fly ash is classified as such due to its low calcium content, generally less than 10%. The results showed that the acoustic performance of the blocks was good, with the highest sound absorption coefficient of 0.82 at 3600 Hz.

Furthermore, Mansour et al. [12] studied the influence of compaction pressure on the mechanical and acoustic properties of compacted earth blocks: an inverse multi-parameter acoustic problem. Their specimens were created by varying the applied compaction pressure, resulting in different bulk densities. Low bulk density CEBs were stabilized by adding 15% cement. The acoustic absorption coefficients of the various specimens were determined experimentally using data obtained from the Kundt tube. Although the focus was on the acoustic and mechanical behavior of compressed earth blocks (CEBs) rather than ICSEBs, the results demonstrated that the applied compaction pressure, including factors such as specimen bulk density and the use of cement as a stabilizer, strongly influenced the acoustic and mechanical behavior of the CEBs. Both studies suggest that ICSEBs can possess favorable acoustic properties and contribute to thermal and acoustic comfort. The acoustic and mechanical behavior of the blocks can be influenced by factors such as compaction pressure, the type of stabilizer used, and the interlocking properties.

This research is centered on investigating the acoustic properties of NBRRI interlocking compressed stabilized earth blocks, focusing on their potential for sound insulation and noise reduction. The results will be compared with other building materials commonly used for sound insulation, and the factors that affect the acoustic properties of ICSEBs will be identified and analyzed. In addition, the research can contribute to developing building codes and standards for ICSEBs, which can help promote their broader use in the construction industry. The findings can also be helpful for architects and builders in selecting the appropriate building materials for sound insulation and noise reduction and for researchers in developing new and innovative building materials that can provide both structural and acoustic benefits. Overall, this research topic is essential for understanding the potential of NBRRI interlocking compressed stabilized earth blocks as a sustainable and eco-friendly building material that can provide acoustic benefits and advantages and contribute to developing more sustainable and resilient buildings.

2. MATERIALS AND METHOD

2.1. Materials and Equipment

The materials used for this research include Soil (Laterite) which was sourced locally from the Du community of Jos-Nigeria (9°50'16.2"N and 8°54'53.6" E as shown in Figure 1, ordinary Portland cement, and water. The equipment used consists of the NBRRI interlocking compressed stabilized earth block molding machine, file cutting machine, BO SOUND amplifier, Bicourbe oscilloscope (GW-INSTEK GDS-2104), and low-frequency generator (LODESTAR FG-20208).

2.2. Method

2.2.1. Laterite Classification

By the Unified Soil Classification System (USCS) specifications [13], the Atterberg limits and grain size distributions of the soil used were established. The results were analyzed on the standard charts that indicated the fines constituent of the soil was predominantly silty than the clayey constituent. Therefore, the soil was classified to be predominantly silty sand.

2.2.2. Production of the Interlocking Compressed Stabilized Earth Blocks

The NBRRI molding machine is used to produce NBRRI ICSEBs, as shown in Figure 2. Laterite is used to make these blocks with a 5% stabilization rate, consistent with NBRRI's recommendations, and they are compressed to 20Mpa. After the blocks are molded and shaped, as

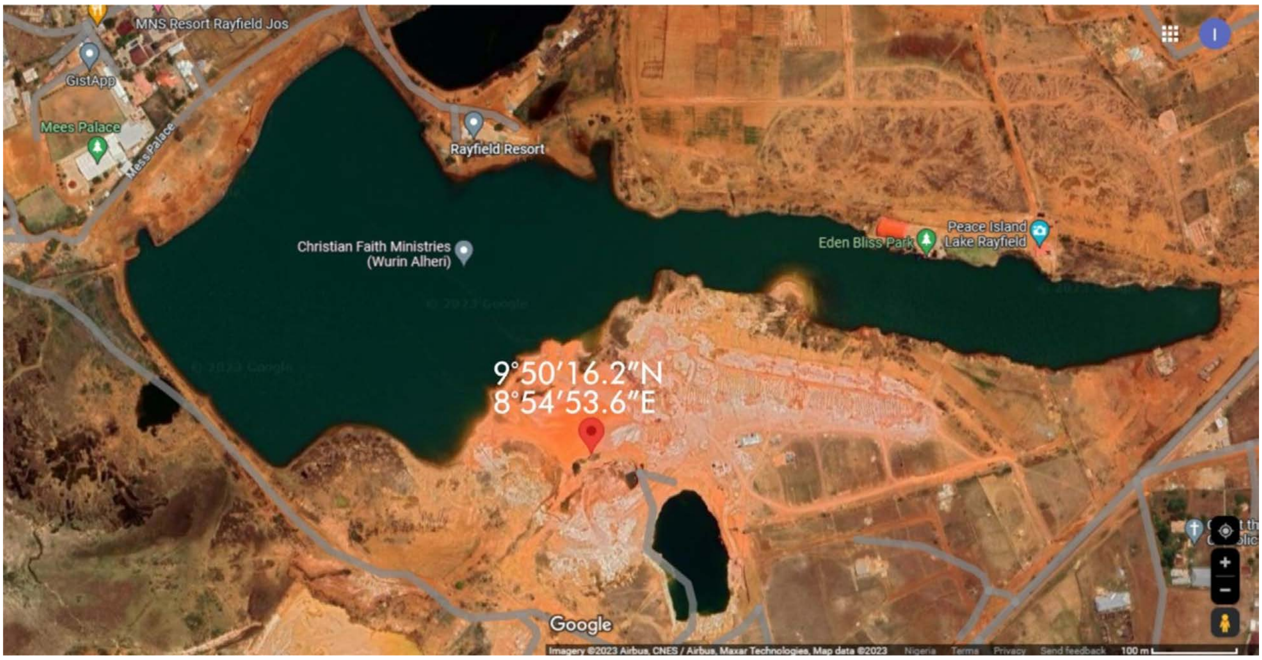

Figure 1. Google Satellite Map of where the Laterite was received.

Figure 2. ICSEB samples produced by NBRRI.

Figure 3. The ongoing building construction using ICSEB.

shown in Figure 2, they are left to cure for 21 days after being covered with polyethylene [6, 14] before putting into use, as depicted in Figure 3.

2.2.3. Measurement of Acoustic Property

Impedance measurement can be performed using any transducers that can measure physical quantities linearly related to pressure or volume. Thus, many systems can be built to measure acoustic impedance. In this study, the setup of the acoustic impedance tube, as shown in Figure 4, is made up of a tube, microphone, sample holder, amplifier unit, functional generator, an oscilloscope was used by ASTM Standard E1050-98 (1998) [15] and ISO 10534 Part 1 and 2 [16]. The determined sound absorption coefficient of the sample was an index of the amount of sound energy of ICSEB that can absorb noise when used as an infill wall material in construction.

3. RESULTS AND DISCUSSION

3.1. Laterite Property

The composition of a particular laterite and its plasticity index affect its suitability for block production. Onaolapo [17] reported that a suitable laterite soil for block production would comprise 15–20% clay, containing silt of roughly 25–40% by volume and approximately 40–70% by coarse sand. The soil plasticity is said to depend primarily on the function of the clay content. Thus, soil with a plasticity index up to 20–30 is suitable for use in the production of building blocks [18].

Based on the previous study on the thermal conductivity and fire resistance of the same block [19], the laterite used in this investigation showed a high liquid limit (35< LL<75) of 59, a plasticity index of 25.95 and from the grading curve, the laterite consisted of 40.75%

Figure 4. Acoustic apparatus.

Table 1. Acoustic coefficient (α) of 20 mm thick ICSEB

Octave band (Hz)	500	1000	2000	4000
V_1	1.10	0.45	0.6	0.62
V_2	0.19	0.15	0.15	0.15
β	5.79	3.00	4.00	4.13
α	0.50	0.75	0.64	0.63

Table 2. Acoustic coefficient (α) of 20 mm thick ICSEB

Octave band (Hz)	500	1000	2000	4000
V_1	1.10	0.40	0.42	0.60
V_2	0.20	0.20	0.20	0.18
β	5.50	2.00	2.10	3.33
α	0.52	0.89	0.87	0.71

fines (silt-clay), 48.65% fine/medium/coarse sand and 10.6% fine gravel. Therefore, the laterite used is said to be predominantly sand with silt, hence classified as silty sand and considered suitable for producing ICSEB. This can likely be due to the silty sand's fine particle size, good compaction properties, and high plasticity. When stabilized with suitable additives, such as cement, lime, or pozzolanic materials, silty sand can produce durable, strong blocks with good thermal and acoustic properties [14].

3.2. Acoustic Property

Having that frequency is a significant determinant in sound transmission, the acoustic coefficients (α) for the respective octave bands that fall within the critical frequencies for noise control were considered for two sample thicknesses of 15 mm and 20 mm, as shown in Tables 1 and 2, respectively.

$$\beta = \frac{V_1}{V_2} \quad (1)$$

$$\alpha = \frac{4\beta}{(\beta+1)^2} \quad (2)$$

Where:
α = Coefficient of acoustic absorption
V_1 = Maximum wavelength recorded on a particular octave band
V_2 = Minimum wavelength recorded on a particular octave band
β = Amplitude ratio

According to [20, 21], the relationship between the coefficient of acoustic absorption and the thickness of the material is a power function of the form:

$$\alpha = aL^b \quad (3)$$

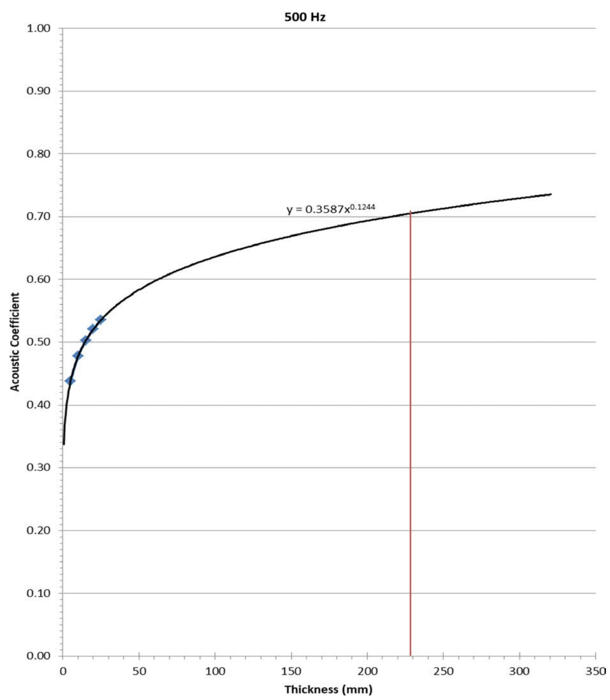

Figure 5. An experimental relationship for acoustic coefficient of ICSEB at 500 Hz.

Where:
α = Coefficient of acoustic absorption
L = Thickness of the material (mm)
a, b = Constants that depend on the material properties and frequency

This means that the coefficient of acoustic absorption (α) increases as the thickness of the material increases but at a decreasing rate. Therefore, the models shown in Figures 1 to 4 were used to determine α for the 230 mm thick ICSEB.

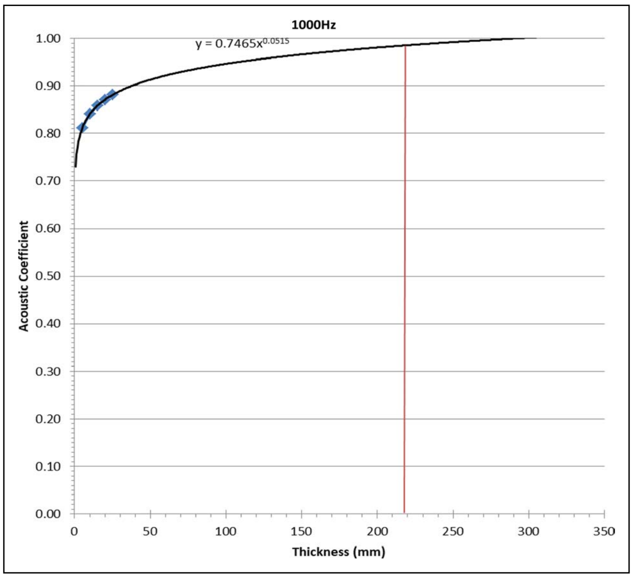

Figure 6. An experimental relationship for acoustic coefficient of ICSEB at 1000 Hz.

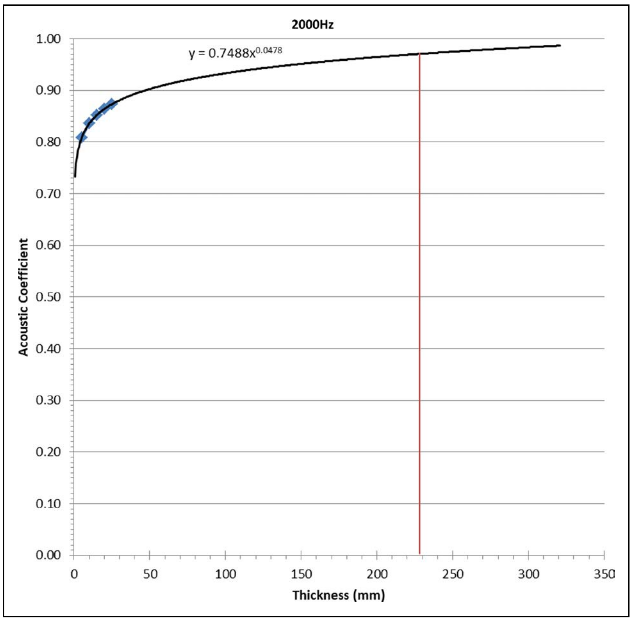

Figure 7. An experimental relationship for acoustic coefficient of ICSEB at 2000 Hz.

Table 3 below shows the R-squared value for the different frequencies of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, and the respective thicknesses of 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm of the ICSEB samples used in this study.

From the results in Figures 5–8, it showed that produced ICSEB with a thickness of 230 mm x 100 mm and cured for 21 days has the acoustic coefficient of 0.71, 0.99, 0.97, and 0.94 at the octave bands of 500 Hz, 1000 Hz, 2000 Hz, and 400 Hz respectively indicates that the material has good acoustic insulation properties. The acoustic coefficient measures the sound absorption of a material, with a higher coefficient indicating a more remarkable ability to absorb sound [22]. The values obtained for the ICSEB suggest that it could effectively reduce sound transmission in buildings,

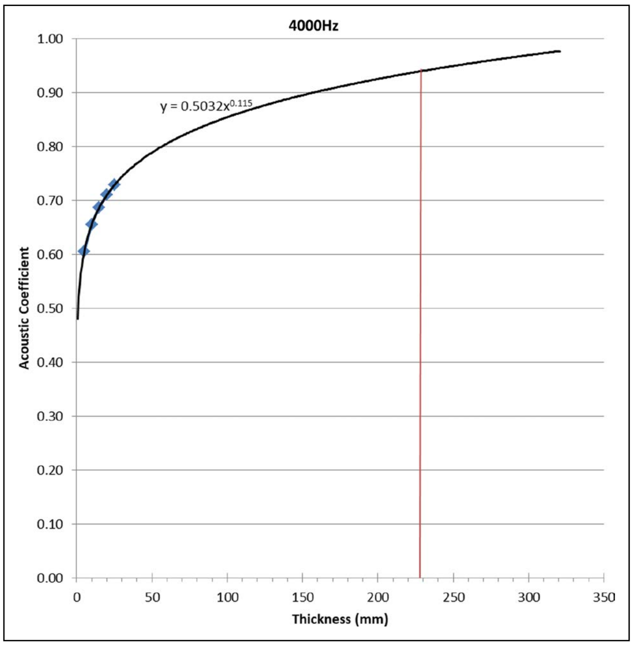

Figure 8. An experimental relationship for acoustic coefficient of ICSEB at 4000 Hz.

Table 3. R-squared value for the different frequencies used

Thickness (mm)	500 Hz	1000 Hz	2000 Hz	4000 Hz
5	0.44	0.81	0.81	0.61
10	0.48	0.84	0.84	0.66
15	0.50	0.86	0.85	0.69
20	0.52	0.87	0.86	0.71
25	0.54	0.88	0.87	0.73
R^2 value	1	0.95	1	1

particularly at higher frequencies where its performance is most notable [23].

A careful look at the results shows that the acoustic coefficient is high at the octave band of 1000 Hz with 0.99, followed by 0.97 at 2000 Hz, 0.94 at 4000 Hz, and 0.71 at 500 Hz. The high coefficient of 0.99 at the octave band 1000 Hz signifies more effective absorption of sound energy at this frequency by the sample. This is because the model absorbs sound energy at higher frequencies less effectively. According to Bhatia's lecture note on M06–026: HVAC systems noise control [24], the decrease in the acoustic coefficient with increasing octave bands beyond 1000 Hz can result from the wavelength of sound, which decreases with increasing frequency. This makes it more difficult for the sample to absorb the sound energy, or the sample thickness becomes less effective at absorbing useful energy at higher frequencies. However, such behavior will be a better subject for further research.

Meanwhile, it is worth noting that the absorption coefficient ranges between 0.00–1.00, one (1.00) meaning no sound energy is reflected and the sound is either absorbed or transmitted. For example, an opened exterior window has an absorption coefficient of one (1.00) because no

Table 4. Coefficient of absorption of different materials

Material	Frequency (Hz)	Coefficient of absorption, α
ICSEB	4000	0.94
Fiberglass	4000	0.90
Plasterboard	4000	0.50–0.70

Source: [29, 30] and Lab work.

sound returns to the room. An effective absorber will have a sound absorption coefficient greater than 0.75 [25].

The thickness of the ICSEB also plays a vital role in its acoustic performance. A thicker block will generally have better sound insulation properties than a thinner block, as it offers more mass and greater impedance to the transmission of sound waves [22]. According to Rivera-Gómez et al. [26] and Silva et al. [27], ICSEBs are influenced by several factors. One of these factors is the applied compaction pressure, which affects the bulk density of the specimen and the added cement used as a stabilizer. Another factor is the type of binder used to stabilize the block. Ouma et al. [28] assessed the potential use of lime and water hyacinth ash (WHA) as binders in producing ICSEBs with good acoustic absorption properties. They found that the transmission coefficient decreased with the compaction pressure and lime addition, while WHA increased the transmission coefficient. Though WHA is not the binder used in producing the ICSEBs in this research, it signified that stabilizers could influence an acoustic property.

Compared to other building materials commonly used for acoustic insulation, the acoustic coefficient values of the ICSEB are competitive and suggest that it could be a viable alternative in certain situations. For example, fiberglass insulation batts, commonly used in walls and ceilings to reduce sound transmission, typically have an acoustic coefficient of around 0.9 at 4000 Hz, as displayed in Table 4, one of the most common frequencies for human speech [29]. This is almost the same as the ICSEB's coefficient of 0.94 at 4000 Hz, as determined in this study. However, it should be noted that the ICSEB's coefficient is still relatively high and competitive, particularly considering its thickness and the fact that it is a solid material rather than a porous one. According to Stani et al. [30], as shown in Table 4, another commonly used material for acoustic insulation is acoustic plasterboard, which typically has a coefficient of around 0.5 to 0.7 at 4000 Hz, depending on its thickness and composition. Again, this is lower than the ICSEB's coefficient, and it should be noted that acoustic plasterboard is typically more expensive and may not be suitable for all applications. This indicates that ICSEB has more capacity to absorb sound energy than commonly used materials such as fiberglass and plasterboard.

4. CONCLUSION

In conclusion, the results of the study indicate that interlocking compressive stabilized earth blocks (ICSEBs) made from the tested laterite soil composition, consisting of 40.75% fines (silt-clay), 48.65% fine/medium/coarse sand, and 10.6% fine gravel, exhibit favorable acoustic insulation properties.

The ICSEBs demonstrated high sound absorption coefficients, with values of 0.71–0.99 at 500 Hz–4000 Hz. These coefficients suggest that the ICSEBs effectively absorb sound energy, and when comparing the acoustic coefficient values to commonly used acoustic insulation materials such as fiberglass insulation batts and acoustic plasterboard.

The ICSEBs are competitive, highlighting their potential as a cost-effective and durable alternative.

However, further research is needed to explore the impact of factors such as composition, thickness, and installation method on the acoustic performance of ICSEBs, ensuring their suitability for specific applications.

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 author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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Research Article

Triggering corporate sustainable performance in construction sector through green training: Moderating effect of barrier in construction management

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ABSTRACT

Construction barrier plays a significant but negative role-play between green training and corporate sustainability performance due to limited resources. The research question in this study is to explore the relationship between green training and sustainable performance in the construction industry, while also considering the moderating role of construction barriers. This study gives extensive knowledge of green training and corporate sustainability performance. Data is obtained from 225 employees using a convenience sampling technique from the construction sector. The research employed SPSS/PROCESS and follows a cross-sectional research design. Study findings show green training is an antecedent of the sustainable performance of the construction sector. The result shows that Green training significantly and positive role-play in sustainable performance. Person-organization fit theory covers the whole phenomenon. That focuses on productivity, performance, and personal well-being. Under P-O fit theory results are showing the compatibility between a person and an organization where they are doing work. This study's results highlight the green training that transforms the employee's mindset towards corporate sustainable performance. In the future, need longitudinal studies that will be more acceptable. This study provides insights to the managers, policymakers, and practitioners of sustainable environment and performance. The current study will help economies in the developing world, such as Pakistan.

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1. INTRODUCTION

This study's objective is to examine the key elements of green training that support corporate sustainability and are restrained by the construction management barrier. The construction industry significantly contributes to raising people's quality of life. However, the expansion of the building industry and its goods has led to global environmental problems [1]. According to estimates, the building industry is responsible for over 40% of global energy consumption, 30% of CO_2 emissions, and 40% of all solid output waste [2]. Therefore, substantial changes are necessary to support the global population while doing more with less. Building modifications are necessary since the built environment is such an integral aspect of society. Utilizing highly renewable materials is the first step. The design and construction of buildings and other facilities is a major area for adopting sustainable changes since the construction industry frequently uses a wide variety of materials in big numbers. According to [2] advancements in building practices and material design are crucial success factors for construction projects.

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Since the construction industry regularly employs a broad variety of materials in large numbers, the architecture of newly constructed buildings is a significant area for adopting sustainable modifications. Advancements in material design and building methods, according to [2] are essential success factors for construction projects. Creating accessible, secure, healthy, and productive buildings while minimizing their impact on society, the environment, and the economy are the cornerstones of green development [3]. Though sustainability concepts are important for the world and future generations, there are several potential barriers to acceptance, as was already mentioned. Since the perception of sustainable buildings is that they have greater initial costs than conventional constructions, it is believed that this is the biggest barrier [4]. Estimate that the initial costs of sustainable constructions are typically 2–7% higher than those of conventional buildings. Unfavorable perceptions of initial costs, according to [5] are one of the challenges in adopting sustainability.

Even though many researchers have looked into different aspects of sustainability, a lot of them have concentrated on green envelope elements because of how well they can lower a building's energy consumption while also delivering indoor thermal comfort and other environmental advantages, as several research studies have demonstrated [6]. The structural components that make up most of a structure are referred to as the built environment. The roof, walls, windows, and flooring are all elements that serve as a physical barrier or interface between the interior and exterior environments [7]. Other studies focused on environmentally friendly buildings (also referred to as green buildings), they used resource-conscious techniques including energy saving and the utilization of renewable radiation for lighting and water heating through solar energy [8].

There is a dearth of sustainability research on green construction approaches. Few studies are focusing on construction companies and sustainability activities, outside of material waste reduction, productivity, and leadership in energy and environmental design (LEED) standards [8]. To quantify the effect of these eco-friendly methods on construction enterprises' long-term profitability, there was also a dearth of information on their sustainability activities. There is a lack of sustainability studies on green building methods. Outside of productivity, material waste reduction, and leadership in energy and environmental design (LEED) standards, there aren't many studies that concentrate on construction businesses and sustainability initiatives. There was also a lack of data on the sustainability efforts of construction businesses, making it difficult to estimate the impact of these eco-friendly techniques on their long-term profitability.

To quantify the effect of these eco-friendly methods on construction enterprises' long-term profitability, there was also a dearth of information on their sustainability activities. Numerous benefits of green building exist, including those related to the environment, the economy, society, health, and public goods. The environment benefits from improved air and water quality as well as decreased power and water usage. Economic benefits include cheaper operating and maintenance costs as well as higher sales and rental rates; social and well-being benefits include better tenant comfort and health as well as reduced risk [8].

The main objectives of this study are to provide a framework for green building techniques and to assess how the suggested framework would affect the long-term success of medium and big construction companies. To accomplish this, a five-point plan of action was used. A Likert-scale survey questionnaire was used to evaluate the adoption of green practices and retraining in the construction industry. The questionnaire was distributed to businesses in the construction sector. A compliance factor analysis was developed to evaluate the association between the variables and their influence on the long-term productivity of the development firm after the components were grouped utilizing analysis.

It is anticipated that adopting a comprehensive green building framework will enhance construction companies' economic performance, competitiveness, speed, and cost. The building industry contributes significantly to growth; thus, the study's conclusions will have an impact on both the economy and the construction sector. Therefore, improving construction performance is essential for attaining both short-term corporate goals and long-term competitive advantage.

The business model for the twenty-first century is to enable organizations to interact differently with the environments in which they thrive, or to adopt sustainable practices that, in addition to generating social and environmental benefits, increase an organization's economic value, and the drive for corporate citizenship that resulted in the creation of social impact judgment tools [9].

Green training is the development of HR abilities, procedures, knowledge, and skills that stop the loss of environmental knowledge, skills, and data. The planning of multitalented personnel who are concerned with the advancement of knowledge and abilities necessary for growth is referred to as GT. HR GT and organizational performance are related because GT equips staff with the knowledge and abilities necessary to accomplish organizational objectives and stand out from the competition. People should be prepared with the fundamental abilities required to perform successfully in work.

1.1. Problem Statement

On the other side of the coin, the construction industry in comparison to other sectors generates more pollution in the environment and creates different ecological like waste generation, air pollution, and water body pollution. Now, literature is showing environment management tools that organizations use to control and push to align the employees with organizational strategy [9]. Organizations align their HR strategies and practices with their goals which shows the organizational steps that move towards sustainability, environmental sustainability, and sustainable performance [9]. Currently, the climate fastly is changing in the world, and environmental organization time to time aware of the general public regarding this challenge. Fast-growing perceptions of the environment are forcing the construction industry to adopt measures that protect the environment. However, these days organization is focusing on the environmentally friendly way of production that will not be harmful to the climate. As per the literature if construction wants sustainable construction so, adopt Green HR, Recycling, less energy use, and chemicals, and need to follow ethics. Green Training considers a key role play in the environment through corporate sustainable performance [10]. Sustainability helps to save natural resources. The destruction of natural resources or depletion means no life on the earth. Financial success, environmental sustainability, and saving natural resources only depend on awareness and training sessions that enhance the importance of ecological issues. As per the Literature Green training best tool for corporate sustainable performance in the construction industry of Pakistan.

1.2. Research Gap

The existing literature does not possess a model for explaining the Corporate Sustainable Performance in the construction industry [10] of Pakistan through Green Training. This study successfully fills this gap. Also, the study proposes for the practitioners, how the Construction Barrier effects the sustainable performance of an organization. Currently, several studies conducted on green training just to counter the issue of employee performance within the organization [11]. Now, this is the challenge for the organization to adopt new technology and meet the current requirements of the construction industry that are friendly to the environment. So, this study fills this gap in the construction industry and provides opportunities for the organization to develop green training and manage sustainable performance in a competitive and turbulent environment outside the organization.

1.3. Research Question

The study aims to explore:

- Does green training play a role to promote corporate sustainability performance in the construction sector of Pakistan?
- Does the construction barrier moderate the relationship between green training and sustainable performance?

1.4. Research Objective the Study Aims to Explore

The aforementioned discussion shows the importance of green training toward sustainable performance. In response, sustainable performance in the construction sector green training serves as a key determinant to achieve superior performance and competitive advantage. However, the prior literature neglects the roles of these important factors in the construction sector. Therefore, the main objective of this study is to investigate the direct impact of green training on sustainable performance. Further, this study aims to understand the moderating role of construction barriers towards the construction sector on the relationships between green training and sustainable performance.

2. HYPOTHESIS

In this study three variables are used: one is the independent variable, the second is the dependent variable and the third is the moderator. The study put forward two hypotheses the first is that green training impact sustainable performance and the second construction barrier plays a moderating role between green training and construction barrier. The theoretical framework of the organization fit theory guides the development of all hypotheses. Organizations create rules that change how people think about goals.

2.1. Study Framework

The person-organization fit theory is used in this study to examine the effectiveness of the current mechanism. The theory known as the "Person-Organization Fit Theory" explains how well people and organizations get along. Positive outcomes will be encouraged when an individual finds a position inside an organization that satisfies his or her personal and professional standards. There are several explanations for this phenomenon, such as "organizational learning theory." One of the main tenets of organizational learning theory is that learning occurs when individuals interact while identifying and resolving issues. Although organizational learning theory does not cover all processes, it does focus on the generation and application of knowledge inside an organization. The person-organization fit paradigm, however, emphasizes performance, productivity, and personal well-being. It fosters compatibility between an individual and the company where they work. Furthermore, the congruence of organizational value patterns and individual value patterns supports the person-organization fit theory. Use person-organization fit theory instead, which adequately addresses the entire phenomenon.

2.2. Green Training and Sustainable Performance

Organizational layers such as "operation, production systems, the complete plant, supply chain, region/country, and globe" are how corporate sustainable performance is organized. Most nations establish ecologically sound performance indicators, much like the most well-known environmental agency in Europe, and these indicators are evaluated by the International Organization for Standardized Environment Indexes. Sustainability indicators are emphasized not just in Europe but also in the United States of America. The condition of the entire plant is highlighted by the Global Report Initiative and Walmart Sustainability Product Index Questions. [10] additionally, several studies demonstrated how sustainable performance evaluation indicator systems may be divided into many functional aspects, including operational performance, marketing performance, and financial performance. [10] recently, most industries, notably those in the mining and automotive sectors, have adopted some sustainability through performance review and the development of specific sustainable performance indicators.

Based on unique requirements, manufacturing facilities may select several indicators to create their own indicator systems of sustainable performance. When comparing performance enhancements across many factories, it is crucial to building a common assessment indicator system of sustainable performance. There is a pressing need for a unified set of sustainable performance evaluation indicators in the context of production.

As a result, several antecedents that support incorporating sustainable performance have been studied in the literature. Examples include the triple bottom approach (which aims to balance the environmental, economic, and social aspects of sustainable development in practice), one of the precursors of CSP [11] green human resource management [10], the knowledge management process [12] and sustainable leadership [13]. When employed for corporate sustainability performance in the construction sector, green training is not supported by research. Employees will receive environmental training to manage, handle, and regulate the environment for sustainable performance [14]. Therefore, the researcher suggests that green training has a favorable relationship with corporate sustainability performance based on the grounds.

(H1): Green Training is positively correlated to corporate sustainability performance.

2.3. Moderating role of Construction Barrier in Management

The green economy is seeing an increase in interest in the subject of green training and performance management. The green economy depends on sustainable methods to boost productivity, save expenses, and improve the environment for coming generations. For green personnel to learn how to use their abilities more effectively while simultaneously minimizing waste, training is crucial. However, green training won't be sufficient to satisfy the demands of green businesses without collaboration between green managers and HR departments [10, 15]. Therefore, the purpose of this study is to determine how the coordination construction barrier in management affects long-term performance.

(H2): Construction barrier is a moderating role between green training and employee corporate sustainable performance.

3. METHODOLOGY

The methodology outlines and covers every step of conducting the study, including how to gather information through interviews or questionnaires. This study uses an instrument to collect data, which is then analyzed in SPSS.

Scholars have mostly employed the positivist paradigm in hypothesis testing to analyze the link [16]. This study is focused on and targets Pakistan's population-building industry. However, because this study is also quantitative, convenient sampling is employed. The cross-sectional research design used for this study, collect data in one span of time.

First, the researcher designed a questionnaire that very complicated part of the study. Questionnaire design is one of the most important factors of survey research as researchers rely on these structured instruments to collect data from respondents. In the questionnaire design, the researchers follow the process of defining the wording, scaling, and respondent identification and lastly putting together all the questions. In this research study, the researcher followed the rules of questionnaire design. Before the collection of data, it is mandatory to assess face validity. In this research study, the researcher assesses face validity by taking suggestions from industry experts, potential respondents, and academia. The researcher distributes questionnaires to companies selected on the basis of convenience sampling techniques through courier and email services. In this quantitative study, Google Forms is used to distribute a questionnaire to respondents to save money, time, and inconvenience while also reducing bias [17]. Online surveys also provide respondents with the option to submit their replies directly into databases, which will eliminate data entry mistakes in software [17]. After questionnaire distribution follow-up call will be made to participating companies to respondents to fill out the questionnaire.

First, Individuals were informed that there are no right or incorrect answers in order to prevent social desirability, and participants' and organizations' anonymity was guaranteed [18]. The supplied information will be held in strict confidence and used exclusively for academic reasons.

Data on several demographic characteristics are gathered in this study to produce more conclusive conclusions. Gender (male and female), as well as various educational levels like intermediate to master and experienced individuals, are the sources of the data. Closed-ended surveys are employed to boost response rates [18].

In the first step send an email to the HR manager to set up a meeting, and then at the scheduled time, discuss the research's value, veracity, and significance for all sectors of the construction industry. The researcher gives the management reassurances concerning the data's confidentiality and the complete secrecy of every employee's comment during the discussion. After confirmation, emails are received, and physical forms are given to the workers. Getting a response from the responders after two to three follow-ups. Start the initial screening after getting the answer, then delete any responses with incomplete information. The total number of organizations included in this study is fifty that are purely related to the construction industry. A total of 300 respondents complete the survey. However, after filtering and handling missing values, the actual data used for analysis is only 225.

For each question in the survey measured by 1 to 5 Likert scale item is utilized, and it looks like this: strongly disagree, disagree, neither agree nor disagree, agree, highly agree.

3.1. Measuring Scale

Existing, tried-and-true questionnaires are used in this investigation. Responses to the variables were rated on a Likert scale with 1 denoting "strongly disagree" and 5 denoting "strongly agree" on a scale of 5 points. Greater scores for each variable denoted higher construct levels.

Dependent Variable, Corporate sustainable performance is measured with a 4-item scale which is developed by [19]. One representative strongly disagrees, and the fifth strongly agrees. Independent Variable, Green training is measured with a scale developed by [20]. This scale includes 3 items. Ask respondents how they agree or disagree with this statement, 1=little extent and 5 great extents, the respondents rate the items 1 to 5. Moderation Variable, The barrier in construction management scale was adopted by [21]. This scale includes 6 items. Ask respondents how they agree or disagree with this statement, 1=little extent and 5 great extents, the respondents rate the items 1 to 5 (Questionnaire is added in Appendix).

4. DATA ANALYSIS

Version 23 of the Statistical Package for the Social Sciences (SPSS) was used to analyze the data for this study. Data is first checked by the researcher for errors and missing numbers, then boxplots are used to determine whether there are any outliers. After the data has been cleaned, the preliminary analysis comprised calculating descriptive and frequencies as well as performing normality checks. The fundamental tenet of multivariate data analysis is normality, which is necessary for correct findings [17]. Measuring item-wise skewness and kurtosis is one way to check if the data are normal.

An indicator of a measure's internal consistency is that measure's dependability. The reliability of the measures employed in this study is assessed using Cronbach's alpha, (Tables mentioned in the appendix) where a value of 0.7 is considered satisfactory. To assess collinearity among the predictor variables, variance inflation factor (VIF) scores and tolerance statistics are also collected [22]. Collinearity is the state of having highly connected independent variables, which increases the amount of variance and the accuracy of the results [23]. As a rule, multicollinearity is present when VIF scores are larger than 2 and tolerance statistics are lower than 0.1 [23]. To examine the proposed correlations between variables, SPSS [24] macro-PROCESS software is used. Model 4 of macros has been applied to measure both direct and indirect impacts [24]. Additionally, results show that all connections are significant in the predicted directions. Additionally, the item-wise skewness scores are less than ±2 and the kurtosis is less than ±3, indicating that the data is normally distributed.

Additionally, the threat of social desirability is a known problem, and certain steps have been taken to lessen its effects (both ex-ante and ex-post). When a single component accounts for more than 50% of the variation, common method bias (CMB) may become a concern. CMB is not viewed as a severe issue because the highest variation explained by a single component is not greater than 30%.

Frequency Tables, all demographic and variable information is included in the frequency tables that follow, along with extensive information regarding the demographic ratio of respondents. Therefore, gender information is included in Table 1.

Table 1. Demographic characteristics

Main category	Subcategory	Frequency	Percent
Gender	Male	151	67.1
	Female	74	32.9
Age	20–30	16	7.1
	31–40	111	49.3
	41–50	42	18.7
	Above 50	40	17.8
Work experience	Less than one year	64	28.4
	2 years–4 years	64	28.4
	5 years–7 years	17	7.6
	8 years–10 years	17	7.6
	Above 10 years	63	28.0
Qualification	Intermediate	35	15.6
	Graduation	70	31.1
	Masters	86	38.2
	M. Phil	32	14.2
	PhD	2	0.90
	Total	225	100.0

Table 2. Bivariate correlation analysis

Variable	1 Green training	2 Corporate sustainable performance	3 Construction barrier
1. Green training	1		
2. Corporate sustainable	0.430**	0.156*	
3. Construction barrier	0.133*	-0.081	0.171**

4.1. Correlation

The link between the variables is assessed using Pearson correlation. This test evaluates the amount and direction of the link between two continuous variables. This software handbook states that findings with a "p" Value would be considered significant. However, if the R-value is more than 0.7, it can be a sign that the variables are collinear [24].

The values of the inter-correlations between the variables are shown in Table 2. Corporate sustainability performance and green training have a significant correlation (r=0.430**, p<0.01). Due to the "p" value being less than 0.05., this result indicates that both the green training and corporate sustainable performance factors are positive, significant, and correlate with one another. A double star on the Value is another indication of a high association. Second, there is a strong and positive correlation between green training and construction barriers (r=1.333*, p<0.01). Additionally, one-star reveals a strong association between the variables. The third relationship between corporate sustainable performance and construction barriers has an R-value of -0.081 and a p-value of 0.001.

Table 3. Regression analysis for hypothesis 1

Job demand	β	P
Green training	0.49	0.000

Table 4. Moderation analysis for hypothesis 2

	β	P
Green training * Corporate sustainable	-0.366	0.03

4.2. Hypothesis Testing

Tables 3 and 4 show the findings of the regression analysis.

The following hypothesis is put forth in this study. Following the formulation of the hypothesis, data from the respondents is collected, and analysis is done to determine whether the hypothesis should be accepted. In this study, SPSS software is utilized for analysis. All hypotheses are supported by the findings.

Below is a list of the potential hypothesis that might be created considering this study and conceptual framework.

Hypothesis 1.

(H1): Green Training is positively correlated to corporate sustainability performance.

(H2): Construction barrier is a moderating role between green training and employee corporate sustainable performance.

4.3. Regression Analysis

The findings of the regression analysis are presented in Table 3. If there are two variables, one of which is an independent variable and the other is a dependent variable, regression analysis is used to determine the effects of the variables.

According to Table 3, green training has a substantial influence on sustained performance (β=0.49). It is indicated by the beta value that if green training is increased by one-point, corporate sustainable performance will be improved by 0.49. According to statistics, the association is significant if the P Values are less than 0.05. The Statistical Package for Social Sciences (SPSS) is used in this study to analyze the data. Therefore, this program uses a "p" value to determine significance and the "βeta" value to indicate the effects of one variable on another.

One of the key presumptions of regression is normality. Regression satisfies all the prior normality assumptions according to statistics. Because all the dots are close to the line in this normality graph, there is no normality in the data. The data is normal if the dots are spread apart from the line, Figure 1 shows the details of normality graph.

The data in Table 4 support Hypothesis 2. The findings indicate that the construction barrier is moderating between green training and corporate sustainable performance since the p-value is less than 0.05. This table's "β" value is negative, indicating that there is a weak correlation between green training and corporate sustainability performance as a result of the construction barrier.

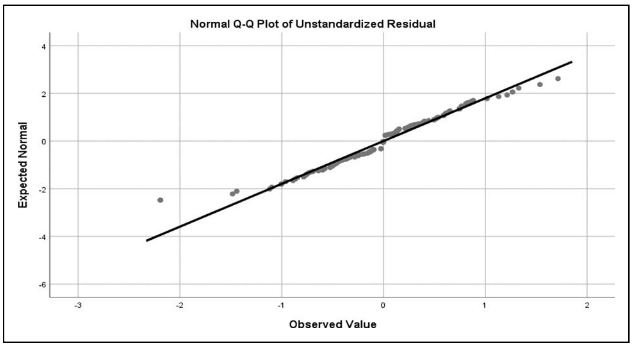

Figure 1. Normality graph details.

5. DISCUSSION

5.1. Green Training and Corporate Sustainable Performance

This study demonstrates a beneficial relationship between green training and corporate sustainability performance. The primary cause of this beneficial relationship is that corporate green training fosters a common understanding of the value of the green environment among employees. Employees who complete this program become more environmentally conscious, which promotes sustainable business practices. As a result, such conduct inspires the employee to work hard to meet organizational objectives. The results of this investigation are in line with the P-O theory's presumptions. This said that when people work well together, there is value congruence (the fulfillment of shared ideals), personality congruence (similarity in personality between an individual and other organization staff members), and other positive outcomes.

The findings indicate that when staff members adopt training-related behavior, both performance and the long-term viability of the organization improve. Since green training inherently has a beneficial influence on corporate sustainable performance, companies that wish to improve performance and survive in the market first focus on it. However, there is a lack of research in this area, as well as green training and sustainable corporate performance. Results, therefore, indicate that both are not only relevant but also have a good connection with one another. However, research indicates that the industrial sector conducts green training in a company that has a significant impact on social, economic, and environmental activities. Such an impression enables other organizations to undertake green training as well.

5.2 Construction Barriers Moderating Role Play

Significant to this study is the moderating construction barrier. The following are a few of the reasons the researcher addresses. According to published literature, building impediments have a detrimental impact on green training and sustainable performance. Prior empirical research supports this claim. Accordingly, the association between corporate sustainable performance and green training and construction barriers is weaker when they are combined in role-play. Pakistan is still considered a developing nation, hence there are no resources or advanced technology to support this technology. This is one of the reasons for the relevance. Thus, the building is required.

Numerous studies have shown that the system's lack of support lowers both personal and organizational performance at the workplace.

5.3. Findings and Implication

This study's findings are relevant to both academic and practical areas. By outlining the effects of corporate sustainability performance, the first findings extend the literature on Green Training and sustainable performance, particularly in the construction sector. Especially after the global warming issues sustainable performance is making a big challenge for organizations. Currently, several studies are conducting on green training just to counter the issue of environmental changes. Now, this is the challenge for the organization to adopt new technology and meet the current requirements.

This study's findings help academics and organizations how to get sustainable performance in this situation. Finding showing a depth understanding of the phenomenon of sustainable performance through green training. This study extends the previous literature that green training enables employee performance within the organization. The recent development in the area of the construction industry provides opportunities for the organization to develop green training and manage sustainable performance in a competitive and turbulent environment outside the organization.

Additionally, the results imply that green training fosters respect between workers and the industrial sector since employees believe they would benefit socially and financially from achieving sustainable corporate performance. As for the study's practical ramifications, it shows Pakistan's construction industry that it has to develop plans and regulations based on the demands of the moment. Pakistan's gross domestic product is significantly influenced by the industrial sector. The present administration provides the construction industry with a liberal environment in terms of norms and processes. Second, Pakistan is more cautious when it comes to environmental preservation. The industrial sector, which is currently working toward a greener environment, as well as the government can benefit from this study. Corporate sustainability performance is influenced both directly and indirectly by employee behavior and green training, both of which are made feasible by an environment that is suitable for both social and economic activity.

5.4. Limitations and Future Research

This study has certain limitations even though it offers encouraging results about the relationship between green training and corporate sustainability performance. This may have a methodological problem because it first used cross-sectional data to analyze how green training affected corporate sustainability performance. This could make it harder to confirm that certain factors influence each other. Future research may examine the relationship between green training and company sustainable performance using longitudinal or time-lagged data. Second, to understand the connection between green training and corporate sustainable performance, this study looked at the impact of the construction barrier as a contextual component. The results indicate that any other contextual elements, such as corporate culture, should be investigated because they may have an inconsequential influence on the construction barrier. Future research may therefore look at how these contextual factors affect the construction industry's ability to support corporate sustainability performance. This study concludes that green training has a favorable influence on the sustainability of organizational operations. Additionally, the results imply that a barrier is being built between staff role-playing and business sustainability. Additionally, there is a large yet unfavorable role-play between corporate sustainability and green training. According to a study, Pakistan's building industry is negatively impacted by barriers to construction simply because of the lengthy procedures and time waste. When the system helps the workers, they perform better.

6. CONCLUSION

The findings of this study provide an in-depth understanding of the phenomena of the impact of green training on sustainability performance and the moderating function of the Construction Barrier. According to the results, the hypothesis is accepted. This study revealed that Green Training plays a significant role in improving Sustainable Performance. The study further asserts that Construction Barrier creates a weak relationship between green training and sustainable performance. These findings are very essential for scholars and practitioners for further studies and implications. Organizations at the time of strategies use the findings of this study because this is the new phenomenon in Pakistan when organizations are moving towards friendly construction that is not harmful to the environment.

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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Appendices

Questionnaire

Green Training

GT-1: I am provided with sufficient opportunities for training and development in environmental management.

GT-2: I receive the environmental training I need to reduce the environmental impact of my job.

GT- 3: Environmental training is given a high priority in this organization.

Corporate Sustainability Performance

CSP1. My company commonly reduces hazardous waste and emissions, etc. to conform to environmental regulations.

CSP2. My company commonly consumes a few resources, such as energy, water, electricity, gas, and petrol.

CSP3. My company achieves profit growth commonly due to energy consumption and materials reduction.

CSP4. My company always commits to better services and the code of ethics to satisfy the public's and the government's needs.

Construction Barrier

Lack of an explicit financing mechanism

Lack of professional education and training

Lack of methods to consistently define and measure "green" features

High risks associate with investment

Lack of renewable energy application in existing infrastructure

Unavailable sustainable technology

Reluctant to adopt changes

Contested functionality for end users

All Variables are reliable because Cronbach's Alpha value is greater than 0.7 (George & Mallery, 2010). Second, in this study validity confirm through bivariate correlation analysis all values of total column are significant that is showing validity of the constructs. (See Appendix Table 1).

Relaibility Analysis

Reliability statistics

Variables	Cronbach's Alpha	Items
Green training	0.789	3
Construction barrier	0.833	8
Corporate sustainable	0.705	4
Total	0.886	15

Correlations

	GT_1	GT2	GT3	Con_1	Con_2	Con_3	Con_4	Con_5	CSP_1	CSP2	CSP3	CSP4	Total
Green_training_1	1	.621**	.586**	.497**	.432**	.428**	.369**	.420**	.373**	.317**	.375**	.347**	.659**
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GT2	.621**	1	.457**	.354**	.313**	.247**	.213**	.409**	.315**	.334**	.280**	.180**	.575**
	0.000		0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.007	0.000
GT3	.586**	.457**	1	.508**	.404**	.475**	.427**	.317**	.355**	.329**	.386**	.402**	.704**
	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Con_1	.497**	.354**	.508**	1	.501**	.565**	.502**	.473**	.374**	.332**	.319**	.337**	.725**
	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Con_2	.432**	.313**	.404**	.501**	1	.598**	.475**	.420**	.351**	.382**	.354**	.411**	.712**
	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Con_3	.428**	.247**	.475**	.565**	.598**	1	.634**	.428**	.372**	.362**	.356**	.459**	.750**
	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
Con_4	.369**	.213**	.427**	.502**	.475**	.634**	1	.401**	.345**	.376**	.343**	.389**	.698**
	0.000	0.001	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000
Con_5	.420**	.409**	.317**	.473**	.420**	.428**	.401**	1	.277**	.419**	.378**	.229**	.653**
	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.001	0.000
Corporate_Sustainable_P1	.373**	.315**	.355**	.374**	.351**	.372**	.345**	.277**	1	.351**	.316**	.337**	.598**
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000
CSP2	.317**	.334**	.329**	.332**	.382**	.362**	.376**	.419**	.351**	1	.520**	.333**	.649**
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000
CSP3	.375**	.280**	.386**	.319**	.354**	.356**	.343**	.378**	.316**	.520**	1	.388**	.634**
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000
CSP4	.347**	.180**	.402**	.337**	.411**	.459**	.389**	.229**	.337**	.333**	.388**	1	.595**
	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000		0.000
Total	.659**	.575**	.704**	.725**	.712**	.750**	.698**	.653**	.598**	.649**	.634**	.595**	1
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

**. Correlation is significant at the 0.01 level (2-tailed).

Validity of the data

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	29.476	1	29.476	94.543	.000[b]
	Residual	69.524	223	.312		
	Total	99.000	224			

a. Dependent Variable: CS PMEAN

b. Predictors: (Constant), GT_MEAN

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	2.380	.152		15.625	.000
	GT_MEAN	.406	.042	.546	9.723	.000

a. Dependent Variable: CS PMEAN

Correlations

		Gender	Age	Education	Experience	GT_MEAN	CB_MEAN	CS_PMEAN
Gender	Pearson Correlation	1	-.280**	-.028	-.324**	.052	.000	.054
	Sig. (2-tailed)		.000	.677	.000	.440	.996	.416
	N	225	225	225	225	225	225	225
Age	Pearson Correlation	-.280**	1	.348**	.806**	-.268**	-.203**	-.137*
	Sig. (2-tailed)	.000		.000	.000	.000	.002	.041
	N	225	225	225	225	225	225	225
Education	Pearson Correlation	-.028	.348**	1	.411**	-.188**	-.120	-.022
	Sig. (2-tailed)	.677	.000		.000	.005	.072	.746
	N	225	225	225	225	225	225	225
Experience	Pearson Correlation	-.324**	.806**	.411**	1	-.202**	-.092	-.070
	Sig. (2-tailed)	.000	.000	.000		.002	.168	.296
	N	225	225	225	225	225	225	225
GT_MEAN	Pearson Correlation	.052	-.268**	-.188**	-.202**	1	.560**	.546**
	Sig. (2-tailed)	.440	.000	.005	.002		.000	.000
	N	225	225	225	225	225	225	225
CB_MEAN	Pearson Correlation	.000	-.203**	-.120	-.092	.560**	1	.633**
	Sig. (2-tailed)	.996	.002	.072	.168	.000		.000
	N	225	225	225	225	225	225	225
CS_PMEAN	Pearson Correlation	.054	-.137*	-.022	-.070	.546**	.633**	1
	Sig. (2-tailed)	.416	.041	.746	.296	.000	.000	
	N	225	225	225	225	225	225	225

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

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Research Article

Timeline approach for antimicrobial paints applied on surfaces

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ABSTRACT

Microbial growth in man-made constructions is a planetary problem. Contaminated surfaces can rapidly spread dangerous infectious illnesses, especially in public places. A few microbes can quickly multiply into millions, especially under current circumstances. A hygienic surface is defined as a component that inhibits micro-population increase. Meanwhile, the use of biocides is expanding, as is research into their antibacterial characteristics and components. There are now various antimicrobial substrates on the market. It is worthwhile to investigate the efficacy and precision of these products. In this paper, an experiment has been made on six different wall paints, which are promoted as antimicrobials and are inspected against bacteria. Wooden panels were painted with six different antimicrobial wall paints. Four different microorganisms were sprayed on the surface using a sterile spraying mechanism. The bacteria used in the study were *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus subtilis*. Each panel was observed for ninety days, and the results were discussed. In contrast, the first paint proved effective on *L. monocytogenes*, *S. aureus*, and *B. subtilis* within the first two weeks and on *E. coli* within the first month. The second paint affected all four bacteria within the first month. The remaining paints proved ineffective until the third month's end.

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1. INTRODUCTION

The humidity of the buildings in which people live, and work has been recognized as an essential issue in the health of individuals in indoor environments during the last 20 years [1–3]. Contaminated surfaces can rapidly spread dangerous infectious illnesses, especially in public places. There are several critical places, such as healthcare buildings and kitchens, where contaminated surfaces induce rapid disease transmission, beginning with a surface and progressing to a person and, finally, among individuals [4]. Antimicrobials kill or prevent the growth of microorganisms such as bacteria, fungi, and algae. Antimicrobial materials should ideally be effective against a broad spectrum of bacteria while being generally environmentally friendly, colorless, odorless, and UV and visible radiation inert [5]. Antimicrobial paint is designed to resist microbes, including viruses, bacteria, and other germs. It can help keep interiors safer, better protected against mold damage, and make them easier to clean [6]. Establishing antimicrobial surfaces could be one of the keys to helping prevent further contagious incidents and breakouts. Therefore, biostatic and dry finish architectural paint mixtures that competently prevent microbial growth or erase them on their dry surface are necessary [4]. An antimicrobial surface must ensure that pathogenic contamination is eliminated or lowered to a minimum. Different biocides are often added to paint formulas to protect the products from microbial assault and to preserve dried films from fungal and algal formations. Microbial growth frequently stains and degrades the qualities of paints [7–9]. There are now various antimicrobial substrates

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Table 1. Paints used within the scope of the study

Ingredient	Concentration
Paint A - Fenomastic Hygiene Silk B Base S2500-N	
Aqueous ammonia solution	%≤0.3
1,2-benzisothiazol-3(2H)-one (BIT)	%<0.1
3-iodo-2-propynyl butylcarbamate (IPBC)	%<0.1
C(M)IT/MIT (3:1)	%<0.025
2-methyl-2H-isothiazol-3-one (MIT)	%<0.0015
Paint B - Fenomastic Stain resistant BB Base S2000-N	
There is no component that is classified as dangerous to health or the environment and required to be reported.	
Consists of 1,2-benzisothiazol-3(2H)-one. May cause allergies.	
Paint C - Fenomastic Pure Silk B Base 3915-G65Y	
There is no component that is classified as dangerous to health or the environment and required to be reported.	
Consists of 1,2-benzisothiazol-3(2H)-one. May cause allergies.	
Paint D - Fenomastic Rich Mat B Base S2500-N	
There is no component that is classified as dangerous to health or environment and required to be reported.	
Consists of 1,2-benzisothiazol-3(2H)-one, 2-methyl-2H-isothiazol-3-one (MIT) and C(M)IT/ MIT (3:1). May cause allergies.	
Paint E - Alpina silan-w Caparol White	
Pyrithione zinc	%≤2,5
1,2-benzisothiazol-3(2H)-one	%≤2,5
3-iodo-2-propynyl butylcarbamate	%≤2,5
Urea tetra methylol acetylene	%≤2,5
2-methyl-2H-isothiazol-3-one	%≤2,5
2-octyl-2H-isothiazol-3-one	%≤2,5
Paint F - Alpina max-w Caparol White	
Pyrithione zinc	%≤2,5
1,2-benzisothiazol-3(2H)-one	%≤2,5
3-iodo-2-propynyl butylcarbamate	%≤2,5
Urea tetra methylol acetylene	%≤2,5
2-methyl-2H-isothiazol-3-one	%≤2,5
2-octyl-2H-isothiazol-3-one	%≤2,5

on the market. It is worthwhile to investigate the efficacy and precision of these products. A few microbes can quickly multiply into millions, especially under current circumstances. Meanwhile, the use of biocides is expanding, as is research into their antibacterial characteristics and components [10]. This study has designed an experiment to test the accuracy of some wall paints, which are currently commercialized for their antimicrobial properties. It has been investigated whether the bacteria will survive or proliferate, and if they do, how long will it take to be diminished into zero on a surface painted with the substances. This study has been conducted on six types of wall paints, observing four types of the most common contaminant bacteria *E. coli*, *L. monocytegenes*, *S. aureus*, and *B. subtilis*.

2. MATERIALS AND METHODS

2.1. Materials

Escherichia coli (ATCC 25922), *Listeria monocytegenes* (ATCC 19111), *Staphylococcus aureus* (ATCC 6538), and *Bacillus subtilis* (ATCC 6633) were used in the evaluation of the paint's antimicrobial effectivity. Six different types of paints were purchased from different paint firms. The paints were indicated to be antimicrobial. The information and the ingredients of the paints investigated are listed in Table 1.

2.2. Samples Preparation

Within the scope of the study, the paints were applied on 6 wood panels sized (50 X 50 cm) and let dry for 10 hours at room temperature. This process was repeated 3 times.

2.3. Microbial Analyses

Painted panels were brought to the laboratory for microbial analysis. *E. coli*, *L. monocytogenes*, *S. aureus*, and *B. subtilis* were sprayed on the surface using a sterile spraying mechanism. Spiking was done with bacteria enriched and 5 log_{10} cfu/ml. All bacteria were sprayed on painted surfaces, let dry, and incubated at room temperature. Surface sampling was made using a sterile swap from 5x5 cm area on days of 1st, 3rd, 5th, 7th, 14th, 21st, 30th, 60th, 90th days after spiking. All microbiological analyzes were held in a commercial laboratory.

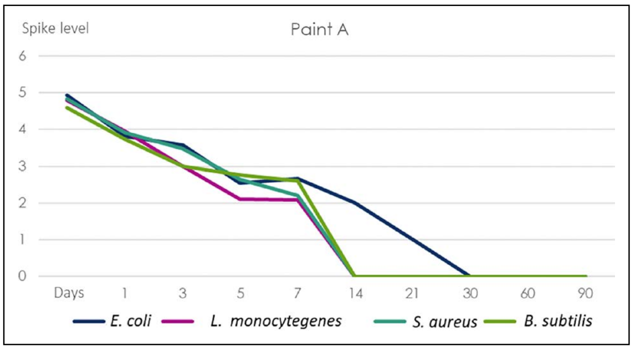

Figure 1. Results of paint A.

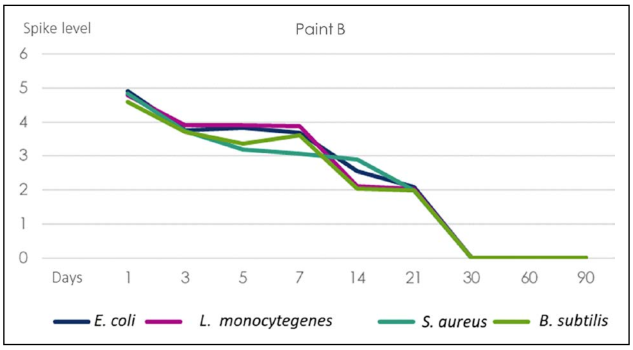

Figure 2. Results of paint B.

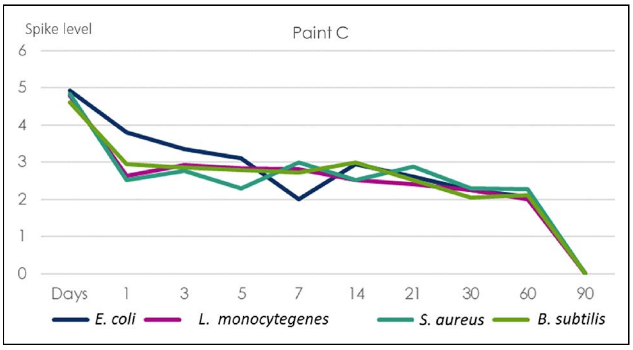

Figure 3. Results of paint C.

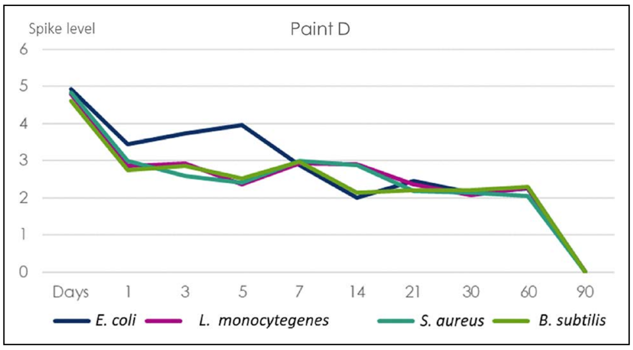

Figure 4. Results of paint D.

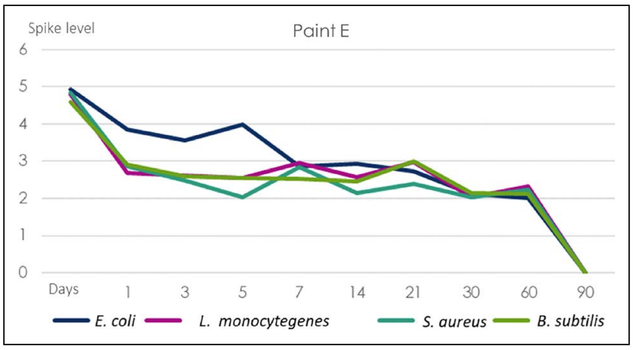

Figure 5. Results of paint E.

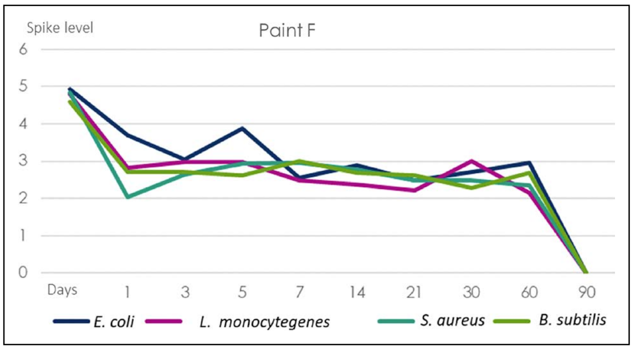

Figure 6. Results of paint F.

3. RESULTS AND DISCUSSION

This study aimed to evaluate and determine the duration of the antimicrobial effect of different paints. All six paints were evaluated for antimicrobial effects on four different bacteria. All paint samples were spiked with approximately 5 log_{10} cfu/ml bacteria. There was a significant ($p<0.05$) decrease in Paint A and Paint B, which decreased bacteria 14th day and 30th day of spiking, respectively. Other paints showed a decrease on the 90th day, possibly due to dehydration of the bacteria of concern. Bacteria need humidity and water to stay alive. As the days pass, humidity and relative water decrease, thus triggering the death of bacteria used in our study. The results obtained from Paint A are shown in Figure 1. According to the results, there was a significant decrease in the numbers of bacteria obtained by the 14th day of spiking where *E. coli* numbers decreased only on the 30th day.

The results obtained from Paint B are shown in Figure 2. According to the results, the number of bacteria significantly decreased by the 30th day.

The results obtained from Paint C to F were similar and were shown in Figures 3, 4, 5, and 6. The overall results suggest a decrease by day 90 due to the bacteria's dehydration.

The most significant amounts of antimicrobial coatings are consumed in the building industry, particularly for producing interior and exterior coatings designed to protect against microorganisms. Other branches in which the consumption of antimicrobial coatings is expected to increase include hospitals, nursing homes, daycares, and medical applications where a high standard of hygiene is required [10, 11]. Various biocides are commonly added to paint formulations to protect the products against microbial attack. Biocides are essential in decreasing the probability of microbial growth on the coated surface [7–9].

Considering these issues, an experiment has been designed to test the efficiency of some of the wall paints in the market, which are currently commercialized for their antimicrobial properties. It has been investigated whether the bacteria will survive or proliferate, and if they do, how long will it take to be diminished into zero on a surface painted with the substances. This study has been conducted on six types of wall paints, observing four types of the most common contaminant bacteria. *E. coli*, *Listeria monocytegenes*, *Staphylococcus aureus* and *Bacillus subtilis*.

There have been varying kinds of studies to investigate the antimicrobial activity of paints over hygiene-related bacteria. In a study held by Hochmannova and Vytrasova, TiO_2 and zinc oxide consisting of aqueous acrylic dispersion interior paints were tested for their photocatalytic activity on *E. coli*, *S. aureus*, *P. aeruginosa*, fungi *Aspergillus niger* and *Penicillium chrysogenum*. This study reveals the hypothesis that zinc oxide and anatase titanium dioxide can be paired in formulations of interior paints [12]. Nano ZnO was the most effective photocatalytic substance on various microorganisms [13].

In a study by Kumar et al. [14], metal nano particle dispersed oil paints were examined for an environmentally friendly paint. Silver nano-particle paint has been observed to be highly effective on both gram-positive (*S. aureus*) and gram-negative bacteria (*E. coli*). These studies have shown that the improvement of the paint can diminish pathogen proliferation on surfaces. Even though the active ingredients are unknown in this paper, Paint A and Paint B are proven to be nearly as effective as the studies that held with similar concerns. Paint A and Paint B has succeeded in diminishing the most common biofilm-forming pathogenic bacteria.

All six of the paints consisted of isothiazole derivatives, known to be an agent with antimicrobial characteristics. Isothiazole derivatives possess antibacterial activity. Multiple 3(2H)-isothiazol one derivative have been synthesized in the previous decade, and the majority of them have antibacterial action against both Gram-positive and Gram-negative bacteria, depending on the substitution pattern [15].

1,2-benzisothiazol3(2H)-one (BIT) is a commonly utilized biocide applied to industrial products with broad antimicrobial activity [16, 17]. BIT has been shown to react with thiol-containing proteins on target microorganisms and is especially effective against actively metabolizing bacteria [18, 19]. It is widely used in food packaging, industrial and consumer products like adhesives, laundry and dish detergents, cleaning and disinfectants, air fresheners, personal care products and sunscreens, paints, and industrial lubricants [20, 21].

4. CONCLUSION

In this study, six different wall paints have been tested for the effectiveness of their antimicrobial properties. While Paint A proved effective on *L. monocytogenes*, *S. aureus*, and *B. subtilis* within the first two weeks and on *E. coli* within the first month, Paint B was effective on all four bacteria within the first month. Paint C, D, E, and F showed to be ineffective until the end of the third month. It is also plausible that the bacteria on paint C, D, E, and F have been eliminated due to various conditions, such as dehydration, other than the components of the paints. All six of the paints consisted of isothiazole derivatives, known to be an agent with antimicrobial characteristics. Although there is insufficient information about the exact formulation of the paints; it can be said that not all the wall coatings in the market that are promoted to be antimicrobial, hygienic, or biocidal are as effective as advertised.

When it comes to finishing constructions and repainting, the preference for antimicrobial paint is a must for selecting a dependable and suitable one. These paints may not be inexpensive but will be cost-effective in the long run. Acknowledging the necessity of antimicrobial paints and their efficiency has been proven to be necessary. Human populations are becoming more vulnerable to contagious diseases as circumstances evolve and the quantity of life increases. Building components with antimicrobial properties such as wall paints can ensure a safer environment against disease-causing bacteria. More tests, informative research, and reliable commercial sources are needed to manage that idea.

ETHICS

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

DATA AVAILABILITY STATEMENT

The author 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 author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

PEER-REVIEW

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Research Article

Synthesis and characterization of bentonite-based zinc complexes

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ABSTRACT

In chemical reactions, the use of environmentally friendly catalysts obtained by transporting transition metals on solid or polymer carrier materials has become quite common recently. Studies in which zinc complexes are used as homogeneous and heterogeneous catalysts are frequently encountered in the literature. In addition to many advantages of homogeneous catalysts, disadvantages include difficulty separating from the reaction medium, recycling, and limited chemical-thermal stability. Solving problems can be solved by using solid catalyst support materials and transferring the active ingredients to these materials. Therefore, catalysts prepared by transporting transition metal complexes onto solid supports have become interesting for researchers. Natural or processed clays can be used as catalysts or catalyst carriers and have many uses due to their cheapness and abundance. In this study, natural Enez/Edirne bentonite was acid-activated (HB) and converted to organo-clay (HB/CTAB) with hexadecyltrimethylammonium bromide (CTAB). Then, heterogeneous catalysts were prepared by direct transport of the synthesized $[Zn(acac)_2H_2O]$ or $[Zn(p\text{-}H_2NC_6H_4COO)_2]1.5H_2O$ complexes onto modified clays separately. The catalysts have been characterized by X-ray diffraction, Fourier transform infrared spectroscopy, thermogravimetric analysis, surface scanning electron microscope, and Brunauer-Emmett-Teller specific surface analysis methods.

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1. INTRODUCTION

The heterogeneous catalyst preparation method by transporting transition metal complexes on solid support materials has become attractive in recent years due to ease of preparation, shape selectivity, recycling of catalysts, product purification, and more accessible transport properties [1, 2]. Metal complexes are used as homogeneous catalysts in various reactions. Although homogeneous catalysts have some advantages, they also have disadvantages as they cannot be used as a sustainable source for reasons such as separating the catalyst from the reaction medium, recycling the catalyst, and limited chemical and thermal stability [3, 4]. These problems can be solved using solid catalyst support materials consisting of inorganic or polymer matrices and transporting the active ingredients onto these support materials [5–7]. Methods such as placing on the support solid and trapping the complex have several advantages over non-covalent interactions [8–10].

Due to their cheapness and abundance, natural or modified clays are used for the chemical industry, agriculture, surface coating, and environmental purposes and directly as catalysts or catalyst carriers [11–13]. Bentonite is clay whose main component is the montmorillonite mineral and has a 2:1 layered structure. There is an octahedral alumina layer between the two tetrahedral silica layers. In montmorillonite containing a dioctahedral structure, 2/3 of the octahedral places are covered with Al^{3+} cations.

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As a result of the replacement of Al^{3+} ions with Mg^{2+} and Fe^{2+}/Fe^{3+} ions (isomorphic substitution), a net negative charge is formed on the surface. These negative charges are balanced by hydratable cations such as Na^{+}, Mg^{2+}, and Ca^{2+} between successive 2:1 layers [10, 14–18].

Studies on bentonite-based catalysts containing various zinc compounds such as zinc oxide and zinc sulfide have been seen in the literature [19–21], but no study has been found involving the transport of acetylacetonate and p-aminobenzoic acid-based zinc complexes onto bentonite.

This study it is aimed to develop new heterogeneous catalysts by transporting synthesized $[Zn(acac)_2H_2O]$ or $[Zn(p\text{-}H_2NC_6H_4COO)_2]1.5H_2O$ complexes directly onto bentonite and modified bentonite. For this purpose, Enez/Edirne bentonite was treated with acetic acid and acid-activated (HB), and this bentonite was converted into organo-clay (HB/CTAB) by interacting with hexadecyltrimethylammonium bromide (CTAB). Catalysts were prepared by transporting the synthesized zinc-based complexes onto the obtained modified clays separately. Characterization of the synthesized catalysts was performed by the methods such as Fourier transform infrared spectroscopy (FTIR), surface scanning electron microscope (SEM), X-ray diffraction (XRD), thermogravimetric analysis (TG/DTG), and Brunauer-Emmett-Teller (BET) specific surface analysis.

2. MATERIALS AND METHODS

2.1. Materials

Acetylacetone (2,4-pentadione) (Merck), zinc nitrate hexahydrate (Merck), zinc sulfate heptahydrate (Merck), ethyl acetate (Fluka), p-aminobenzoic acid (PABA) (Fluka), hexadecyltrimethylammonium bromide (CTAB) (Merck) and used other chemicals are analytical reagent grade and no purification was made before use. A natural clay Enez/Edirne bentonite was used in the study.

Refrigerating-heating circulator (Polyscience 9006), magnetic shaker (Heildolp MR 3001), grinder (Retsch PM 200), and pH meter (Denver 215) were used in the experiments.

2.2. Preparation of $[Zn(acac)_2H_2O]$ Complex

0.02 mol of acetylacetone (2,4-pentadione) and 0.02 mol sodium hydroxide were dissolved in 10 mL of ultrapure water. This solution was slowly added to a 0.01 mol zinc sulfate heptahydrate solution dissolved in 10 mL of water. The resulting mixture was stirred for 1 hour. The resulting white precipitate was filtered under a vacuum, washed with distilled water, and left to dry at room conditions. The resulting raw product (Fig. 1) was recrystallized from 20 mL of hot ethyl acetate solution containing 1 mL of acetylacetone [22].

2.3. Synthesis of $[Zn(p\text{-}H_2NC_6H_4COO)_2]1.5H_2O$ Complex from Stratified Zinc Hydroxide

A solution of 10 mL PABA (3.6 mmol) was titrated with $Zn(NO_3)_2.6H_2O$ solution (3.65 mmol). One molal of NaOH solution was used to adjust the pH of the solution to 7. The mixture was stirred for 1 hour and then filtered. The filtrate was held for several days to form $[Zn(p\text{-}H_2NC_6H_4COO)_2]1.5H_2O$

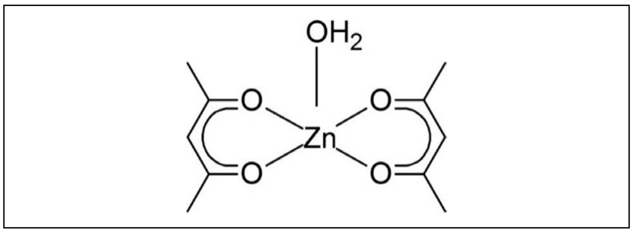

Figure 1. Structure of $[Zn(acac)_2H_2O]$ complex.

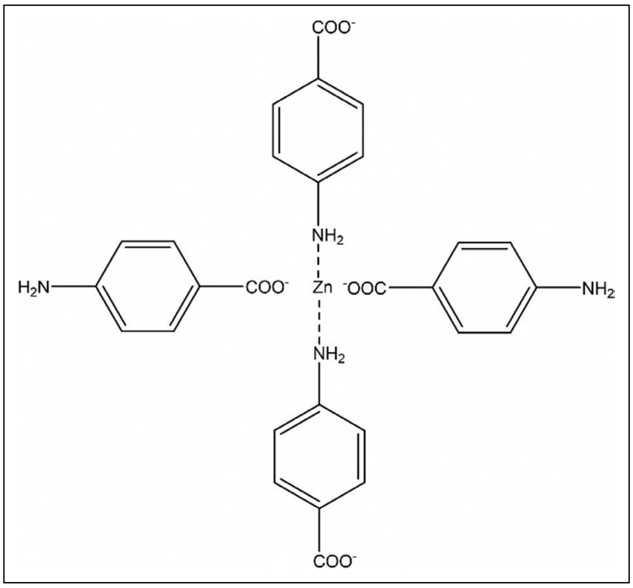

Figure 2. Structure of $[Zn(PABA)_2]1.5H_2O$ complex.

($[Zn(PABA)_2]1.5H_2O$) crystals, and the crystals were washed several times with distilled water, filtered and dried (Fig. 2) [23].

2.4. Preparation of Acid Activated Clay

0.1 M CH_3COOH solution was added to 100 g of natural bentonite and mixed in a magnetic shaker for 6 hours. The mixture was centrifuged, and the intermediate phase was taken from the three phases and washed with ultrapure water many times. The resulting acid-activated clay (HB) was dried at 110 °C for 6 hours, ground at 500 rpm for 15 minutes, and passed through a 70-mesh sieve [24].

2.5. Preparation of Organo-clay

25 g of HB was slowly added to the 250 mL solution of 5 g CTAB. The mixture was stirred for 18 hours at 25 °C, filtered, and washed several times with ultrapure water (controlled with 0.1 M $AgNO_3$ solution) to remove Br- ions. The obtained organo-clay (HB/CTAB) was dried at 110 °C for 6 hours, ground at 500 rpm for 15 minutes, and passed through a 70-mesh sieve [25].

2.6. Transport of Complexes on Modified Clays

0.360 mmol $[Zn(acac)_2H_2O]$ complex was dissolved in 200 mL of chloroform, and 2.4 g of HB was slowly added to this solution. The suspension was refluxed at 300 rpm at 75 °C for 24 hours. The mixture was rested, filtered, and the product was dried at 80 °C, and the transport of $[Zn(acac)_2H_2O]$ complex on HB was achieved (Fig. 3). The resulting complex was named ($[Zn(acac)_2H_2O]$-HB) [26].

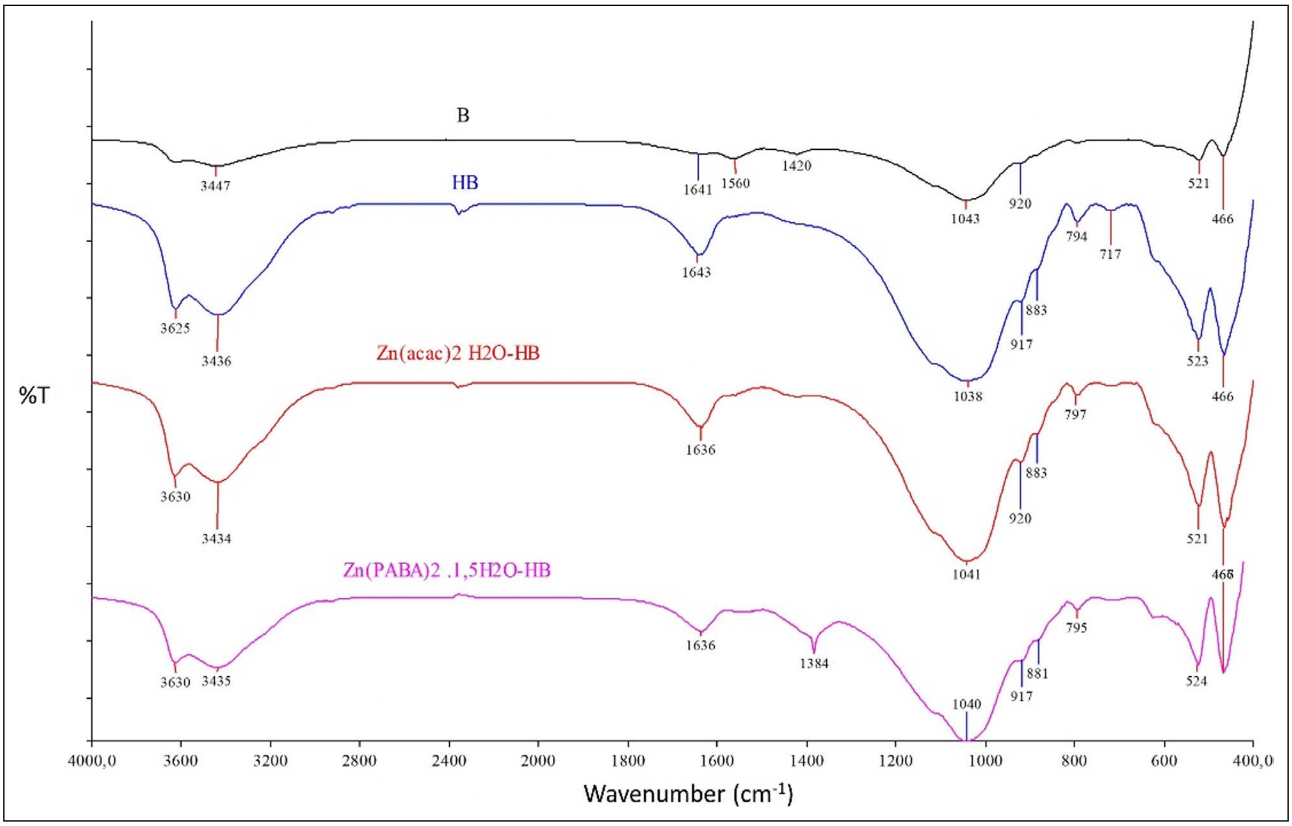

Figure 3. FTIR spectra of HB-based catalysts, including B, HB, and zinc complexes.

In the study, the transport of $[Zn(PABA)_2]1.5H_2O$ complex on HB and the transport of $[Zn(acac)_2H_2O]$ or $[Zn(PABA)_2]1.5H_2O$ complexes on HB/CTAB were also repeated according to the method described above for HB. The prepared catalysts were named as ($[Zn(PABA)_2 1.5H_2O]$-HB), ($[Zn(acac)_2H_2O]$-HB/CTAB), ($[Zn(PABA)_2 1.5H_2O]$-HB/CTAB), respectively.

2.7. Structure Analysis of Complexes

The synthesized catalysts were characterized by using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TG/DTG), surface scanning electron microscope (SEM), and Brunauer-Emmett-Teller (BET) specific surface analysis methods. XRD analyses were performed with a Rigaku-Rint 2200/PC (Ultima 3) diffractometer using Cu Kα radiation at a scanning speed of 0.4 degrees/minute in the 2θ range of 2–10°. Perkin–Elmer Spectrum BX-II Model FTIR spectrophotometer was used for FTIR analysis. KBr pellets were analyzed with a resolution of 4 cm^{-1} in the range of 4000–400 cm^{-1} as an average of 25 scans. TG/DTG analyses of the complexes were performed with Perkin Elmer Diamond TG/DTG analyzer in porcelain pans at 25–1000 °C at a heating rate of 10 °C/min under a nitrogen atmosphere. SEM analyses were performed with FEI Quanta FEG 250 SEM Scanning Electron Microscope at an acceleration voltage of 5 kV, and before the analysis, the surfaces of the complexes were coated with a gold layer. The specific surface areas of the samples were determined by the Brunauer-Emmett-Teller (BET) method after N_2 adsorption-desorption at 77 K with the Quantachrome Corporation Autosorb-6 device.

Table 1. 2θ/° and d (Å) values of catalysts

Sample	2θ/°	d/Å
B	7.04	12.55
HB	7.12	12.40
$[Zn(acac)_2H_2O]$-HB	7.80	11.32
$[Zn(PABA)_2]1.5H_2O$-HB	8.54	10.34
HB/CTAB	5.22	16.92
$[Zn(acac)_2H_2O]$-HB/CTAB	5.28	16.72
$[Zn(PABA)_2]1.5H_2O$-HB/CTAB	5.72	15.44

3. RESULTS AND DISCUSSION

3.1. XRD Analysis

XRD patterns and results of the complexes are given in Figure 4 and Table 1. With the acid modification (HB), the reflection peak (2θ/°) and basal spacing (d/Å) values of the bentonite's (001) surface slightly changed, and it was observed that the basal spacing value was increased from 12.55 Å to 16.92 Å and the value of 2θ/° shifted from 7.04 Å to 5.22 Å with the organo-clay modification (HB/CTAB). In all synthesized catalysts, it is considered that $[Zn(acac)_2H_2O]$ and $[Zn(PABA)_2]1.5H_2O$ complexes have been placed between the layers of HB and HB/CTAB.

3.2. FTIR Analysis

FTIR spectra of the catalysts are given in Figure 3 and Figure 5. The stretching and bending bands observed in the spectrum of bentonite (Fig. 3) at 3630 cm^{-1} and 883 cm^{-1}, respectively, are Al-Mg-OH vibrations, considered

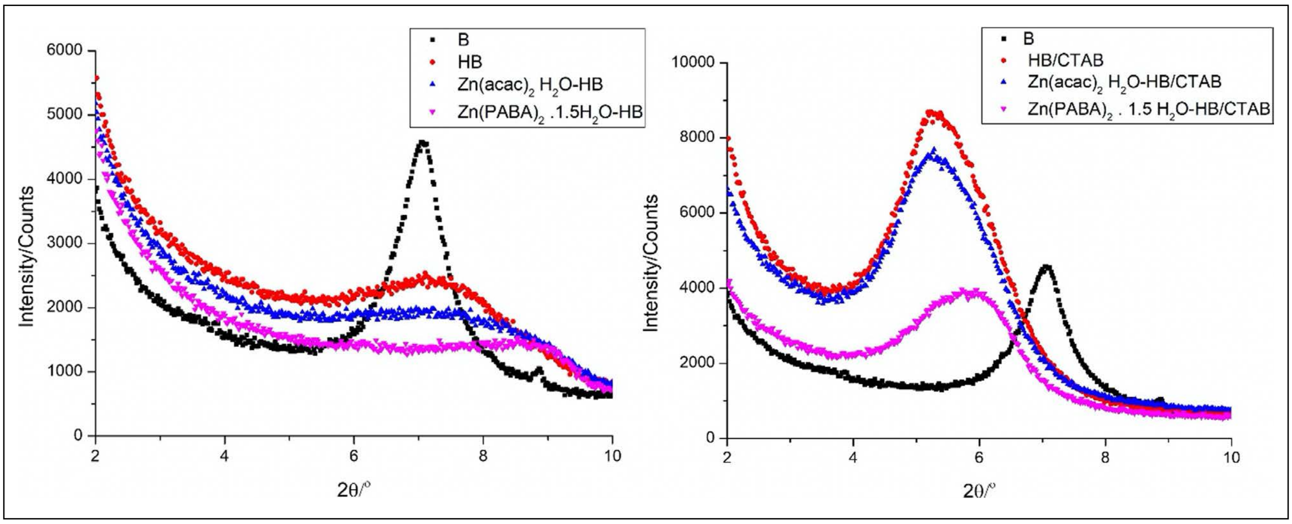

Figure 4. XRD patterns of zinc complex /modified bentonite-based catalysts.

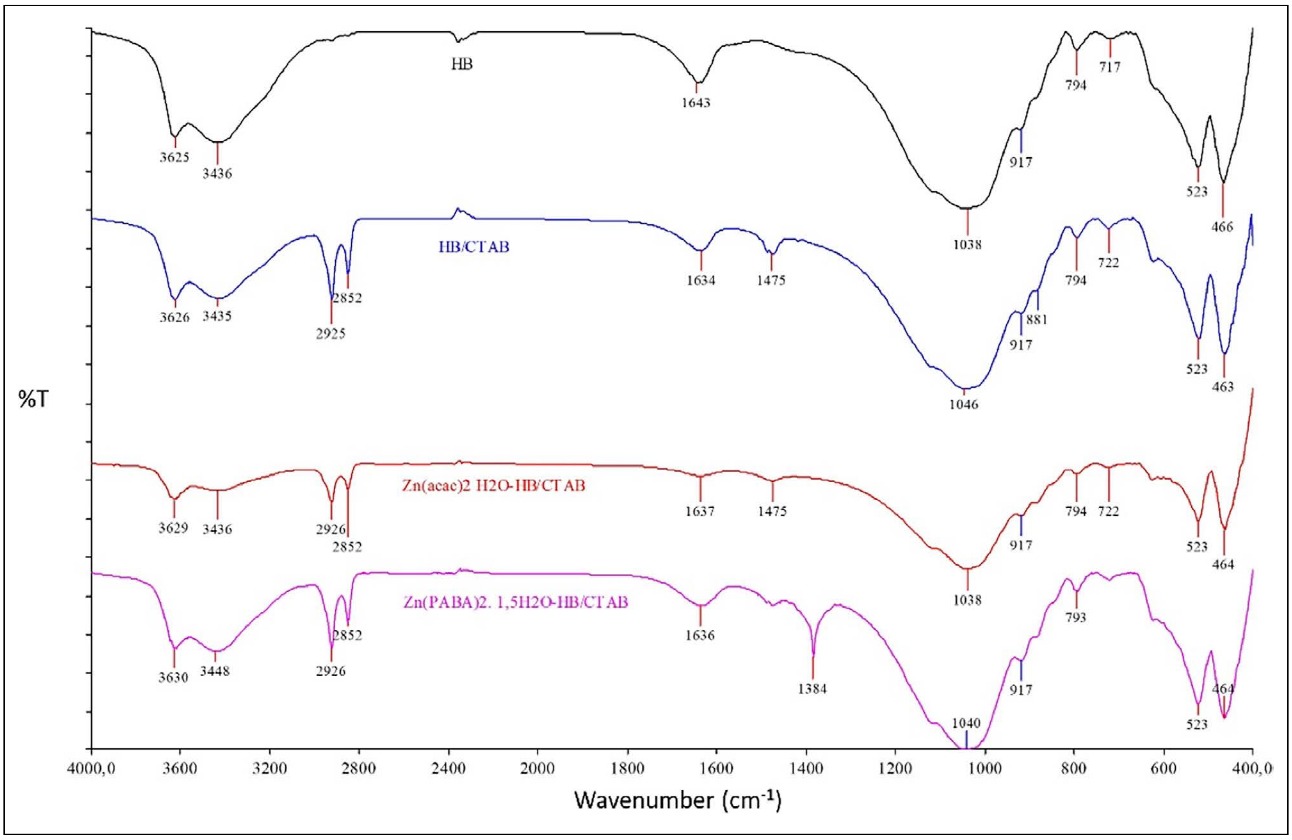

Figure 5. FTIR spectra of HB/CTAB-based catalysts, including HB, HB/CTAB, and zinc complexes.

characteristic bands of smectite minerals containing large amounts of Al in the octahedral layer. The -OH vibrations about water that exist in bentonite were observed at 3448 cm^{-1} and 1621 cm^{-1}, respectively. The bands observed in 1600–1400 cm^{-1} are attributed to Si-O-Si stretching's [27]. The bands observed at 1041 cm^{-1} and 792 cm^{-1} represent the Si-O- in the plane for the layered silicates and Si-O stretching vibrations, indicating the presence of quartz and silica, respectively [28]. The bands belong to Al-Al-OH, octahedral Si-O-Al and Si-O-Si bending vibrations were observed at 920 cm^{-1}, 521 cm^{-1} and 466 cm^{-1}, respectively [29]. When the FTIR spectra of HB and B were compared, it was seen that there were small shifts in the frequencies of the bands, and their intensities increased considerably. The bands in the range of 1600–1400 cm^{-1} observed in the spectrum of bentonite have undergone significant changes in the spectrum of HB, and some bands have not been observed at all.

The bands observed in the HB/CTAB are generally consistent with those observed in the spectrum of B and HB (Fig. 5). The -CH stretching bands of methyl and methylene groups observed at 2926 cm^{-1} and 2852 cm^{-1} in the spectrum of HB/CTAB are characteristic of organo-bentonite. It can be considered that the bands

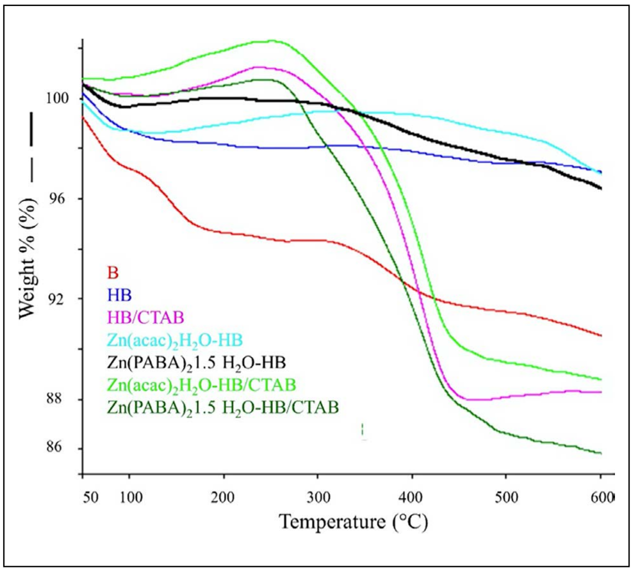

Figure 6. TG/DTG curves of HB/CTAB-based catalysts, including B, HB, HB/CTAB, and zinc complexes.

observed at 1476 cm^{-1} belong to the deformation of the methyl and methylene groups in organo-bentonite or the NH_4^+ bending vibration and that these bands overlap with each other. Moreover, the stretching vibration band of the NH_4^+ group is also considered to be covered by the -OH stretching band of water in bentonite. On the other hand, when the bands in the spectra of raw materials HB and HB/CTAB were compared with the bands in the spectra of HB and HB/CTAB-based catalysts containing [Zn(acac)$_2$H$_2$O] and [Zn(PABA)$_2$]1.5H$_2$O complexes, no significant difference in the intensities of the bands but only small shifts in their frequencies were observed.

3.3. TG/DTG Analysis

The thermal stability of all synthesized catalysts was evaluated by the obtained thermograms (Fig. 6) and thermogravimetric analysis data (Table 2).

Thermograms of HB and HB/CTAB samples agree with each other (Fig. 6). The first step of the two different degradation steps corresponds to the loss of moisture in the structures. In the second decomposition step, while the water molecule in the bentonite structure gives a decomposition of approximately 6.85%, it is seen that the amount of water due to the interlayer ion exchange decreases (0.76%) in the HB structure. The second degradation step in the thermogram of the organo-clay (HB/CTAB) corresponds to the decay of the CTAB molecule (13.17%). When the second step decompositions of [Zn(PABA)$_2$]1.5H$_2$O-HB and [Zn(acac)$_2$H$_2$O]-HB complexes were examined, the loss of 1.5 hydrate water and 1 mole of water molecule bound as a ligand were determined as 4.06% and 3.34%, respectively. In the second step of decomposition of the [Zn(acac)$_2$H$_2$O]-HB/CTAB complex, it can be seen that (Table 2), the CTAB molecule decomposes, and the water molecule remains in the structure. On the other hand, in the [Zn(PABA)$_2$]1.5H$_2$O-HB/CTAB complex, CTAB and 1.5 hydrate water decompose together.

Table 2. TG/DTG analysis data of HB/CTAB-based catalysts, including B, HB, HB/CTAB, and zinc complexes

Sample	First step Weight loss (%)	Second step Weight loss (%)
B	1.92	6.85
HB	2.28	0.76
HB/CTAB	0.56	13.17
[Zn(acac)$_2$H$_2$O]-HB	1.69	3.34
[Zn(PABA)$_2$]1.5H$_2$O-HB	0.34	4.06
[Zn(acac)$_2$H$_2$O]-HB/CTAB	1.53	13.57
[Zn(PABA)$_2$]1.5H$_2$O-HB/CTAB	0.27	15.13

Table 3. Specific surface areas of catalysts

Sample	A_{BET} (m^2/g)
B	65
HB	64
HB/CTAB	25
[Zn(acac)2H2O]-HB	67
[Zn(PABA)2]1.5H2O-HB	31
[Zn(acac)2.H2O]-HB/CTAB	34
[Zn(PABA)2]1.5H2O-HB/CTAB	26

3.4. SEM Analysis

SEM images of the catalysts are shown in Figure 7. When the surfaces of the catalysts are examined for ×5000 magnification, unlike B, HB, HB/CTAB, it has been observed that the particles in the catalysts containing the complexes are in the form of aggregates, and these aggregates are smaller and scattered in the catalysts containing the [Zn(PABA)$_2$]1.5H$_2$O complex compared to the catalysts containing [Zn(acac)$_2$H$_2$O].

3.5. BET Analysis

The results of the BET analysis of the samples are given in Figure 8 and Table 3, respectively. It was observed that the surface area of bentonite (65 m^2/g) did not change so much with the acid activation (64 m^2/g). In the organo-clay modification, the surface area decreased significantly (25 m^2/g), as expected, with the penetration of the "CTAB" molecule between the layers of HB. The surface areas of the synthesized [Zn(PABA)$_2$]1.5H$_2$O-HB and [Zn(PABA)$_2$]1.5H$_2$O-HB/CTAB catalysts decreased due to the large molecular structure of the "PABA" ligand. However, the same manner did not observe in [Zn(acac)$_2$H$_2$O]-HB catalyst due to the smaller molecular structure of the "acac" ligand, while the surface area of [Zn(acac)$_2$.H$_2$O]-HB/CTAB catalyst relatively decreased depending on "CTAB" molecule.

4. CONCLUSIONS

Clays and clay minerals are used directly as catalysts or support solids in many chemical processes. Today, natural and unprocessed clays are only exported

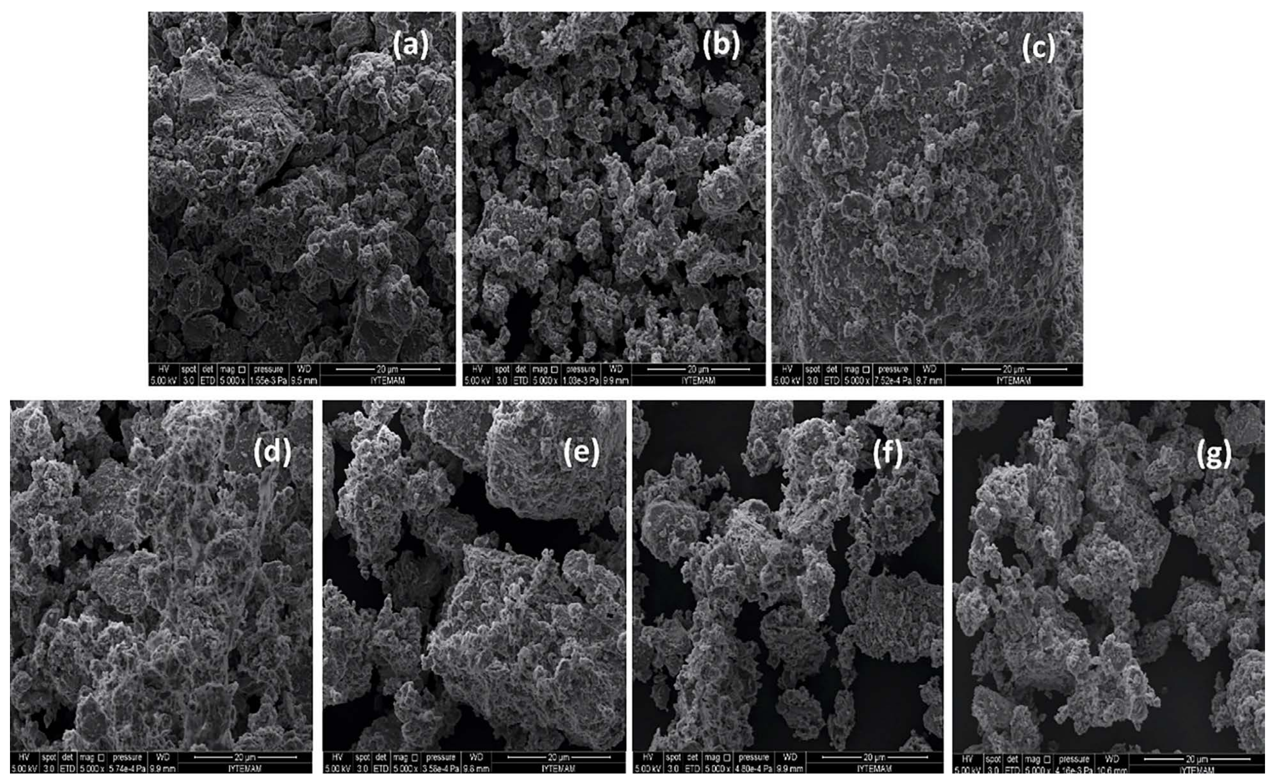

Figure 7. SEM photos of synthesized catalysts at a magnification of ×5000 **(a)** B, **(b)** HB, **(c)** HB/CTAB, **(d)** [Zn(acac)$_2$H$_2$O]-HB, **(e)** [Zn(acac)$_2$H$_2$O]-HB/CTAB, **(f)** [Zn(PABA)$_2$]1.5H$_2$O-HB, **(g)** [Zn(PABA)$_2$]1.5H$_2$O-HB/CTAB.

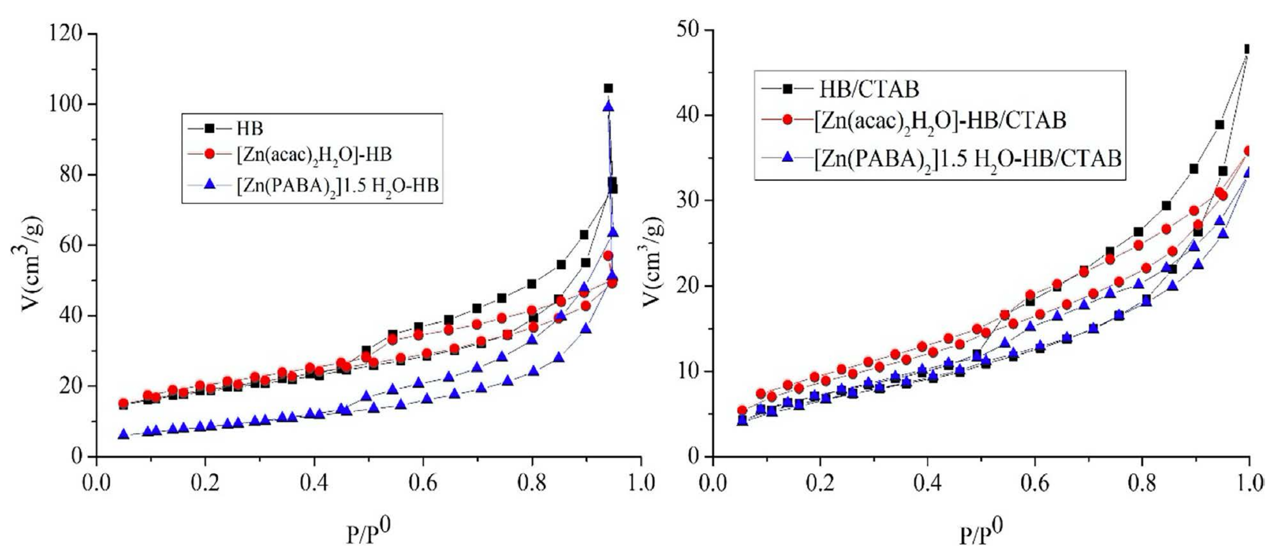

Figure 8. Multi-point BET adsorption-desorption isotherms of HB, HB/CTAB, and synthesized catalysts from N$_2$ gas phase at 77K.

at a very low cost. With this study, an environmentally friendly method has been developed, and a new area of use has been opened for bentonite-type clays, which are abundant and naturally found in our country. According to XRD results, it is considered that [Zn(acac)$_2$H$_2$O] and [Zn(PABA)$_2$]1.5H$_2$O complexes have been placed between the layers of acid-activated and organo-clays. Synthesized catalysts have been observed in aggregates, unlike their raw materials, especially in the catalysts containing the [Zn(PABA)$_2$]1.5H$_2$O complex. These aggregates are smaller and scattered due to the SEM images. The surface area of bentonite did not change so much with the acid activation, while it was significantly decreased in the organo-clay modification with the penetration of the "CTAB" molecule between the layers of acid-activated clay. As a result, the prepared bentonite-based zinc catalysts have the potential to be used as heterogeneous catalysts in various reactions.

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

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Research Article

Strengthening of RC frames with infill walls using high strength lightweight concrete panels

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ABSTRACT

This study proposed a practical seismic retrofit method for RC frames. For this purpose, a quasi-static loading was applied to 8 RC frames in finite element analysis software, Abaqus, and frames were pushed 45 mm laterally. High-strength fiber-reinforced lightweight concrete panels strengthened infill walls inside the RC frames. To apply them to the walls, epoxy binder and polyurethane binder were used, and their behavior was compared. Using panels increased the lateral load capacity of the whole frame according to the numerical analysis performed with Abaqus. In the worst case, the retrofitted frame carried approximately two times the traditionally infilled frame's capacity. In the best case, the RC frame carried 4.29 times the lateral load traditionally infilled frame. Polyurethane binder prevented the separation of panels from walls and provided a ductile behavior to frames even in large drifts.

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1. INTRODUCTION

Strong earthquakes cause significant damage to buildings, and human lives are lost. In the past, Northridge 1994, Kocaeli 1999, and Kobe 1995 earthquakes caused significant damages. Recently in Pazarcık, Kahramanmaraş, an earthquake magnitude of 7.7 caused extensive damage. Only 9 hours later, another earthquake happened in Elbistan, Kahramanmaraş, with a magnitude of 7.6. The distance between the two earthquakes' locations is only around 100km. This means the modern seismic code approach, which relies on the ductility of RC structures to save lives in earthquakes, could not guarantee the survival of buildings even if they were built according to the code provisions. Also, it was observed that RC buildings were not ductile enough to consume the earthquake energy. The lack of quality of RC buildings and the lack of quality in controlling RC buildings in Turkey were observed in past earthquakes also. A big earthquake is expected to happen in İstanbul soon.

One way to prepare for such a big earthquake is to use seismic retrofit methods to strengthen the risky building stock. However, the difficulties of applying seismic retrofit methods affect the decisions of residents or building owners. Usually, they do not want to leave the building for a long time during the retrofitting process. Seismic retrofit of an RC building is not affordable for many residents. A quick and practical seismic retrofit method is needed. A method that can be easily applied, like a simple repair inside the flat, is needed. Previously, retrofitting the infill walls inside RC frames by using CFRP strips was proposed, and a behavior model was developed for the retrofitted frames. The model was verified experimentally by using the results of two sovereign studies. Then by using this model, the analysis of a three-story RC structure (which was built in the 1970s) was performed, and it was concluded that, according to the pushover results, CFRP-based retrofitting of infill walls increased the stiffness and strength capabilities of the structure without needing any other retrofitting strategy [1]. CFRP material

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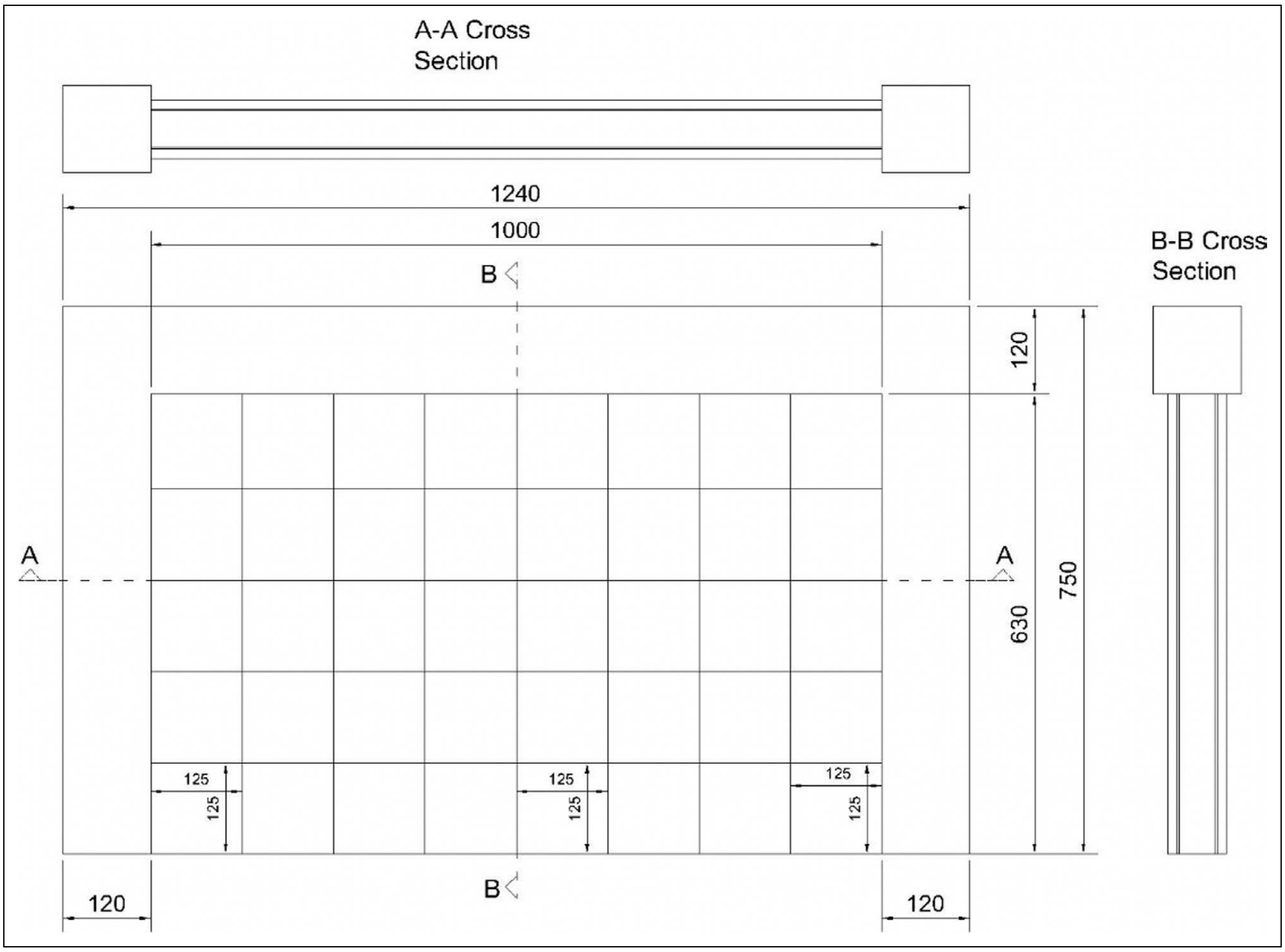

Figure 1. Proposed retrofitting of infill wall inside RC frame.

is beneficial for strengthening purposes. However, its cost limits the usage of the material widely. In another past study, a method was proposed, and experiments were performed to test the idea. The idea was to use precast RC panels to strengthen the infill walls inside the RC frames [2]. Although this was a practical idea, it can still be improved. Instead of precast RC panels, which need quality workmanship to be produced, another panel type can be used. Also, different types of binders rather than epoxy must be considered. So, in this study, an attempt was made to improve the idea, and fiber-reinforced high-strength lightweight concrete is used for panels, and the effect of polyurethane binder between wall and panel was investigated. The suggested infill wall strengthening and Abaqus modeling of the strengthened wall is seen in Figure 1 and Figure 2. In the strengthening process, panels with two different thicknesses (5 cm, 3 cm) and 0.5 m x 0.5 m dimensions were assumed for the study. The thickness of the binder between the wall and panels is assumed as 1cm. A scaled frame was used in the analysis, which is why all dimensions were divided by 4. Epoxy is compared with the highly deformable polyurethane binder. Highly deformable polyurethane binders were proposed by a past study to reduce the stress concentrations in structural elements in seismic retrofitting of masonry structures, and it was seen that such kind of binders provides some amount of ductility to structures also [3]. Abaqus analysis was made only in this

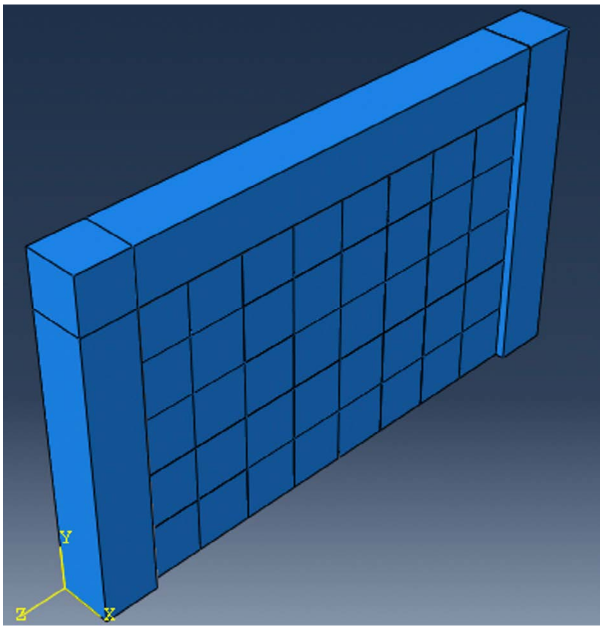

Figure 2. Demonstration of Abaqus modeling of RC frame with infill wall and attached panels.

study, and no experiments were performed for frames. However, the material properties were taken from the experimen-

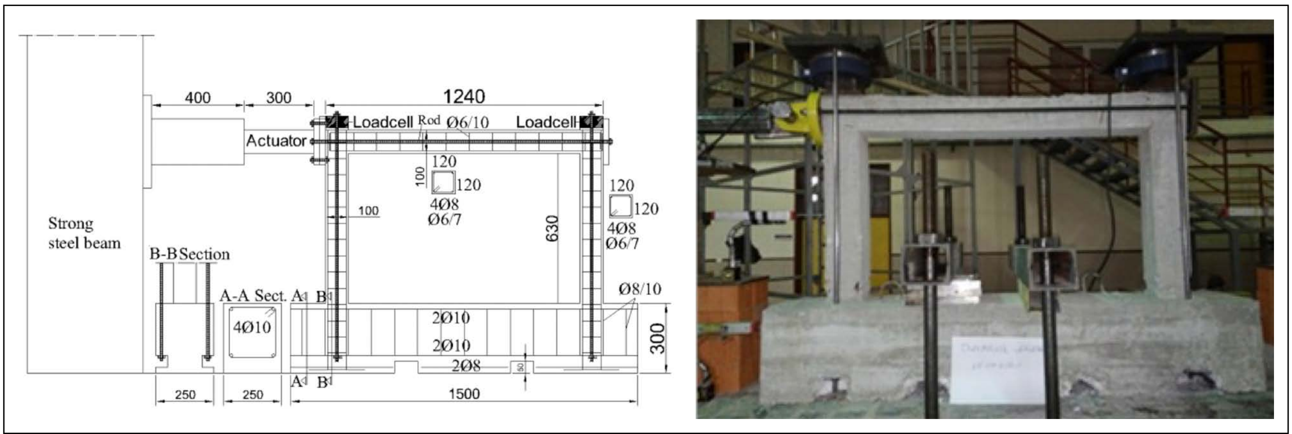

Figure 3. The scaled frame used in the past study [4].

tal work of past studies. In past studies, Abaqus is a powerful tool to perform a finite element method (FEM) analysis to obtain results very close to the experimental work [4].

2. NUMERICAL ANALYSIS

The 1/4 scaled RC frame used in a past study [4] was used again to test the effect of panels and polyurethane binder. The frame in the previous study was designed by assuming a 600kN load for each column and a 250kN lateral load. In the design of the frame, columns and beams with dimensions of 40 x 40 cm were assumed, and rebar design was performed following the 2018 Turkish earthquake code (TSC 2018). The height of the assumed frame is 3m, and the bay length of the frame is 4m. Due to the constructive reasons for the experimental part of the past study [4], the beam and columns are assumed to be in the same dimension, which leads to the lack of a robust column-weak beam mechanism. This fact is also considered in this study because it is well-known that buildings without strong column-weak beam collapse mechanisms exist in the risky building stock. After structural analysis, the following internal forces were obtained for the RC design, N_d=700KN (axial), V_d=126kN (shear), M_d=206kNm (moment) for the column, and V_d=92kN, M_d=172kNm for the beam. A 1/4 ratio scaled the frame by using a practical proper modeling approach but instead of 10 x10cm dimensions, a frame of 12 x 12cm with a height of 0.75m and width of 1m is obtained due to constructive reasons for the experimental work in the past study [4]. The RC design was re-checked for the new size, and no change was found. The stir-up length was taken as 3.5 and 3cm in columns and beam ends, respectively. According to the practical proper modeling approach, the distances between rebars were also assumed to be scaled by the scaling ratio. The details of the practical, accurate modeling approach were explained in a past study [5]. It is known that, in practice, there have been problems with concrete pouring and curing of concrete in Turkey. This study changed the properties of the frame's concrete to represent the risky building stock. Concrete's cubic compressive strength is assumed as 17.5Mpa (Abaqus use cubic specimen result). The details of the RC frame can be seen in Figure 3 [4].

Bare frames without infill walls, frames with traditional infill walls, and frames with infill walls and panels were analyzed in Abaqus. In frames with infill walls and panels, the effect of binder material is analyzed using epoxy and polyurethane-based adhesive. Eight types of frames were analyzed under vertical and horizontal loading. The first type of frame was the bare frame without any infill walls. The second type of frame included traditional infill walls only. In the third type of frame, panels were attached to the infill wall with an epoxy layer as a binder material. Also, panels surrounded by RC frames were assumed to be anchored to the frame members. In the fourth type of frame, differently than the third type, no anchorage was assumed between panels and frame members. The fifth type of frame was prepared like the third frame; however, the binder material was changed, and polyurethane (polymer) material was used. In the sixth type of frame, panels were attached to the infill wall using a polymer layer between the wall and panels, and no panel was assumed to be anchored to the frame members. In the seventh type of frame, panel thickness was decreased, and a 3 cm panel was assumed for an actual structure. Because of the scaled model in this study, a 7.5mm panel was used in the analysis, and panels surrounded by frame members were assumed to be anchored to frame members. Again, panels with 7.5mm thickness were used in the eighth frame, but differently than the seventh frame, polyurethane (polymer) binder was assumed as a binder material. In all the frames, 5 MPa axial loading was applied on columns, and 0.21 MPa loading was applied on the beam's upper surface to represent an actual loading on a fundamental structure. The base of the frame was assumed as fixed support, and the frame was pushed 45mm laterally.

In Abaqus, the analysis could be done by implicit analysis. However, explicit dynamic analysis is used. Detailed dynamic analysis in Abaqus uses the central difference method to solve the equation of motion. This method has a relatively low computational cost because the stiffness, mass, and damping matrices are not formed for every iteration, and the displacements in I+1 step are found by using the displacements in I and I-1 steps. Significant computational power is not needed. Detailed dynamic analysis can be used under some circumstances for quasi-static loading

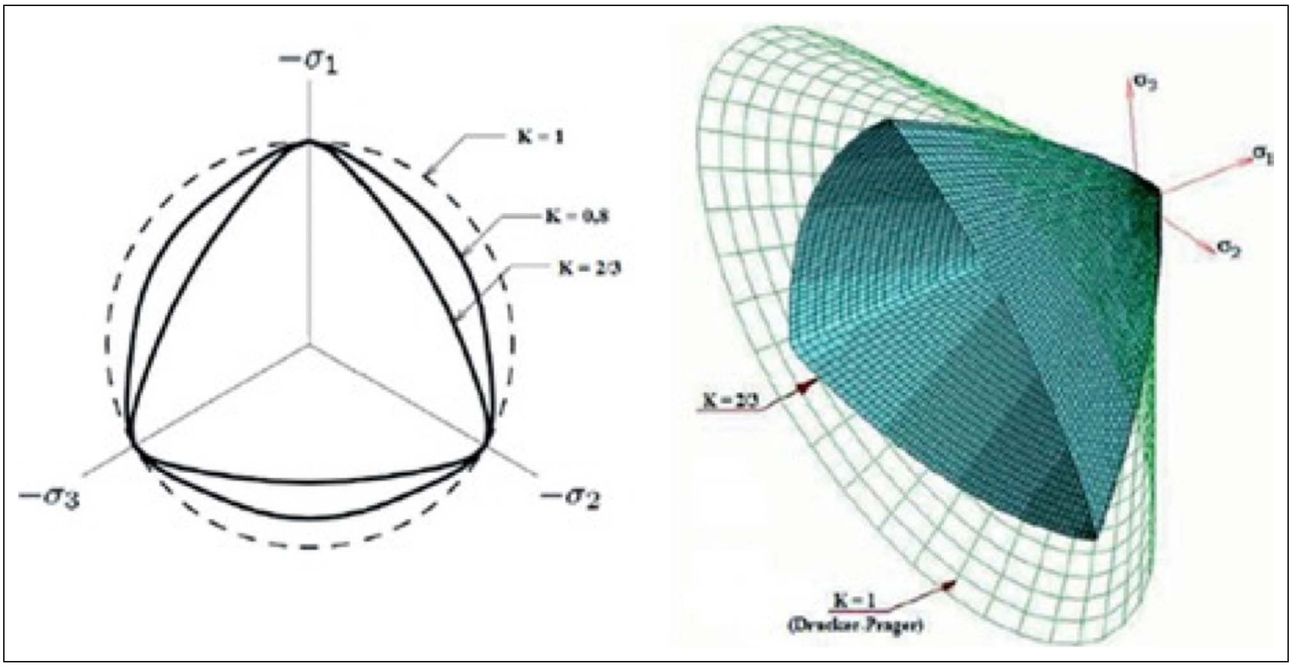

Figure 4. CDP model [6].

because a static problem is changed to an emotional one. However, if the inertial forces were kept under a specific level, the problem can be considered static. After the analysis, this can be determined by checking the kinetic energy/total internal energy ratio. The analysis is considered static loading if this value is under or equal to 0.10. The details were explained in a previous study [5].

2.1. Material Properties and Modelling

2.1.1. Modelling of Concrete

In Abaqus software, the CDP model is available to model concrete. In literature, there are several failure theories to predict if a material will undergo plastic deformations under stress. This can be done by separating the stress tensor into hydrostatic and deviatoric components. Von Misses' theory assumes that the hydrostatic part of stresses does not cause plastic deformations. However, in the Drucker-Prager model, hydrostatic part is also taken into account. The CDP model is derived from Drucker -Prager model. As seen in Figure 4, K coefficient determines the modification. In CDP model K is equal to 2/3, whereas in Drucker Prager model it's equal to 1.

The stress-strain relationship of concrete is considered as shown in Figure 5 in Abaqus [7]. In Figure 5, dc parameter indicates the effects that changes the slope of stress strain diagram of concrete in compression. The stress and inelastic strain values are used in Abaqus in CDP model. Two kinds of concrete were modelled in this study. One of them is RC frame's concrete and the other one is a kind of high strength lightweight concrete used for the panels.

The properties of the concrete for frame were taken from a previous study where a real RC bridge's concrete was modelled [8]. The compressive strength of concrete was 17.5Mpa (cubic specimen strength is used in Abaqus). Young modulus of concrete for frame was taken as

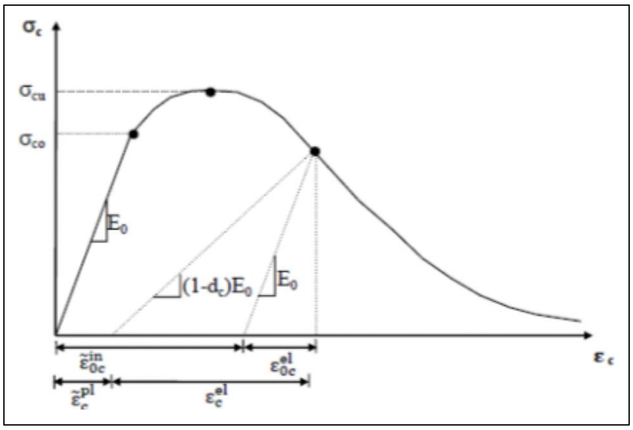

Figure 5. Stress strain relationship of concrete [7].

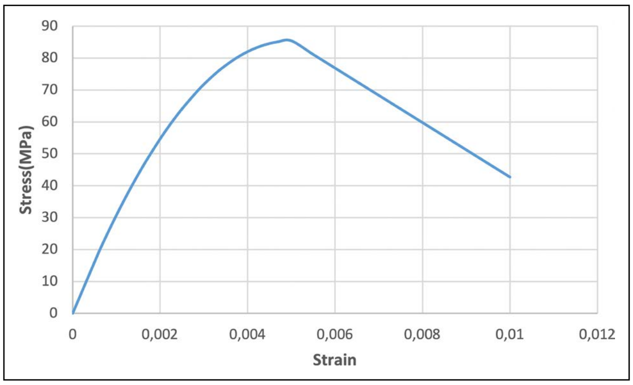

Figure 6. Stress strain relationship of high strength lightweight concrete.

19662MPa. The dilation angle, was taken as 40 degrees for concrete. Eccentricity determines the ratio of concrete's tensile strength to concrete's pressure strength and it was taken as 0.1. fbo/fco ratio was assumed as 1.14. fbo expresses the

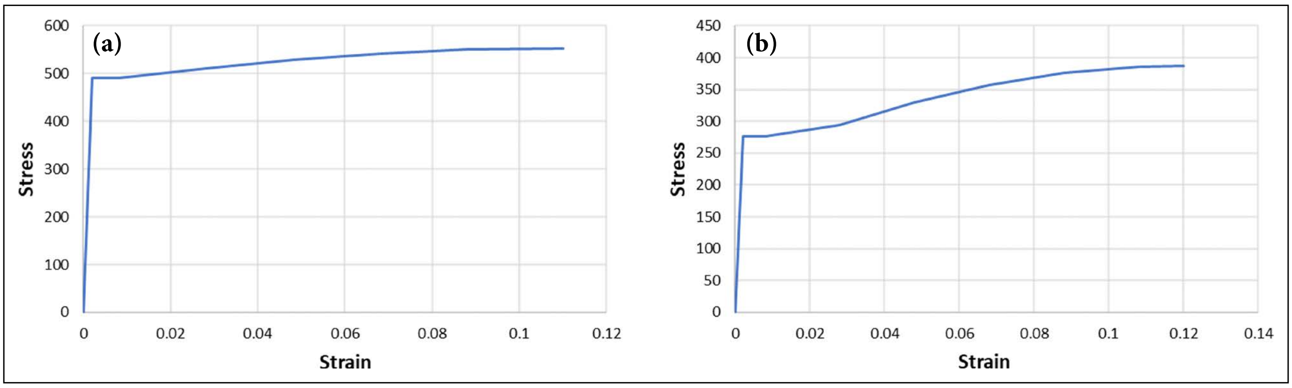

Figure 7. **(a)** Stress strain relationship of S420b; **(b)** Stress strain relationship of SAE for confinement [4].

strength of concrete in the situation when stresses acting two dimensionally. fco is the strength of concrete when it's loaded one dimensionally.

For panels, a steel fiber reinforced, high strength, lightweight concrete which is produced with expanded clay aggregates was used. The properties of the concrete were taken from a past study. In the past study, the different mixtures were used to produce lightweight concrete and the effect of steel fiber amount inside the concrete was investigated. It was seen that the compressive strength of concrete is affected by the aspect ratio of fibers and fiber volume fraction. Test results showed that a high strength lightweight concrete with a compressive strength of 85.4MPa and with a density of 1966kg/m^3 can be produced by using 520kg/m^3 cement amount and 2% fiber volume fraction. The modulus of elasticity of this concrete was calculated as 28000 MPa in the study, and an equation was developed for finding it. Poisson ratio of this concrete was taken as 0.16 [9]. Dilation angle was assumed as 38 degrees, eccentricity as 0.1, f_{bo}/f_{co} as 1.16. Based on the strength values obtained experimentally in the past study, the stress strain relationship of the concrete were determined by using Hognestad model which is widely known. The strain corresponding to maximum stress was assumed as 0,0022 in Hognestad model. In Abaqus, inelastic strains were implemented to CDP model. The stress strain relationship of high strength lightweight concrete (based on the results of a previous experimental study) with steel fibers with an amount of 156kg/m^3, can be seen in Figure 6.

2.1.2. Modelling of Steel

The properties of steel rebars were taken from a previous study. The producers' tensile test results (which were performed according to TS708) were utilized to predict the behaviour of steel. The yield strength and tensile strength of S420b, utilized as 8mm bars in RC frames, were determined to be 491MPa and 553MPa, respectively based on the experimental results of producer company. The yield strength and tensile strength of SAE 5.5 steel, which was employed as confinements in RC frames, were calculated as 277 MPa and 387 MPa, respectively. Effects of strain hardening were taken into consideration during modelling. The stress strain equations as described in section 5 of Turkish Seismic Code 2018 was taken into account as seen in Figure 7, 8. In the model described in Figure 8, f_{sy} is the yield strength, f_{su} is the ultimate strength, ε_{sy} is the yield strain, ε_{su} is the ultimate strain of the steel material and ε_{sh} describes the strain at the beginning of strain hardening. Ultimate strains for steel materials were taken as 0.11 for S420b and 0.12 for SAE steel in modelling based on the experimental results mentioned in past study [4].

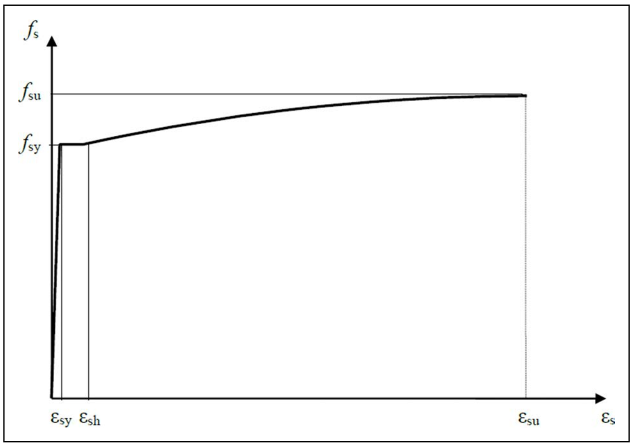

Figure 8. Stress strain relationship for nonlinear analysis of steel as described in Turkish Seismic Code 2018.

2.1.3. Modelling of Infill Wall

The infill walls inside a frame can be modelled by using micro modelling approach or macro modelling approach. For micro modelling approach, the mechanical properties of brick, mortar and brick-mortar interface must be determined separately. Macro modelling can be done by homogenization of wall by analysing a small portion of wall or using some formulas given in codes. In a previous study, traditional hollow brick's mechanical properties were determined experimentally. The average compressive strength, modulus of elasticity and tensile strength of hollow bricks was determined as 3.56MPa, 1111.49MPa, 0.9MPa respectively [4].

The mortar used to build the wall was a 1:2:9 (cement: lime: sand) mortar. In Abaqus, the CDP model was utilized to simulate the behaviour of mortar. Unlike concrete modelling, the dilation angle was determined to be 36.4 degrees. Mortar's compressive strength, young modulus, Poisson's ratio, and tensile strength were found to be, respectively, 4.97MPa, 700MPa, 0.157, and 0.257MPa experimentally [4].

Based on the results of experiments, quasi-static loading of an RC frame was performed in Abaqus by using micro modelling approach of walls and it's compared with macro modelling approach. There was an acceptable small discrepancy between the results of two analysis. However, after large lateral displacement of RC frame discrepancy increased. Compressive (Equation 1) and tensile strength (Equation 2) of infill wall in macro modelling approach was found in this study by using the following formulas based on Eurocodes [4]:

$$f_{ck}=0.4\times 3.56^{0.75}\times 5^{0.25}=1.57MPa \quad (1)$$

$$f_{ctk}=0.4\times 0.9^{0.75}\times 0.257^{0.25}=0.26MPa \quad (2)$$

And the modulus of elasticity of the infill wall was determined by the homogenization of a small portion of the wall. It's assumed as 1012.24MPa. The details of the experimental work and determination of young modulus can be seen in the previous study [4].

2.1.4. Modelling Of The Binders Between Panels and Wall

Two kinds of binders were used between panels and the wall in this study. One of them is epoxy and the other one is a two-component polyurethane binder called polymer pm. It's a two-component binder which can be applied as a fluid first but it gets hardened quickly in a few minutes after mixing with other component. When hardened it becomes a rubber like material. In a previous study, epoxy and a polyurethane binder were compared for seismic retrofit of masonry structures by using fiber reinforced polymers (FRP) [10]. In this study, Mooney Rivlin theory was proposed to model the behaviour of polyurethane binder. Mooney Rivlin theory is a theory used to model the hyper elastic materials like rubber. The stress strain curve of hyper elastic materials is not linear. Also, after large strains there is an increase in the stress. So classical theories are not used to explain the behaviour of hyper elastic materials. Instead, strain energy function which indicates the area under the stress strain curve is defined. The Mooney Rivlin theory is shown in the following equations (3–7), as indicated in a previous study [10]:

$$W^{M-R}=C_{10}\left(\Delta^2+\frac{2}{\Delta}-3\right)+C_{01}\left(\frac{1}{\Delta^2}+2\Delta-3\right) \quad (3)$$

$$S_1=\frac{F}{A_0}=\frac{dW^{M-R}}{d\Delta}=2(C_{10}\left(\Delta-\frac{1}{\Delta^2}\right)+(C_{01}\left(1-\frac{1}{\Delta^3}\right)=2\left(1-\frac{1}{\Delta^3}\right)(\Delta C_{10}+C_{01}) \quad (4)$$

$$E_0=3G_0=6(C_{10}+C_{01}) \quad (5)$$

$$G_0=2(C_{10}+C_{01}) \quad (6)$$

$$\Delta=\frac{L}{L_0}=\varepsilon+1 \quad (7)$$

Here, $W^{(M-R)}$ is the strain energy function of the hyper elastic material, S_1 is the stress, E_0 is the young modulus, G_0 is the shear modulus, ε is the strain, L is the length after loading and L_0 is the initial length. C_{10} and C_{01} are the coefficients of Mooney-Rivlin Theory. C_{01} was calculated as -0.05 and C_{10}, as 0.47, based on the experimental results of a previous study [11].

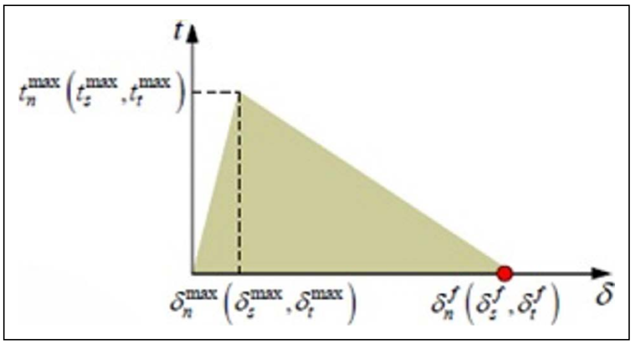

Figure 9. Traction separation laws [13].

For epoxy binder Sikadur 30 is used. The modulus of elasticity, Poisson's ratio, ultimate strain of Sikadur 30 is 1308MPa, 0.36, 3.8% respectively. The properties of this material can be seen in a previous study. Also, in that study it's said that epoxy can be assumed as a linear-elastic material [10]. So, in this study epoxy is considered as a linear elastic material which behaves linear until the stress of 49.7 MPa and after that it fails. This approach is consistent also with a previous study where epoxy's stress-strain curves are shown [12].

2.1.5. Modelling of The Interaction Between Binder and Materials

In Abaqus, one way for modelling the interaction between binders and materials is using surfaced based cohesive behaviour. Surface based cohesive behaviour allows an approach for modelling connections with negligibly small interface thickness, using the traction separation constitutive model. The surface based cohesive behaviour formulae are very similar to those used for cohesive elements with traction separation behaviour [13]. Traction separation laws are used to define the behaviour of joints in tension and shear failure modes (Fig. 9). When the assembly was first loaded, the joint performs a linear elastic behaviour, and K_n, K_s, K_t expresses the stiffness of the joint. After the peak traction value, the plastic response of joint starts. t_n^{max}, t_s^{max}, t_t^{max} are the maximum values of stress, δ_n^{max}, δ_s^{max}, δ_t^{max} are separation values at the maximum stress and, δ_n^f, δ_s^f, δ_t^f are the separations at failure as shown in Figure 9 [13].

Damage initiation was defined using the maximum nominal stress criterion. In mortar situation, the joint's tensile strength was assumed to be 0.173MPa. Cohesion coefficient was set to zero and pressure was multiplied by the coefficient of friction in the Mohr-Coulomb behaviour model (0.66). To characterize the behaviour following joint failure, the Mohr-coulomb shear sliding behaviour was defined with a coefficient of friction equal to 0.66. Thus, if the shear stress rises above the critical shear stress, the joint will slide. The experiments were used to determine the joint's fracture energies. Modified fracture energy was 0.10N/mm for failure mode of mod 1 (tension) and 0.183N/mm for failure mode of mod 2 (shear). All values were taken from experimental work of past study [4]. The formulas utilized for cohesive elements with traction separation behaviour and those used for surface-based cohesive behaviour were extremely similar, as stated in the Abaqus manual [13]. The region under the traction-separation graph, known as the fracture energy, was therefore considered to be constant. The Benzeggagh-Kenane rule was used to capture the mixed mode behaviour in Abaqus. According to results from a previous study, when there is no difference between the critical fracture energies of second and third mode shear failures, the Benzeggagh-Kenane mode is the best choice for capturing the critical mixed mode fracture energy. According to the same study's recommendations for brittle behaviour, the Benzeggagh-Kenane exponent was chosen to be 2 [14].

The fracture energies of flexible joints and mortar joints were examined in a past study, which demonstrated that polymer joints have significantly higher damage and overall fracture energy [15]. Their analysis yielded polyurethane joint fracture energies of 4.22N/mm and 10.93 N/mm for first and second mode behaviour, respectively [4, 15]. For epoxy situation, based on the experimental results of joint failure of CFRP and brick in shear mode, as stated in a previous study K_s, K_t values are assumed 15 N/mm^3 and the fracture energy in shear mode was taken as 0.103N/mm [10]. Here, for the analysis in this study, tensile rigidity is assumed as half of the shear rigidity, so, K_n value is assumed as 7.5N/mm^3.

2.1.6. Finite Elements of The Frame

C3D8R elements were used for solid elements like concrete, homogenized infill wall, mortar, polyurethane and epoxy binders in the modelling. Rebars inside the RC frame was modelled using wires which are available in Abaqus for modelling solid elements whose cross-sectional dimensions are too small compared with its length. C3D8R elements are 8 node cube elements with reduced integration. The mesh of the model with panels is seen in Figure 10.

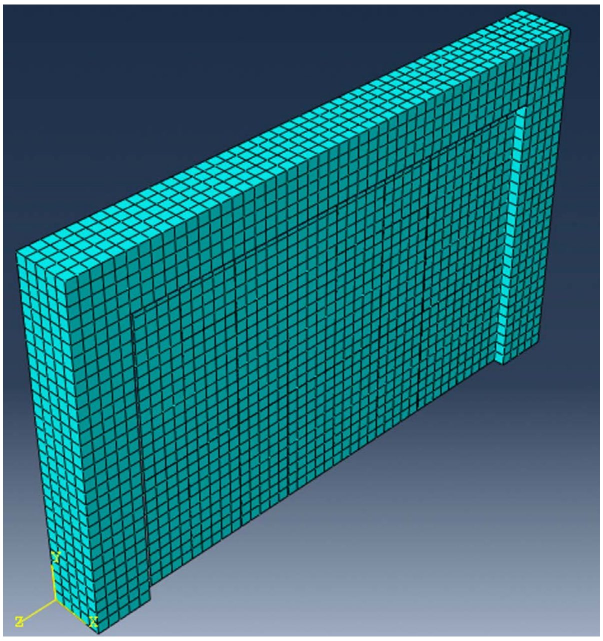

Figure 10. Mesh of model with panels.

3. RESULTS AND DISCUSSION

3.1. Load Displacement Curves

Bare frame carried maximum lateral load of 42757 N. The initial stiffness of the frame can be calculated by using the slope of the curve. For this purpose, the load of 32918 N is chosen because at this load linear part of the load-displacement curve finishes. The initial stiffness of the frame can be assumed as 11841N/mm. The traditionally infilled frame carried a total load of 50591N. This means a 18% increase if it is compared with bare frame. Normally a higher load can be expected, but the wall was considered to be constructed by putting the hollow bricks vertically to represent the weakest situation in practice. The initial stiffness of the frame can be considered as 19362N/mm if 33109N load is considered as the load where linear-elastic behaviour finishes. This means a 63% increase in initial lateral stiffness when compared with bare frame.

In the third frame in which infill walls were strengthened with 12.5mm panels, the maximum lateral load was 202559N. In this frame the panels near the RC frame were assumed to be anchored to the frame. As the binder material epoxy was used. The frame's lateral load carrying capacity was 4.73 times of bare frame and 4 times of traditionally infilled frame. The initial stiffness of frame was 61996.41 N/mm. This was 3.20 times of traditionally infilled frame. In the 4th frame to see the effect of anchorage, no panels were assumed to be anchored to RC frame. When compared with the third frame lateral load capacity slightly decreased to 188783.2 N. However, after maximum load the frame's ductility was not as high as the third frame. The anchorage provides higher energy consumption in large lateral displacements. Also, the initial stiffness of the frame decreased to 50000N/mm level.

In the fifth frame in which infill walls were strengthened with 12.5mm panels, the maximum lateral load was 147728.5N. In this frame the panels near the RC frame were assumed to be anchored to the frame. As the binder material polyurethane binder (polymer) was used. The polyurethane binder decreased the initial stiffness when compared with epoxy situation in the third frame, however the behaviour of the frame behaved in a ductile way in large deformations. The initial stiffness was 32767.22N/mm which is approximately the half of 3rd frame. Using polymer binder instead of epoxy decreased the maximum load carried by 37%. But still the lateral load capacity of the frame was nearly 3 times of the frame with traditional infill. In the sixth frame the effect of anchorage is investigated when polymer binder is used. For this purpose, no anchorage was used for any panels. The maximum lateral load carried by the frame was 116335.2N. This means 27% decrease in lateral load capacity when compared with fifth frame just because the panels were not anchored to RC frame. The initial stiffness of

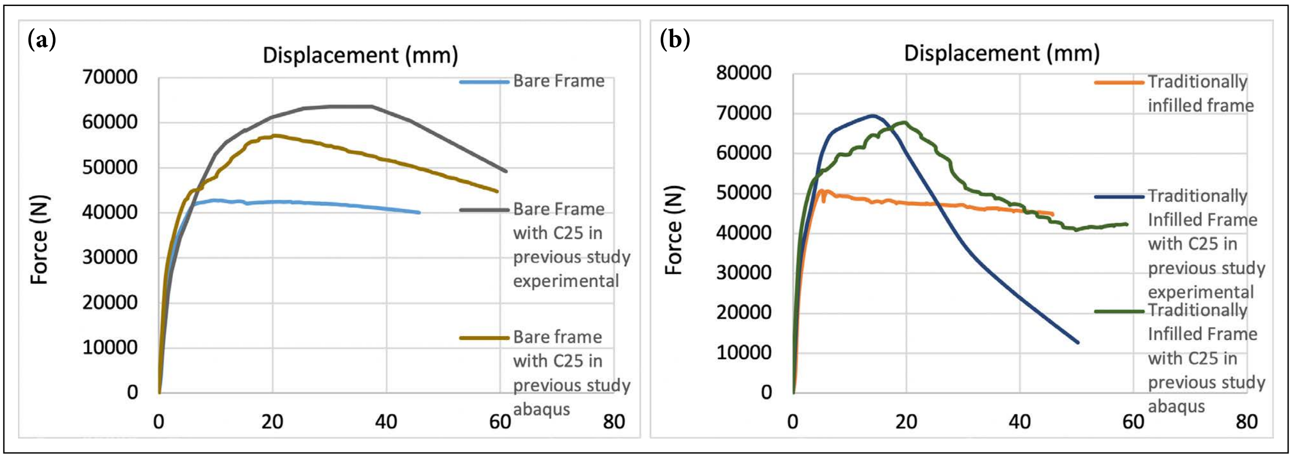

Figure 11. **(a)** Lateral load- lateral displacement curve of bare frame; **(b)** Lateral load-lateral displacement curve of traditional frame.

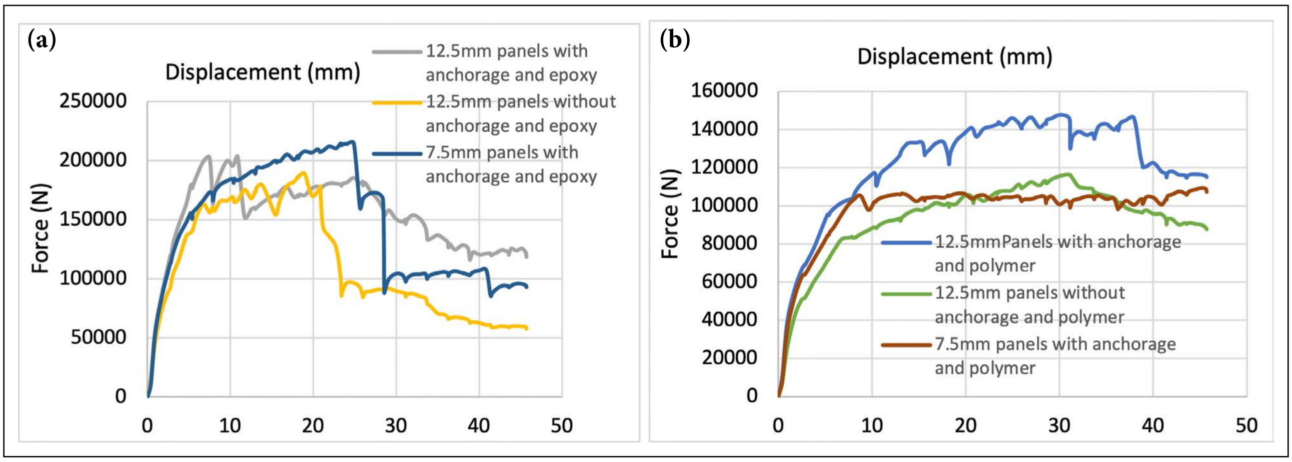

Figure 12. **(a)** Lateral load- lateral displacement curve of frames with epoxy; **(b)** Lateral load-lateral displacement curve of frames with polymer.

the frame decreased to 24473N/mm which indicates a 33% decrease with the anchorage situation. However, the lateral load capacity of the frame was 2.3 times of the frame with traditional infilled frame.

In the 7th and 8th frames, panels were changed with thinner ones to control the possibility of lowering the weight of the total frame. Because the panels were constructed with high strength fiber reinforced concrete with a compressive strength of 85.4 MPa. In these frames 7.5 mm thickness were assumed in the model for panels. In the seventh frame where epoxy binder was used the lateral load capacity was 214294.57N which is the highest of all models. The lateral load was increased by 5% when compared with thicker panels. However as seen in the graphs, by using thicker panels, after 30mm displacement more load can be carried. A sudden decrease in lateral load was observed around 30mm displacement in thinner panels situation. The initial stiffness of the frame can be assumed as same with 3rd frame. In the 8th frame thinner panels were compared when polymer binder was used. Lateral load capacity of the frame was decreased to 106080N from 147728.5N when panel thickness was decreased. But the lateral load capacity of frame was approximately 2 times more than the frame with traditional infill. The results can be seen in Figure 11, 12. According to the results, panel strengthening seems promising for seismic retrofit purposes.

3.2. Stress Analysis in The Frames

In Abaqus, after the analysis, equivalent Misses stresses can be seen. The Misses stresses in the components of the assembly (RC frame, infill wall, binder layer etc.) can be observed individually in the results section. In the bare frame analysis, in rebars, inside corner regions of the frame, equivalent misses stress reached to 550,9 MPa which indicates that rebars nearly failed. In the bay region of the beam the equivalent Misses stresses reached around 367MPa. In concrete material, Misses stresses reached 20–25 MPa in light blue regions on the corners. Then cracks and failure can be expected on those regions. Results are convenient if they are compared with the results of the bare frame with same dimensions from a previous study [4]. Results of the Misses stresses in concrete material can be seen in Figure 13. In traditionally infilled frame, in the infill wall, in the middle of the wall in a small zone the Misses stress reached 0.8Mpa. Around this zone, Misses stresses were around 0.55MPa to 0.41MPa. This indicates that they already exceeded the tensile strength of infill wall which is assumed as 0.25MPa.

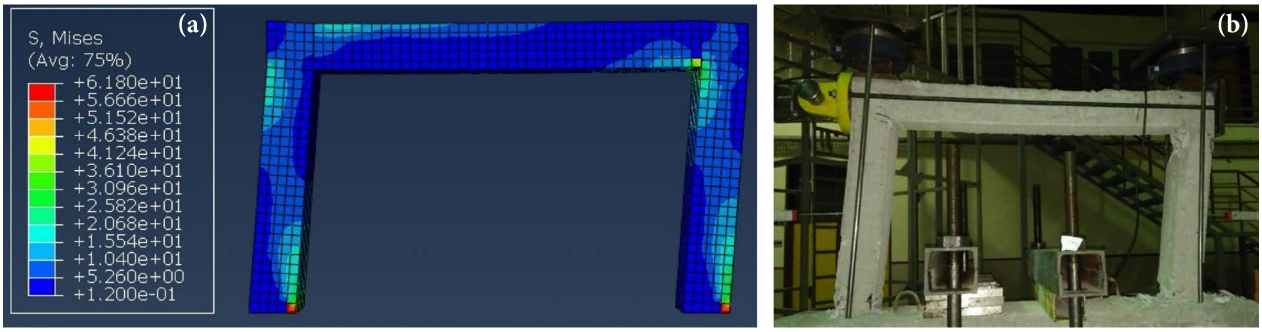

Figure 13. **(a)** Misses stress in bare frame's columns and beam; **(b)** Misses stress in bare frame in a previous experimental study[4].

In the third type of frame with anchored panels and epoxy binder, in the rebars, Misses stress distribution was slightly changed. In the corner regions of frame again the max. Misses stresses were observed as 522MPa. In the concrete of the frame, the stress distribution was changed when compared with traditionally infilled frame without panels. In some regions in the corners, it reached values like 89.2MPa, 59.5MPa, where the values are much beyond the strength of the material, which indicates that in these regions the material cracked. If the infill wall was observed separately, in the right corner at the bottom, in a big zone, equivalent Misses stresses reached 0.549MPa which is beyond the tensile strength of the material. So, demolition can be expected in that zone in infill wall. In the epoxy layer, maximum Misses stress was around 40 MPa which is smaller than the strength of the material, however it's loaded nearly up to limit. In the panels, the max Misses stress were around 5–10 MPa except some panels in the corners. The usage of high strength fiber reinforced lightweight concrete with 85.4 MPa compressive strength and 11.8MPa tensile strength prevented most of the panels to be cracked. In corner zones the stresses reached 40–50 MPa. Also, the separation of the panels from epoxy layer was observed and panels dropped.

In the fourth type of frame where panels were not anchored to RC frame, and epoxy binder was used, in the rebars, the maximum Misses stress was 542MPa in the tension zone of column ends, and around 361.8 MPa in the bay region of beam. The stress distribution was changed when compared with traditionally infilled frame without panels. In RC frame's concrete, cracking can be expected in the regions on the corners of frame 41.26 MPa Misses stress is higher than the concrete's strength. In infill wall of the frame, in bottom left corner of the loading side, and near the bottom region in the middle, Misses stresses reached 0.37–0.48MPa which exceeds the tensile strength of material. Cracks and failure were expected in the regions according to Misses stress. In the epoxy layers in backside and front side of walls, Misses stresses reached around 25 MPa which is lower than the epoxy strength. The Misses stresses in panels reached to a value of 29 MPa in the corner of frame. Panels at the top left corner especially, were separated from layer and dropped. All of the results can be seen in Figure 14–16.

In the situation of anchored panels and polymer binders (5^{th} type of frame), in rebars, maximum Misses stress was 532 MPa in tension zones of columns and beams. and around 355–400MPa values were seen in rebars at the bottom of beam. In the concrete of RC frame, cracking can be expected in the regions on the corner regions of frame where Misses stresses reached 25MPa in a wide region and reached 50.34MPa around the regions of loading. In the right corner in a small region, stresses reached even 75.48MPa. In the infill on the bottom left side especially the Misses stresses reached 0.49MPa which is higher than the tensile strength of material. In polymer material the maximum Misses stress was 1.74 MPa only in a small region, tearing off the material could be expected however deformation capacity of polymer is very high. Generally, beyond this region, in polymer material stresses does not exceed the tensile strength of the material. In especially in anchored panels at the bottom corner, high Misses stresses around 60 MPa was observed. These stresses are beyond the tensile strength of material. Therefore, cracking can be expected in these regions.

In the frame with panels without anchorage and polymer binder (6^{th} type of frame), in rebars, maximum Misses stress was 550 MPa in tension zones of columns. and around 367–412MPa values were seen in longitudinal rebars of beam and stir-ups of columns. In the concrete of RC Frame, on corner zones of frame, Misses stresses varied between around 20–40MPa. Damage happened on these corners. In the infill wall, Misses stresses reached 0.37 MPa at the top and bottom edges of wall. This stress exceeded the tensile strength of material so damage is expected on these zones. Polymer binder, when compared with epoxy counterpart, decreased the stresses in most regions of the infill especially in the frame without any panel anchored to RC frame. In the polymer layer in the infill wall, the maximum Misses stress is 1.14MPa which is smaller than the tensile strength of material (1.4MPa). In panels except regions around corners and bottom of frame, Misses stresses were around to be around 8 MPa which is smaller than the tensile strength of the material. On the corners stresses reached around 54.63 MPa. No separation between polymer layer and panels was observed. The results and Misses stress distribution can be seen in Figure 17–19.

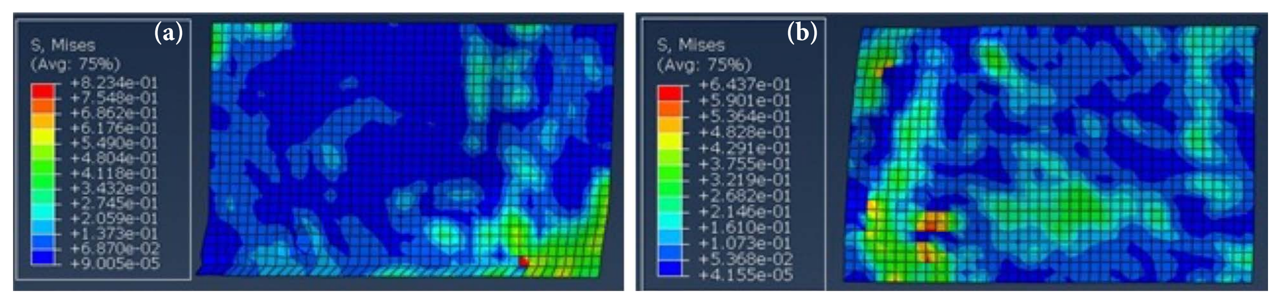

Figure 14. **(a)** Misses stress in 3rd frame's infill wall; **(b)** Misses stress in 4th frame's infill wall.

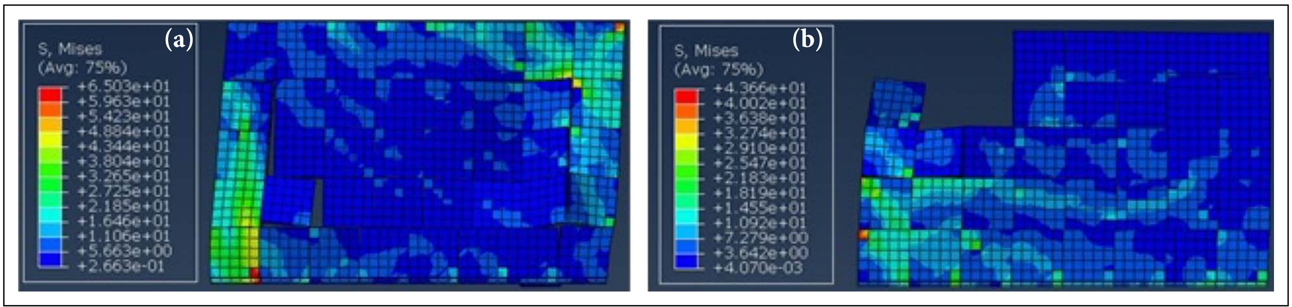

Figure 15. **(a)** Misses stress in 3rd frame's panels; **(b)** Misses stress in 4th frame's panels.

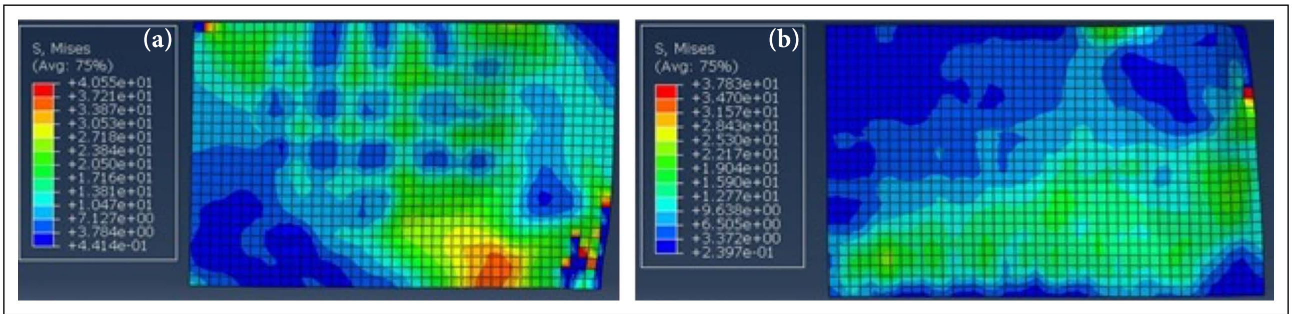

Figure 16. **(a)** Misses stress in 3rd frame's epoxy layer; **(b)** Misses stress in 4th frame's epoxy layer.

In the 7th type of frame with 7.5mm panels and epoxy, in rebars maximum Misses stress was 526MPa in column longitudinal rebars and stir-ups. In the concrete of RC frame, Misses stress distribution was similar with previous frames. In the infill wall of this frame, at the corner zones of frame, Misses stresses varied between 0.37–0.64 MPa which is higher than the tensile strength of material. But in most parts of infill wall stresses were lower than the tensile strength of 0.25MPa. Damage can be expected in corner zones. In the epoxy layer, the Misses stresses were around 31MPa in wide regions around the top and bottom corner zones. This is lower than the strength of material. Again, the separation of panels from epoxy was observed and many panels were dropped from wall. The Misses stresses were around to be around 52–59 MPa around corner regions of frame.

In the 8th type of frame with 7.5mm panels and epoxy, in rebars maximum Misses stresses reached 541MPa in column and around 360MPa in beam. In the concrete of RC frame, Misses stress distribution was similar with previous frames. In the polymer layer of the frame maximum Misses stress was slightly higher than the tensile strength of material (1.4MPa) with a value of 1.44MP only in a small zone existing vertically. In the infill wall of this frame, at the top and bottom parts of the wall, Misses stresses were around 0.4–0.5 MPa which is higher than the tensile strength of material. But in most parts of infill wall stresses were lower than the tensile strength of 0.25MPa. In panels except regions around corners and bottom of frame, Misses stresses were around to be around 6.70MPa which is smaller than the tensile strength of the material. On the corners stresses reached around 52.86 MPa mostly and no separation between polymer layer and panels was observed. All of the results can be seen in Figure 20–22.

3.3. Evaluation of Results

The method proposed here can be compared with the retrofitting method by using CFRP proposed by past studies [1, 16]. In one of these studies, experimental work was performed, and in the other one, a numerical analysis was performed with the results of experiments by proposing a behavior model for the idealization of load-displacement curves.

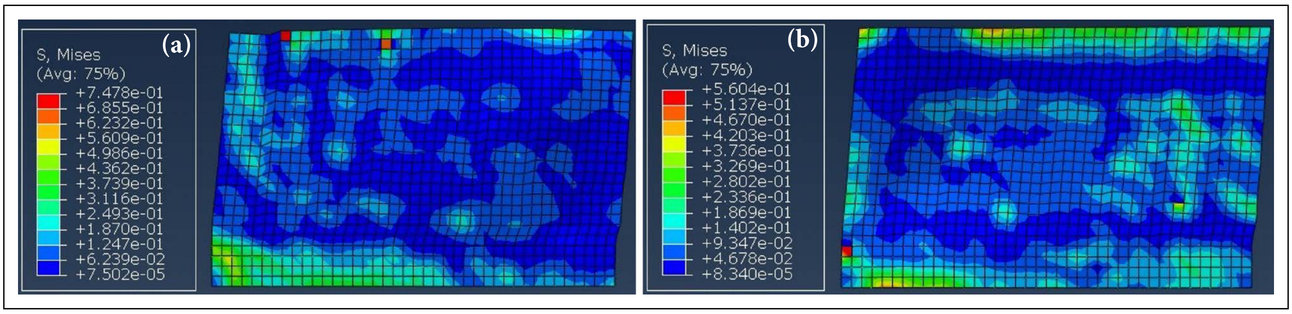

Figure 17. **(a)** Misses stress in 5th frame's infill wall; **(b)** Misses stress in 6th frame's infill wall.

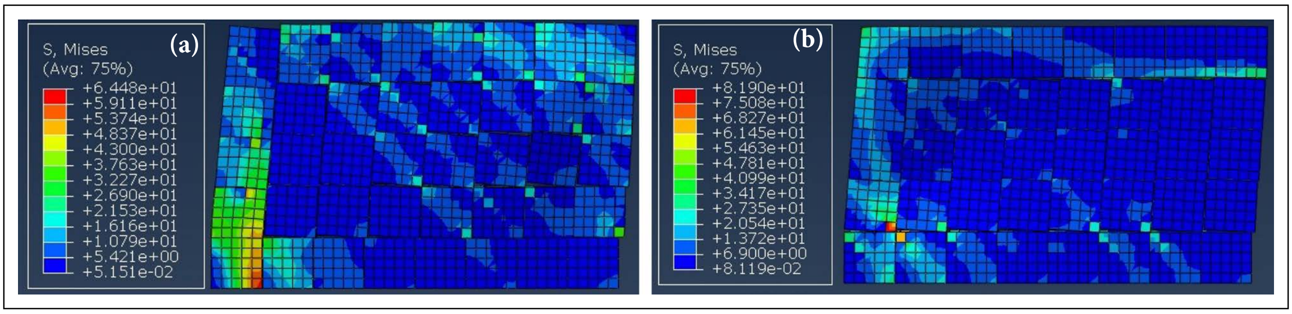

Figure 18. **(a)** Misses stress in 5th frame's panels; **(b)** Misses stress in 6th frame's panels.

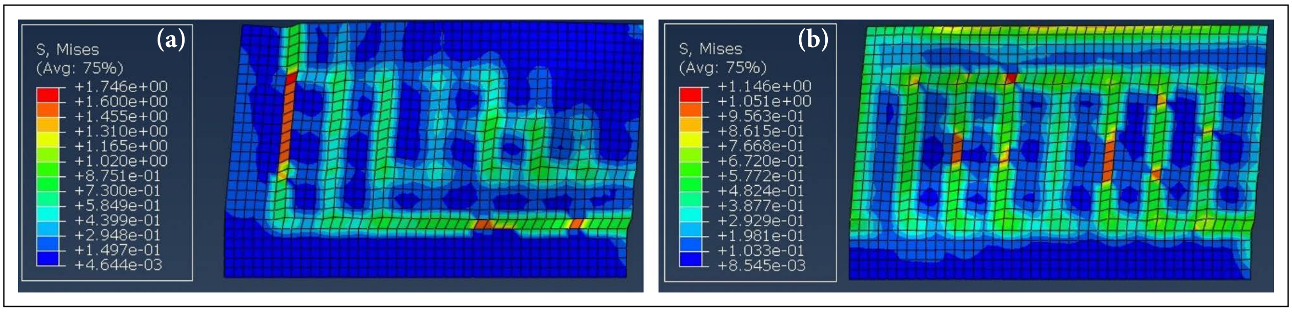

Figure 19. **(a)** Misses stress in 5th frame's polymer layer; **(b)** Misses stress in 6th frame's polymer layer.

Before comparing the behavior of retrofitted specimens, it would be reasonable to compare the results of non-retrofitted traditionally infilled RC frames with the experimental results of past studies [16]. In the past study, 1/3 scaled RC frames were constructed with a bay length of 933mm and a column height of 1 m. The column and beam dimensions were 100 x200mm, and concrete with a compressive strength of 19MPa (cylinder) was used. The steel material used for reinforcement bars had a yielding stress of 420MPa and ultimate stress of 500MPa. The features of the specimens were quite similar to the frame used here. Six different RC frame specimens were constructed. One was an ordinary specimen with traditional hollow brick infills, and the others were retrofitted using CFRP. The RC frames were subjected to cyclic loading until approximately a 4–6% drift ratio. According to the lateral load-displacement curves, RC Frame with a traditional infill wall without retrofit carried a 120 KN maximum load. If Figure 11 is observed, it can be seen that the traditionally infilled frame showed similar behavior to the frame of the past study [4]. It is worth mentioning that the result of the numerical analysis done in the previous study [4] for traditionally infilled frames is also consistent with the load-displacement graph in the other experimental study [16]. However, the concrete used in this study is a low-strength concrete different than the mentioned studies, which is why it carried 50591N maximum load, which is smaller than past studies. These results show that Abaqus's analysis of traditionally infilled frames is consistent with two past studies [4, 16].

Diamond cross-braced retrofitting with CFRP increased the lateral load capacity of RC frame by 1,69 times compared with the traditionally infilled frame in the past study [16]. However, in this study, the proposed method increased the lateral load-carrying capacity of the RC frame by 4.29 times.

Maximum story drift corresponding to maximum load was around 0.5%–1,10% in CFRP retrofitted frames in the past study [16]. This result is reasonable compared to the other study where some data is compiled from literature, and the following statement was written: "For bare infills, the average drift corresponding to the ultimate strength was in the range of 0.90–1.00 %. The aver-

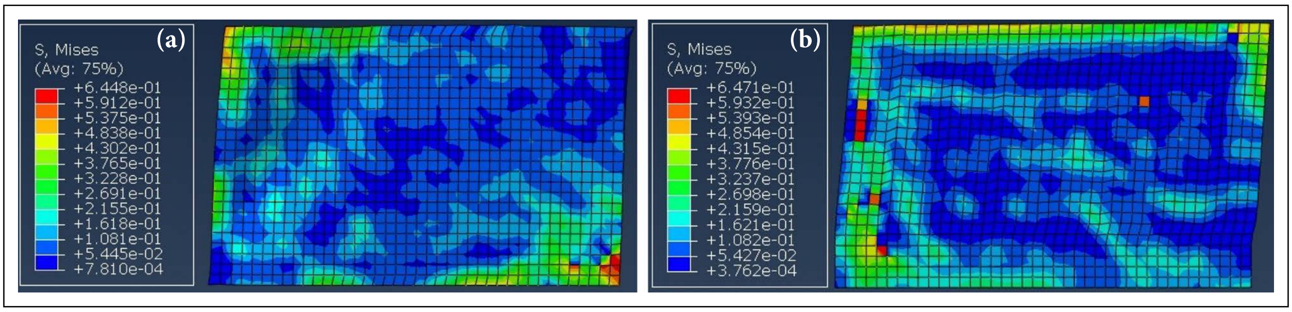

Figure 20. **(a)** Misses stress in 7th frame's infill wall; **(b)** Misses stress in 8th frame's infill wall.

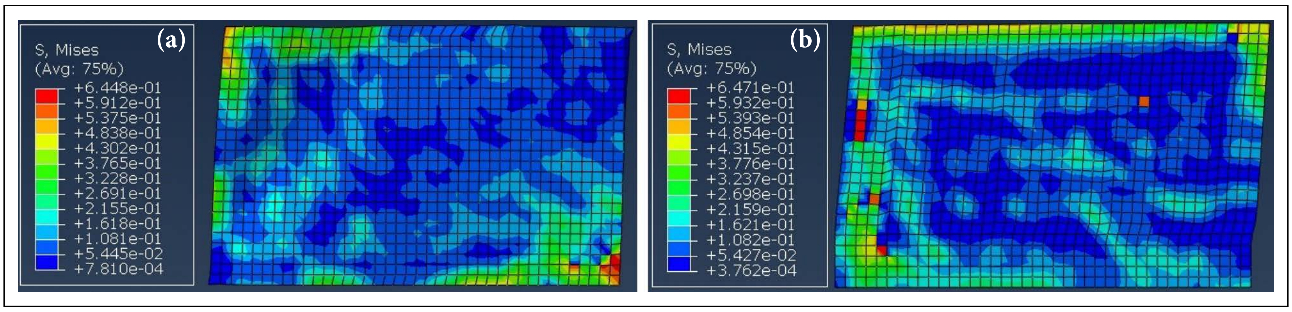

Figure 21. **(a)** Misses stress in 7th frame's panels; **(b)** Misses stress in 8th frame's panels.

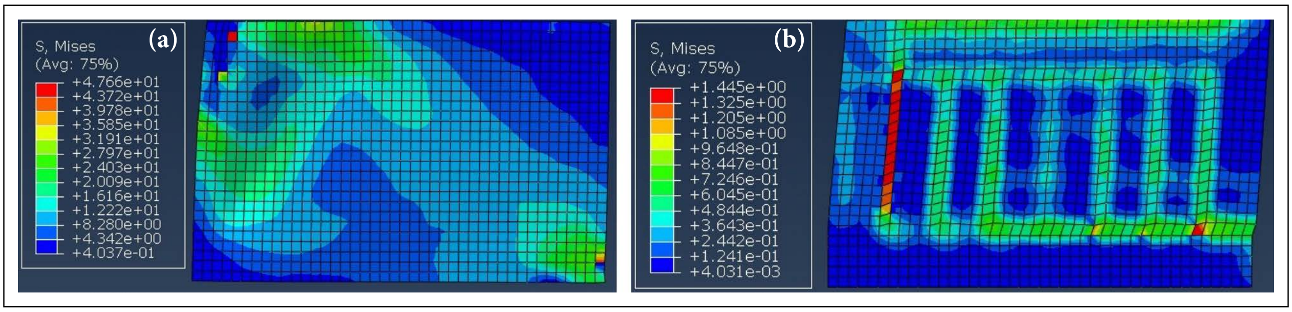

Figure 22. **(a)** Misses stress in the 7th frame's epoxy layer; **(b)** Misses stress in the 8th frame's polymer layer.

age drift corresponding to the ultimate strength for the retrofitted infills was 0.70–1.15 %. (CFRP retrofitted)" [1]. In this study, the best specimen with 7.5mm panels drift corresponding to maximum load is 0.0293%. So, the proposed retrofitting method here allowed more lateral drift corresponding to maximum load. However, a more critical aspect is that, especially in the case of a polymer, the behavior of frames in this study is very ductile until the lateral drift of 6%. The specimens continued to carry loads even in large drifts. In the past study with CFRP retrofitting, the experimental results showed that ultimate strains for retrofitted frames were around 2,5–4%.

As mentioned before, the initial stiffness of the traditionally infilled frame can be considered as 19362N/mm in this study. In the best case, the proposed retrofitting here with panels and epoxy increased the initial stiffness of the RC frame to 61996.41 N/mm. This indicates an increase of 3.20 times compared to the traditionally infilled frame. The CFRP retrofitting in the past study increased the initial stiffness of the RC frame by 3.11–4.03 times in the best cases to a range of 39800–55600N/mm [16]. The results show that the proposed retrofitting method with panels increases the initial stiffness of frames as much as CFRP retrofitting.

In the other study, for CFRP retrofitted specimens, a piecewise linear capacity curve model was proposed by using the hysteresis curves of past studies [1]. The model was validated by comparing the numerical results with experimental results of 1/3 scaled one-story frames. Also, another independent comparison was performed for two story frames. After verification of results, the model was used to analyze an existing structure. It was seen that the CFRP retrofitting increased the total base shear of the structure from 1750KN to 9600KN in the X direction and from 2300 KN to 7700KN in the Y direction. This indicates an increase of 5.48–3.34 times in the X and Y directions.

In this study, a formerly proposed idea was improved. In the formerly proposed method, precast panels were used to strengthen the frames with the help of an epoxy binder. In the previous study, where an experimental study was conducted with 1/3 scaled frames, precast panels were used for strengthening, and lateral load capacity increased from 65.5–86.6 KN to 148.9–254.7KN levels. This indicates an increase of 3.88 times in the best case [2]. According to the results of that study, when the epoxy binder was used, in the best case, the RC frame's lateral load-carrying capacity increased by 4.29 times when compared with the traditionally infilled RC frame. A polymer binder can be used to achieve ductile behavior in large lateral drifts after a 3% lateral drift ratio. In the best case with a polymer binder, the RC frame's lateral load-carrying capacity increased by three times when compared with the traditionally infilled RC frame.

4. CONCLUSION

In this study, an attempt was made for a practical seismic retrofit method. Infill walls were strengthened using high-strength lightweight concrete panels for that purpose. High-strength, lightweight concrete panels can be constructed quickly, and the production process does not need sophisticated methods. Also, different kinds of binders were used to apply panels to the infill walls. The results of load-displacement curves show that the proposed method is a prospect for the future. It allows retrofitting structures using 0.5m x 0.5m concrete panels with a 3cm thickness only, and careful crafting or leaving the house during the retrofit process is unnecessary. When epoxy binder was used, in the best case, the RC frame's lateral load-carrying capacity increased by 4.29 times compared to the traditionally infilled RC frame. Polymer binder can be used to achieve ductile behavior in large lateral drifts after 3% lateral drift ratio. In the best case with a polymer binder, the RC frame's lateral load-carrying capacity increased by three times when compared with the traditionally infilled RC frame. In the best case, the proposed retrofitting here with panels and epoxy increased the initial stiffness by 3.20 times compared to the traditionally infilled frame.

The stress analysis shows that most high-strength lightweight concrete panels could bear the stresses during loading, even in large drifts. However, for some regions, optimization can be performed in the future. With proper optimization, the behavior can be improved. The stresses in a polymer binder are lower than the strength of the material. The panels are not separated from the wall, even with a sizeable lateral drift of 6%. This is important to protect people from falling walls during strong earthquakes.

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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PEER-REVIEW

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Research Article

Cost analysis of insulation materials used to increase energy performance in buildings with Net Present Value method

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ABSTRACT

Today, producing solutions for the effective and efficient use of energy resources is among the priority areas in almost every sector. In terms of energy consumption, each solution developed in the building sector significantly reduces total energy consumption. In this study, different types of insulation materials used in walls and roofs were investigated in terms of cost-effectiveness to improve the energy performance of a building located in the 1st-degree day zone in Türkiye. Four commonly preferred insulation materials for walls and roofs were tested at specific thicknesses. The Design-Builder simulation program simulated scenarios for the specified thicknesses, and energy consumption values were determined. The initial investment costs of each alternative were calculated, and energy savings were determined. The initial investment costs and energy savings were evaluated according to the Net Present Value method, and each alternative's priority ranking was revealed. According to the results obtained, when the materials used in the study are compared, it is determined that the material with the highest net present value for the roof is glass wool, and the material with the highest net present value for the wall is stone wool.

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1. INTRODUCTION

Many factors, such as rapid population growth, global warming, the oil crisis, and environmental pollution, have made using energy resources efficiently and effectively mandatory. Energy consumption in buildings accounts for 40% of total energy consumption. For this reason, measures should be taken to use energy effectively and efficiently to reduce energy dependency and greenhouse gas emissions in the building sector [1]. In Türkiye, it is known that there is rapid growth in terms of building stock. Consequently, buildings with the highest energy consumption nationwide can potentially create significant energy savings [2].

The most significant part of the energy demand in buildings is heating and ventilation due to heating ventilation air conditioning (HVAC) [3]. Insulation of the building envelope in buildings following climatic conditions can reduce the energy required by the building to a great extent. It is stated in the literature that 76.8% of energy savings can be made in a building with only wall and roof insulation [4]. In this context, building insulation materials are necessary to reduce negative environmental impacts and energy consumption [5]. The correct selection and thickness of the insulation material according to the application area play a vital role in indoor thermal comfort conditions and energy savings [6]. Exterior insulation of the facade affects the total heat loss in a building by 50–60% [7].

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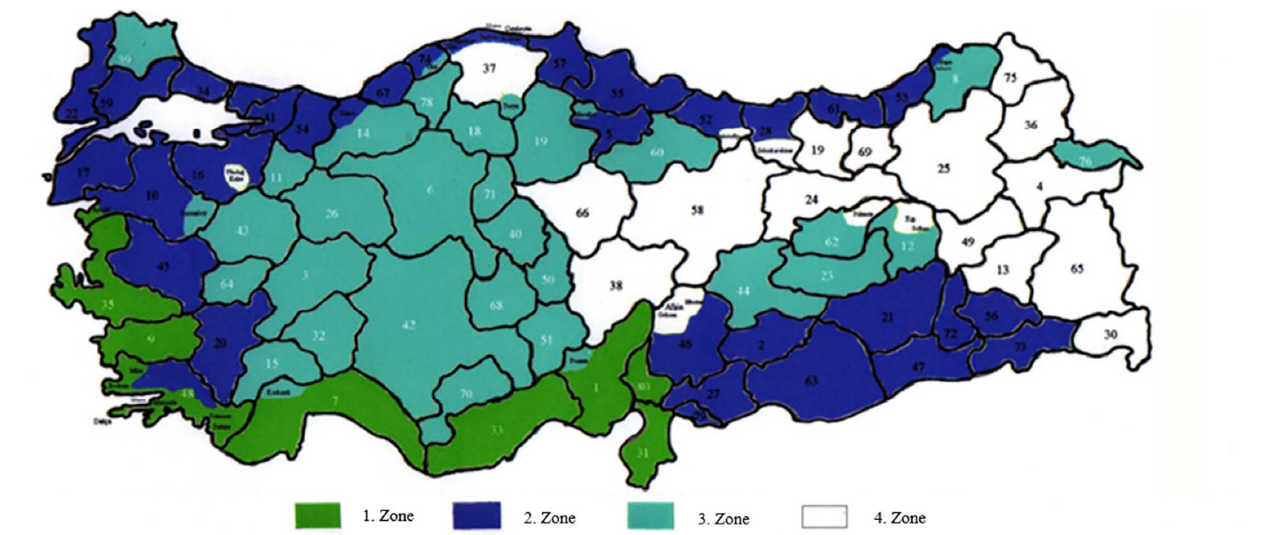

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02- ADIYAMAN	11- BİLECİK	20- DENİZLİ	29- GÜMÜŞHANE	38- KAYSERİ	47- MARDİN	56- SİİRT	65- VAN	74- BARTIN
03- AFYON	12- BİNGÖL	21- DİYARBAKIR	30- HAKKARİ	39- KIRKLARELİ	48- MUĞLA	57- SİNOP	66- YOZGAT	75- ARDAHAN
04- AĞRI	13- BİTLİS	22- EDİRNE	31- HATAY	40- KIRŞEHİR	49- MUŞ	58- SİVAS	67- ZONGULDAK	76- IĞDIR
05- AMASYA	14- BOLU	23- ELAZIĞ	32- ISPARTA	41- KOCAELİ	50- NEVŞEHİR	59- TEKİRDAĞ	68- AKSARAY	77- YALOVA
06- ANKARA	15- BURDUR	24- ERZİNCAN	33- İÇEL	42- KONYA	51- NİĞDE	60- TOKAT	69- BAYBURT	78- KARABÜK
07- ANTALYA	16- BURSA	25- ERZURUM	34- İSTANBUL	43- KÜTAHYA	52- ORDU	61- TRABZON	70- KARAMAN	79- KİLİS
08- ARTVİN	17- ÇANAKKALE	26- ESKİŞEHİR	35- İZMİR	44- MALATYA	53- RİZE	62- TUNCELİ	71- KIRIKKALE	80- OSMANİYE
09- AYDIN	18- ÇANKIRI	27- GAZİANTEP	36- KARS	45- MANİSA	54- SAKARYA	63- ŞANLIURFA	72- BATMAN	81- DÜZCE

Figure 1. Degree day zones in Türkiye [9].

In energy-efficient building design, there are many active and passive system solutions such as high insulation, heat bridge-free detail solution, mechanical ventilation, natural lighting, and utilization of renewable energy sources such as solar energy-wind energy. In line with the directives published by the European Union and those published in Türkiye, buildings must be insulated within specific limit values. However, when determining the level of insulation, it should be taken into account that the highest level of insulation is not always the cost-effective choice.

According to the Energy Performance in Buildings Directive (EPBD) 2010/31/EU, a building must be cost-effective throughout its life cycle regarding energy needs and high energy performance. Therefore, according to the directive, buildings and structural elements should be constructed using a cost-effective methodology. When constructing cost-effective high-energy performance buildings, a cost-effective assessment for one-by-one individual building elements or combinations of building elements is required. EPBD 2010 recommends the "net present value" method for cost-effective assessment [1].

It is possible to choose the most appropriate one among different alternatives with the Net Present Value method, which enables a cost-effective choice in selecting material type and thickness while insulating. This study investigates the cost-effectiveness of different insulation materials used on different surfaces at various levels.

2. ENERGY-EFFECTIVE IMPROVEMENT AND INSULATION IN BUILDINGS

With EPBD 2002 and EPBD 2010 published by the European Union, the obligation to construct high-energy performance buildings has been put forward that are insulated within certain limits and where a portion of the energy needed is met from renewable energy sources [1, 8]. In Türkiye, with the 2013 Energy Performance of Buildings Directive, it is mandatory to construct buildings that include appropriate measures for degree day zones as specified in TS 825 [9]. According to TS 825, limit thermal conductivity (U-value) values are determined separately for buildings' walls, roofs, floors, and windows to be built in Türkiye's 4-degree day zone.

Table 1. According to TS 825, U-value requirements for buildings in Türkiye according to degree day zones (1, 2, 3, 4) [9]

	U- value (W/m²K)			
	Degree day zones			
	1	2	3	4
Wall	0.7	0.6	0.5	0.4
Roof	0.45	0.4	0.3	0.25
Floor	0.7	0.6	0.45	0.4
Window	2.4	2.4	2.4	2.4

Determined U-values; are the maximum values required for buildings to have an Energy Performance Certificate (EPC). According to the degree day zones specified in TS 825, the provinces are shown in Figure 1, and the maximum U-values are shown in Table 1. In this study, the maximum U-values specified in TS 825 for the 1st-degree day zone were taken as the limit, and the selected insulation thicknesses were used.

Thermal insulation materials reduce the heat transfer between two environments at different temperatures [10]. It is possible to minimize the heat transfer between the in-

Table 2. Physical properties of the materials used

Material	Conductivity (W/mk)	Spesific heat (J/kgK)	Density (kg/m^3)
Glass wool	0.04	840	12
XPS	0.035	1400	35
Rock wool	0.033	710	100
EPS	0.04	1400	15
Aerated concrete	0.04	1004	550

door and outdoor environment by insulating the building envelope elements such as walls, roof, and floor, which are in contact with the external environment, at the appropriate level with the selection of materials according to the surface used. As a result of proper insulation, indoor comfort conditions continuity can be ensured with high energy performance.

In this study, fibrous and foamed materials were used insulation products commonly used in Türkiye. Thermal insulation materials used in the application phase of the study; glass wool, rock wool, XPS, EPS, and aerated concrete. The features sought according to the application to be used in thermal insulation materials are listed below;

- Conductivity (W/mK)
- Density (kg/m^3)
- Fire class (DIN 4102, BS 476)
- Mechanical strength (kPa)
- Water absorption
- Temperature resistance
- Vapor diffusion resistance
- Dimensional stability [11].

The physical properties of the insulation materials used in the study, such as conductivity, specific heat, and density, are shown in Table 2.

Glass wool is a mineral fiber heat insulation material. Glass wool is produced by melting raw materials such as sand, soda ash, limestone, etc., and turning them into fibers [12]. According to TS EN 13501-1, uncoated glass wool products are in class A1, which are non-combustible materials, and their thermal conductivity value is $0.031 \leq \lambda \leq 0.043$ W/mK [13]. Glass wool is a widely used insulation material in Türkiye, especially in roofs; between rafters, on rafters or slabs. Its thermal properties are similar to rock wool [6].

Stone wool is produced by melting raw materials such as basalt, dolomite, and diabase at high temperatures and turning them into fibers [10]. Stone wool products are in the A1 class, which are non-combustible materials according to TS EN 13501-1, and their thermal conductivity value is $0.033 \leq \lambda \leq 0.040$ W/mK [14]. Stone wool can be used in pitched roofs, flat roofs, ventilated walls, and wall applications.

XPS is produced by extrusion from polystyrene raw material [6]. It is a thermal insulation material in fire class E according to TS EN 13501-1. The thermal conductivity value is $0{,}031 \leq \lambda \leq 0{,}043$ W/mK. It can be used in many application areas, such as flat roofs, pitched roofs, exterior walls, and sandwich panels.

The raw material of EPS, which is widely used in the construction industry, is expandable polystyrene beads [15]. EPS can be produced as plates in different sizes according to the place and purpose of use. Its thermal conductivity value is $0.032 \leq \lambda \leq 0.040$ W/mK, and it is a thermal insulation material in fire class E according to TS EN 13501-1.

Aerated concrete is a mineral-based insulation material manufactured using raw materials such as fly ash, sand, slag, etc. It is a preferred material for its lightweight, high thermal insulation, and energy saving [16]. Thanks to the hollow structure of aerated concrete, its thermal conductivity is up to 20 times lower than regular concrete [17, 18]. According to TS EN 13501-1, the thermal conductivity value of aerated concrete in fire class A is 0.044 W/mK. It can be used as a thermal insulation material on reinforced concrete surfaces and exterior walls.

3. METHODOLOGY

This study investigates the cost-effectiveness of material type and thickness choices in the structural envelope of buildings located in the 1st degree day zone in Türkiye. Insulation materials commonly used in energy-efficient building designs are selected for roofs and walls. For the study, the following path was followed;

1. Different thicknesses of the selected insulation materials were determined according to the applied surface to remain below the limit U-values specified in TS 825 for the 1st-degree day zone. The useful life of the insulation materials was determined.
2. Therm conductivity values were calculated separately in the model created for the study, and the heating-cooling energy requirement was determined for each alternative using the Design Builder simulation program.
3. The initial investment cost per m^2 was calculated using the Construction Unit Price list for all alternatives.
4. With the energy consumption, savings, and initial investment cost data obtained, cost analyses were made using the Net Present Value method.
5. The results obtained were evaluated in terms of net present value.

3.1. Case Study

In order to determine the effect of different thicknesses of different types of materials used in building elements on energy performance in terms of cost, a study was conducted on a building assumed to be located in İzmir/Karşıyaka province in the 1st-degree day zone in Türkiye. The building, modeled using İzmir province climate data, has a floor area of 42.5 m^2. The building is used at all times of the year. There are 3.6 m^2 windows on the east-west facades and 4.6 m^2 on the north and south. The Design-Builder model of the building used in the study is shown in Figure 2.

It belongs to the model created. The material layers of the exterior wall and roof, the physical properties of the materials, and the thermal conductivity values (U-value)

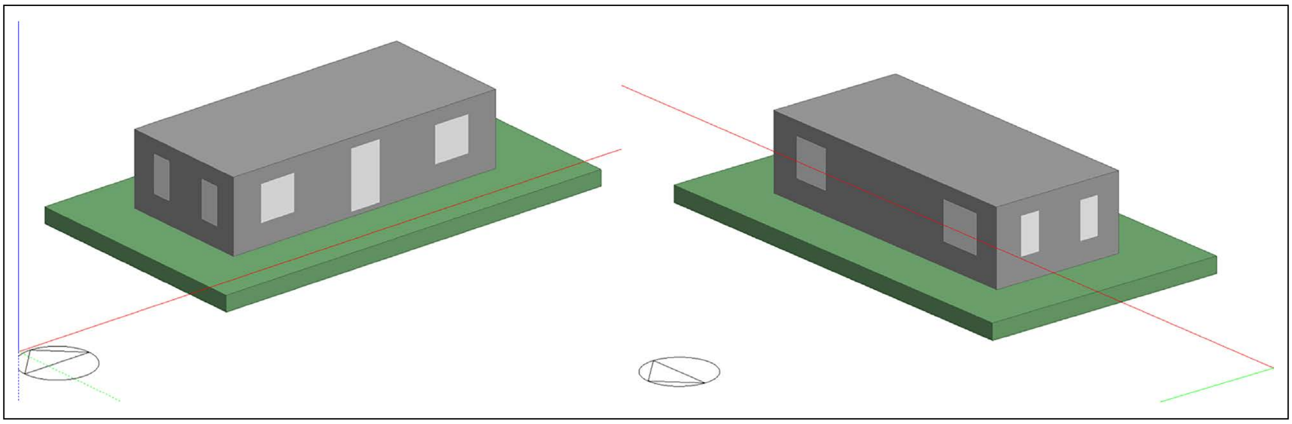

Figure 2. Design builder model of the building used in the study.

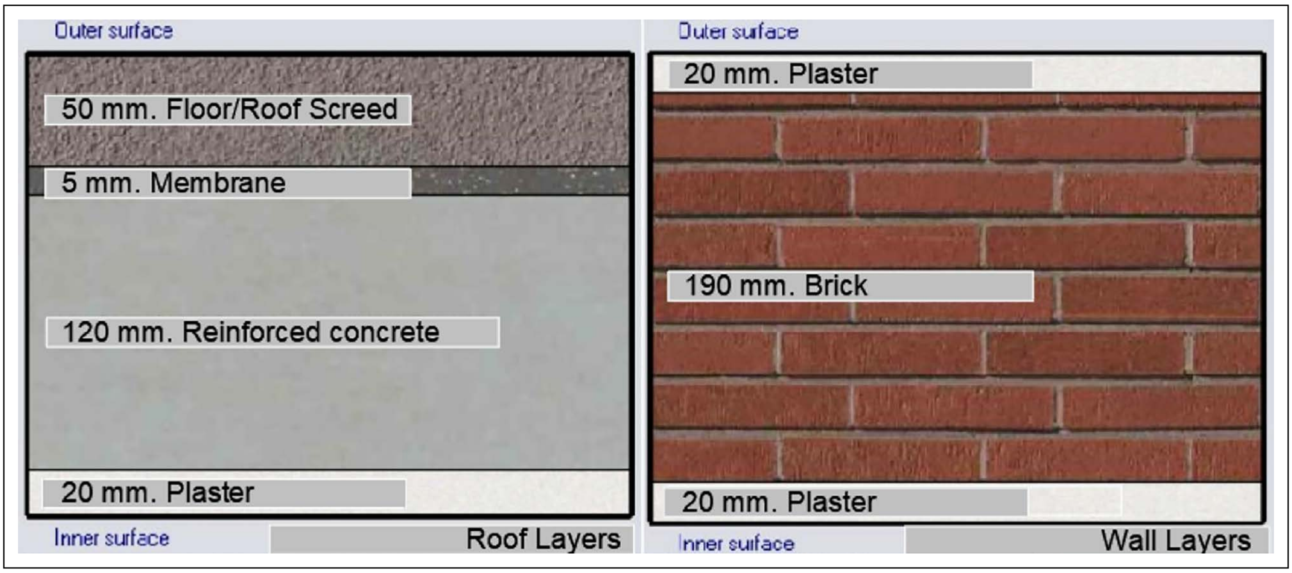

Figure 3. Layers of materials are used in the roof and walls.

obtained for each building element are shown in Table 3. In the current state of the building without insulation, the U-value of the exterior walls is 1.946 W/m²K, and the U-value of the roof is 2.8 W/m²K. Partial sections of the modeled building showing the material layers of the exterior walls and roof are shown in Figure 3.

The thermal conductivity value (U-value) of multilayer building components is calculated using the thicknesses of the individual building elements and the thermal conductivity calculation values of these elements. The formulas used in U-value calculation are shown in equations (1), (2) [9].

$$U = \frac{1}{Ri+R+Re} \quad (1)$$

$$R = \frac{d1}{\lambda h1} + \frac{d2}{\lambda h2} + \cdots + \frac{dn}{\lambda h} \quad (2)$$

U: Total thermal conductivity of the building component (W/m²K)

R: Thermal transmittance resistance (m²K/W)

Ri: Thermal conduction resistance of the inner surface (m²K/W)

Re: Thermal conduction resistance of the outer surface (m²K/W)

λ: Thermal conductivity value (W/mK)

dn: Layer thickness (m.)

3.2. Simulation

The model used in the study was simulated without insulation, and the current situation's heating, cooling and primary energy needs were determined. Since it is aimed to determine the effect of different thicknesses of different insulation materials used in the wall and roof on energy demand and savings, separate insulation scenarios were determined for the wall and roof. The materials used for wall insulation are EPS (0,04 W/mK), rock wool (0,033 W/mK), XPS (0,035 W/mK), and aerated concrete (0,044 W/mK). The materials used in insulation for the roof are glass wool (0,04 W/m²K), XPS (0,035 W/m²K), rock wool (0,033 W/mK), and EPS (0,04 W/mK).

According to TS 825 (Table 1), in buildings located in the 1st-degree day zone, the thermal conductivity value for the wall should be below 0.70 W/m²K, and the thermal conductivity value for the roof should be below 0.45 W/m²K. In this direction, all the insulation alternatives selected for the wall and roof were determined to be below the limit values specified in TS 825. Table 4 shows the type and thickness of the insulation materials used in the

Table 3. Physical properties of the exterior wall, roof, and floor materials

	Material	Width (cm)	Conductivity (W/mk)	Spesific heat (J/kgK)	Density (kg/m³)
Exterior wall	Plaster	2	0.5	1000	1300
	Brick	19	0.72	840	1920
	Plaster	2	0.5	1000	1300
U-value (W/m²K)			1.946		
Flat roof	Floor/Roof screed	5	0.41	840	1200
	Insulation membrane	0.5			
	Concrete, reinforced	12	0.41	840	1200
	Plaster	2	0.5	1000	1300
U-value (W/m²K)			2.8		
Ground floor	Granite	3	2.8	1000	2600
	Floor/Roof screed	3	1.13	1000	2000
	Insulation membrane	0.95			
	Cast concrete	10	1.13	1000	2800
U-value (W/m²K)			2.269		

scenarios for the roof and the energy requirement values obtained. Table 5 shows the type and thickness of the insulation materials used in the scenarios for the wall and the energy requirement values obtained.

3.2. Cost Analysis

For each thickness of the materials used to improve the existing building in an energy-efficient way, initial investment costs were calculated using the Construction Unit Price for 2023 [19]. The exposure numbers of the materials used in the unit price tables are for EPS 10.310.1301, for rock wool 10.310.1101, for XPS 10.310.1501, for aerated concrete 10.330.3301, for glass wool 10.310.1002. Using the initial investment costs and the annual energy savings obtained from the simulation, cost analyses were made with the Net Present Value method.

The net present value method (NPV), which is one of the dynamic methods that take into account the present value of money, is a method that determines the difference between the present value of the cash inflows of the project and the cash outflows and recommends the acceptance of the project if the difference is more significant than zero [20]. With the net present value method, the economic benefit of a project can be measured [21]. Today, the most preferred and advanced economic valuation technique is the NPV approach [22].

Since interest rates in our country do not follow a certain acceleration and show decreases and increases over the years, making precise forecasts for the future is not rational. For this reason, a discount rate for the future was determined by utilizing the discount rates of the past years. Interest rates for the last 10 years were determined for Türkiye by using the interest rate data of the Central Bank of the Republic of Türkiye. For the discount value to be used in the NPV method, the data of the last 10 years were utilized, and the discount value in the study was determined by averaging the data. Interest rates and their averages in Türkiye between 2012 and 2022 are shown in Figure 4.

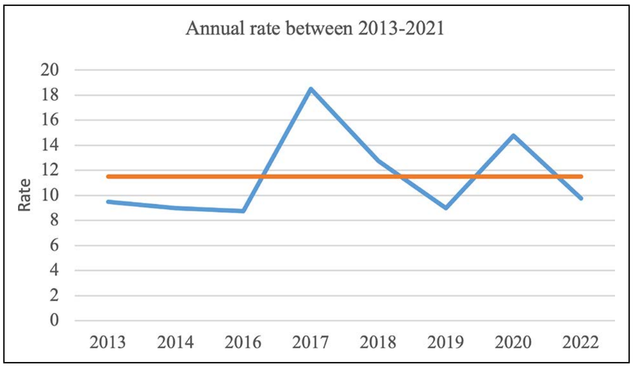

Figure 4. According to data from the Central Bank of the Republic of Türkiye, interest rates and averages for the last 10 years [23].

Based on the average obtained from historical data, the interest rate used in the study is set at 11. NPV can be calculated with the equation (3), (4), (5), (6) [20].

$$NPV=PV-C \quad (3)$$

NPV: Net present value
PV: Present value
C: Cost

$$PV = R * \frac{(1+r)^n - 1}{(1+r)^n * r} \quad (4)$$

R: Annual income
r: Rate
n: Time
C: Total cost
ci: Annual investment cost

$$C = \sum_{i=1}^{n} \frac{c_i}{(1+r)^n} \quad (5)$$

$$NPV = R * \frac{(1+r)^n - 1}{(1+r)^n * r} - \sum_{i=1}^{n} \frac{c_i}{(1+r)^n} \quad (6)$$

Table 4. Energy requirement according to simulation results obtained with different insulation materials and thicknesses for the roof

	Roof				
	No	Thickness (cm)	U-value (W/m²k)	Heating-cooling demand (kWh)	Heating-cooling saving (KWH)
	Existing	–	2.800	4092.563	
Glass wool 0.04 W/mK	1	8	0.442	2865.545	1227.018
	2	10	0.362	2827.614	1264.949
	3	12	0.306	2801.310	1291.252
	4	14	0.266	2781.846	1310.717
	5	16	0.235	2766.620	1325.943
	6	18	0.210	2754.912	1337.651
	7	20	0.190	2745.381	1347.182
	8	22	0.173	2737.292	1355.271
XPS 0.035 W/mK	9	7	0.442	2869.038	1223.525
	10	8	0.392	2845.649	1246.914
	11	10	0.32	2812.590	1279.973
	12	12	0.274	2789.659	1302.904
	13	14	0.235	2772.328	1320.235
	14	16	0.207	2759.678	1332.885
	15	18	0.185	2749.405	1343.158
	16	20	0.167	2741.183	1351.380
Rock wool 0.033 W/mK	17	7	0.419	2859.720	1232.843
	18	8	0.372	2837.987	1254.576
	19	10	0.304	2806.963	1285.600
	20	12	0.256	2784.726	1307.837
	21	14	0.222	2768.645	1323.918
	22	16	0.196	2756.697	1335.866
	23	18	0.175	2746.827	1345.736
	24	20	0.158	2738.799	1353.764
EPS 0.04 W/mK	25	8	0.442	2866.648	1225.915
	26	10	0.362	2828.990	1263.573
	27	12	0.306	2802.854	1289.709
	28	14	0.266	2783.704	1308.859
	29	16	0.235	2768.563	1324.000
	30	18	0.210	2757.161	1335.402
	31	20	0.190	2747.839	1344.724
	32	22	0.173	2739.885	1352.678

The insulation material used in this study is considered an investment, and the investment's net present value is determined. In this direction, firstly, the useful lives of the insulation materials used in the study were determined. The literature states the useful life of glass wool, XPS, and rock wool as a building lifetime. The useful life of EPS is stated as 35–50 years [24]. The manufacturer states the useful life of aerated concrete as a building's lifetime.

The useful life of buildings using concrete, masonry, iron, and steel is 50 years, according to the depreciation rates published by the Revenue Administration [25]. In line with this data, the useful life of a building is assumed to be 50 years while performing the cost analysis; calculations are made over 50 years for materials that can be used throughout the life of the building and over 35 years for EPS. The useful lives of the materials used in the study are shown in Table 6.

Net present values were calculated using the energy-saving data and initial investment costs obtained for each scenario resulting from the simulation scenarios. Table 7 shows the net present values obtained with the materials used for roof insulation and different thicknesses within the scope of the study. Table 8 shows the net present values obtained with the materials used for wall insulation and their different thicknesses.

For energy-efficient retrofitting of buildings, the effect of different insulation materials used in walls and

Table 5. Energy requirement according to simulation results obtained with different insulation materials and thicknesses for the wall

	Wall				
	No	Thickness (cm)	U-value (W/m²k)	Heating-cooling demand (kWh)	Heating-cooling saving (KWH)
	Existing	–	1.946	4092.563	
EPS 0.04 W/mK	33	4	0.646	3305.751	786.812
	34	6	0.488	3224.043	868.520
	35	8	0.392	3173.525	919.038
	36	10	0.328	3137.964	954.599
	37	12	0.282	3110.538	982.025
	38	14	0.247	3088.519	1004.044
	39	16	0.22	3070.033	1022.53
	40	18	0.198	3054.515	1038.048
Rock wool 0.033 W/mK	41	3	0.686	3334.056	758.507
	42	5	0.485	3233.944	858.619
	43	7	0.375	3180.662	911.901
	44	9	0.305	3145.863	946.700
	45	11	0.258	3120.545	972.018
	46	13	0.223	3100.249	992.314
	47	15	0.196	3083.075	1009.488
	48	17	0.175	3068.044	1024.519
XPS 0.035 W/mK	49	3	0.712	3344.911	747.652
	50	5	0.506	3240.028	852.535
	51	7	0.392	3183.578	908.985
	52	9	0.321	3146.595	945.968
	53	11	0.271	3119.16	973.403
	54	13	0.235	3098.015	994.548
	55	15	0.207	3080.535	1012.028
	56	17	0.185	3065.308	1027.255
Aerated concrete 0.044 W/mK	57	4	0.686	3378.853	713.710
	58	6	0.523	3309.339	783.224
	59	8	0.423	3260.313	832.25
	60	10	0.355	3220.902	871.661
	61	12	0.305	3188.289	904.274
	62	14	0.268	3163.018	929.545
	63	16	0.239	3142.315	950.248
	64	18	0.216	3124.414	968.149
	65	20	0.196	3127.945	964.618

roofs on energy savings and the net present value of each case was investigated. The graph showing the NPV-U-value relationship for retrofit scenarios with glass wool, XPS, rock wool, and EPS materials used in the roof is shown in Figure 5.

In the scenario alternatives for the roof, when different insulation materials are evaluated in terms of net present value;

- The NPV values of all materials evaluated in roof insulation investments were positive. NPV values vary between 19.562 TL and 6.557 TL.
- Roof insulation with glass wool has the highest NPV value at all levels. The NPV value is 19,562 TL for the roof scenario with 0.042 W/m² K U-value using glass wool and 17,286 TL for the roof scenario with 0.173 W/m² K U-value.

Table 6. Useful lives of the materials used in the case [24]

Material	Service life
Glass wool	Building lifetime
XPS	Building lifetime
Rock wool	Building lifetime
EPS	35–50
Aerated concrete	Building lifetime

Table 7. Insulation materials used for roof and cost analysis according to different thicknesses

	Roof					
	No	**U-value (W/m²k)**	**Heating-cooling saving (TL)**	**Investment amount (m²/TL)**	**Investment amount (TL)**	**NPV**
Glass wool 0.04 W/mK	1	0.442	2454.036	53.600	2626.400	19562.993
	2	0.362	2529.898	67.000	3283.000	19592.334
	3	0.306	2582.505	80.400	3939.600	19411.412
	4	0.266	2621.435	93.800	4596.200	19106.813
	5	0.235	2651.886	107.200	5252.800	18725.551
	6	0.210	2675.303	120.600	5909.400	18280.686
	7	0.190	2694.364	134.000	6566.000	17796.441
	8	0.173	2710.543	147.400	7222.600	17286.128
XPS 0.035 W/mK	9	0.442	2447.050	126.000	6174.000	15952.230
	10	0.392	2493.827	144.000	7056.000	15493.187
	11	0.320	2559.946	180.000	8820.000	14327.030
	12	0.274	2605.808	216.000	10584.000	12977.716
	13	0.235	2640.470	252.000	12348.000	11527.131
	14	0.207	2665.771	288.000	14112.000	9991.8978
	15	0.185	2686.316	324.000	15876.000	8413.6711
	16	0.167	2702.759	360.000	17640.000	6798.349
Rock wool 0.033 W/mK	17	0.419	2465.686	128.100	6276.900	16017.834
	18	0.372	2509.151	146.400	7173.600	15514.145
	19	0.304	2571.200	183.000	8967.000	14281.790
	20	0.256	2615.673	219.600	10760.400	12890.517
	21	0.222	2647.835	256.200	12553.800	11387.928
	22	0.196	2671.732	292.800	14347.200	9810.600
	23	0.175	2691.471	329.400	16140.600	8195.682
	24	0.158	2707.528	366.000	17934.000	6547.470
EPS 0.04 W/mK	25	0.442	2451.830	74.800	3665.200	18045.758
	26	0.362	2527.147	93.500	4581.500	17796.385
	27	0.306	2579.417	112.200	5497.800	17342.939
	28	0.266	2617.7188	130.900	6414.100	16765.800
	29	0.235	2648.000	149.600	7330.400	16117.640
	30	0.210	2670.804	168.300	8246.700	15403.268
	31	0.190	2689.447	187.000	9163.000	14652.057
	32	0.173	2705.355	205.700	10079.300	13876.620

- When evaluated in terms of NPV value, glass wool NPV values are followed by EPS. In the EPS scenarios, the highest NPV value is 18,045 TL with a U-value of 0442 W/m² K, while the lowest NPV value is 13,876 TL.
- Regarding NPV in roof insulation, similar values were reached in scenarios using XPS and rock wool. The highest NPV value in the scenarios using XPS and rock wool is 16,017 TL in the roof, where 0.419 W/m² K U-value is reached with rock wool. The lowest NPV is 6547 TL in the roof, where 0.158 W/m² K U-value is reached with rock wool.

The graph showing the NPV-U-value relationship for the retrofit scenarios with XPS, aerated concrete, rock wool, and EPS materials used in the wall is shown in Figure 6.

- The highest NPV value in wall insulation was obtained using rock wool material. It was found that NPV values fell below 0 in some scenarios.
- The scenario with a U value of 0.686 W/m² K in wall insulation made with rock wool has the highest NPV with 10,225 TL. In wall insulation with XPS, the scenario with 0.185 W/m² K U value is the lowest NPV with -10,128 TL.
- Following the rock wool material, the highest NPV values were calculated in the alternatives using aerated concrete.
- In wall insulations made with XPS and EPS, it was observed that the NPV was negative in scenarios with U-values between 0.282–0.185 W/m² K.
- For scenarios with U values below 0.175 W/m² K for rock wool and below 0.196 W/m² K for aerated concrete, the NPV was negative.

Table 8. Insulation materials used for the wall and cost analysis according to different thicknesses

	Wall					
	No	U-value (W/m^2k)	Heating-cooling saving (TL)	Investment amount (m^2/TL)	Investment amount (TL)	NPV
EPS 0.04 W/mK	33	0.646	1573.624	65.400	5969.189	7965.252
	34	0.488	1737.040	98.100	8953.783	6427.706
	35	0.392	1838.076	130.800	11938.380	4337.785
	36	0.328	1909.198	163.500	14922.970	1982.976
	37	0.282	1964.050	196.200	17907.570	-515.904
	38	0.247	2008.088	228.900	20892.160	-3110.540
	39	0.22	2045.060	261.600	23876.760	-5767.750
	40	0.198	2076.096	294.300	26861.350	-8477.520
Rock wool 0.033 W/mK	41	0.686	1517.014	38.250	3491.154	10225.690
	42	0.485	1717.238	63.750	5818.590	9708.676
	43	0.375	1823.802	89.250	8146.026	8344.792
	44	0.305	1893.400	114.750	10473.460	6646.661
	45	0.258	1944.036	140.250	12800.900	4777.076
	46	0.223	1984.628	165.750	15128.330	2816.672
	47	0.196	2018.976	191.250	17455.770	799.811
	48	0.175	2049.038	216.750	19783.210	-1255.800
XPS 0.035 W/mK	49	0.712	1495.304	55.500	5065.596	8454.943
	50	0.506	1705.070	92.500	8442.660	6974.583
	51	0.392	1817.970	129.500	11819.720	4618.361
	52	0.321	1891.936	166.500	15196.790	1910.097
	53	0.271	1946.806	203.500	18573.850	-970.832
	54	0.235	1989.096	240.500	21950.920	-3965.510
	55	0.207	2024.056	277.500	25327.980	-7026.470
	56	0.185	2054.510	314.500	28705.040	-10128.200
Aerated concrete 0.044 W/mK	57	0.686	1427.420	40.800	3723.898	9182.834
	58	0.523	1566.448	61.200	5585.846	8577.976
	59	0.423	1664.500	81.600	7447.795	7602.614
	60	0.355	1743.322	102.000	9309.744	6453.374
	61	0.305	1808.548	122.400	11171.690	5181.198
	62	0.268	1859.090	142.800	13033.640	3776.250
	63	0.239	1900.496	163.200	14895.590	2288.694
	64	0.216	1936.298	183.600	16757.540	750.467
	65	0.196	1929.236	204.000	18619.490	-1175.340

4. CONCLUSION

High insulation is one of the most widely used solutions for the effective and efficient use of energy in buildings and to improve building energy performance. The Energy Performance of Buildings Directive states that a cost-effective building design is as important as its energy performance. For this reason, this study investigates the cost-effectiveness of a building located in Türkiye's 1-degree-day climate zone depending on the choice of insulation materials.

In this study, to determine the cost-effectiveness of increasing the energy performance of buildings by insulation, different thicknesses of different insulation materials for walls and roofs were applied to a model. The NPV for each alternative was calculated using the energy savings and initial investment cost data obtained. As a result, it can be said that the NPV values of all material alternatives used in the study for the roof are positive. In other words, regarding NPV, roof insulation is positive in all types. It was found that the NPV value was negative at high thicknesses of the materials used for the wall. In both building components, decreasing insulation material thickness increased the NPV value.

In line with the boundaries of this study, the model is in place in the 1st-degree day climate zone. For a building located in the 1st-degree day zone, in terms of the NPV value of the materials used in the study; among the material alternatives used in the study, it was determined that

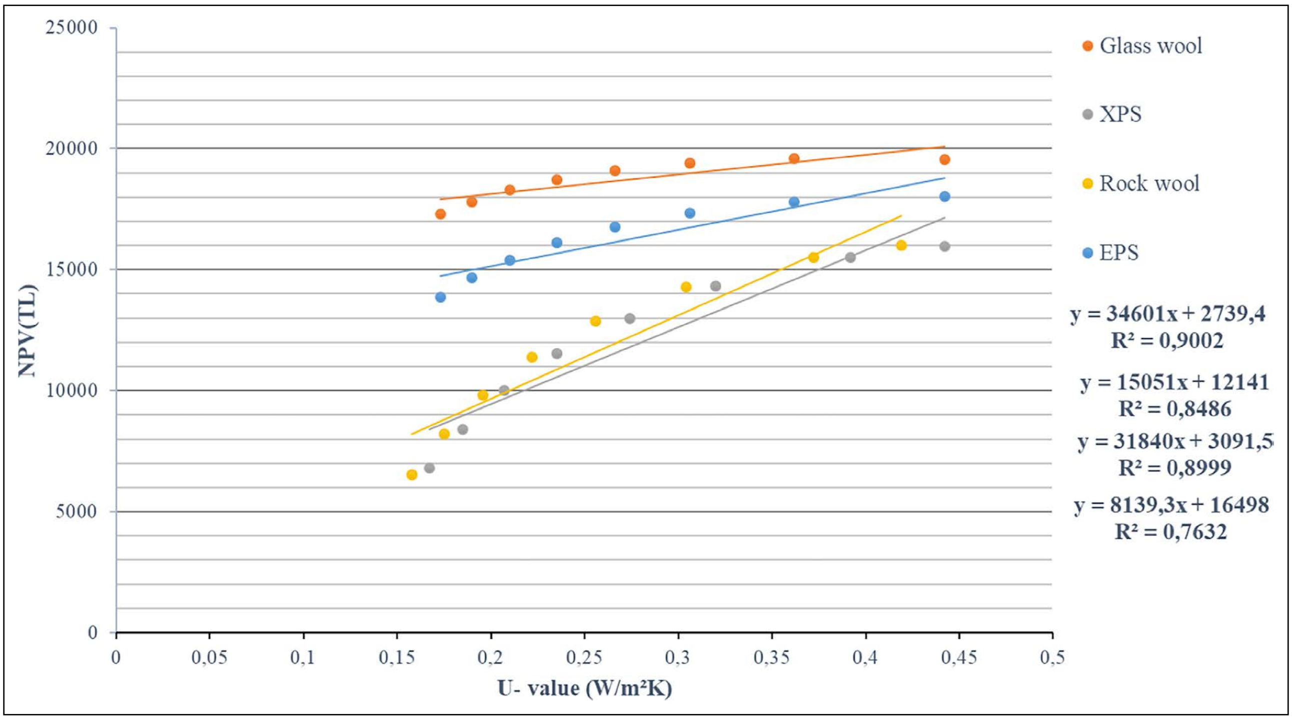

Figure 5. NPV-U-value relationship for insulation thickness scenarios with glass wool, XPS, rock wool, and EPS materials used in the roof.

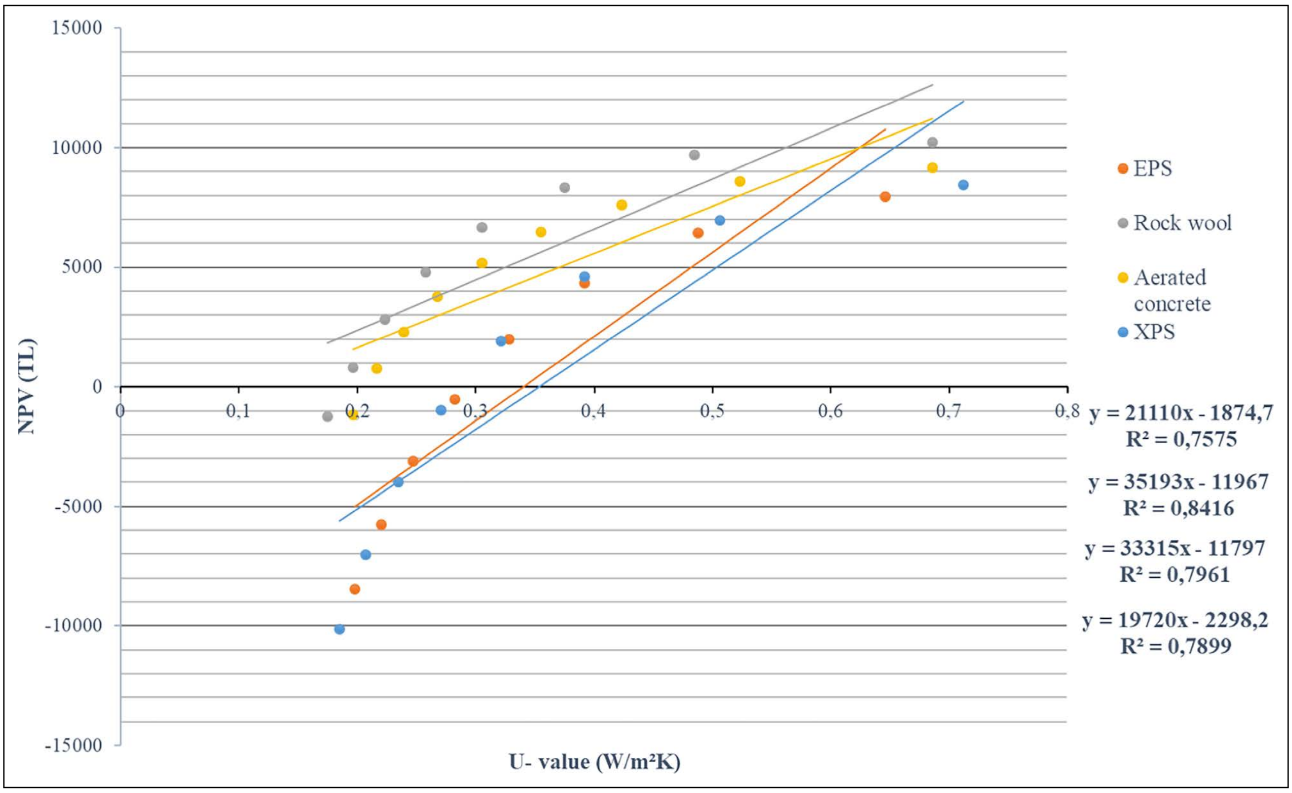

Figure 6. NPV-U-value relationship for insulation thickness scenarios with XPS, aerated concrete, rock wool, and EPS materials used in the wall.

the most efficient material for the roof was glass wool and the most efficient material for the wall was stone wool. When the study is conducted for buildings in different degree day zones, it is possible to reach different NPV values according to the building component. In future studies, it is recommended that this method be applied to buildings located in different degree day zones with different material alternatives.

Based on the results obtained, although the insulation materials used to increase energy performance in buildings are used in thicknesses that will give the same thermal conductivity value, the NPV values of each material are quite different. As stated in the Energy Performance of Buildings published by the European Union, it is as essential to use cost-effective solutions as it is for buildings to have high energy performance. This study emphasizes the importance of investigating cost-effective solutions while achieving similar savings with different materials.

In the study, although in terms of cost-effectiveness, highly insulated alternatives seem to be disadvantageous compared to less insulated alternatives, high levels of insulation can significantly reduce energy demand in the long term. For sustainable architecture, constructing each building as a building that meets its energy from renewable energy sources, with high insulation and low energy needs, will make a tremendous environmental contribution in the long term.

With energy-efficient design or improvement interventions for each building, the total energy consumption of buildings, which have a significant share in the energy sector, can be reduced. In this way, foreign dependence on energy will be reduced in our country, and a significant contribution will be made both nationally and individually economically.

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

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Review Article

A review on blockchain operations in construction management

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ABSTRACT

This study investigates the important role that the blockchain plays to manage the information about who did what and when and hence provides a strong base for any legal potential conflicts. Blockchain technology permits you to distribute, encrypt, and secure the records of digital transactions. In addition, bitcoin and other cryptocurrencies are encompassed in it. Even though the construction industry has traditionally been a late user of innovative technology compared to other sectors of the economy, it faces various hurdles in terms of trust, accessibility, information sharing, and process automation. As a result, stakeholders, clients, subcontractors, contractors, and suppliers have been unable to work together effectively. Even if building information modeling is employed, which envisions a centralized building, the primary benefit of blockchain is the secure storage of sensitive sensor data.

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1. INTRODUCTION

The construction industry has a great impact on any country's economy. Recently, there have been new advancements in the technologies regarding construction management. One of these technologies is blockchain operations. The aim of this review is to provide information for the scientific studies which are focusing on the field of construction management and the effect on blockchain technology with respect to it. The structure of this article is as follows: introduction, body, result and conclusion.

A blockchain is considered to be a distributed ledger system. This means that it is a general agreement of shared and synchronized digital data. In addition, it is going to be distributed geographically among numerous sites,cities or institutions. To put it another way, there is no central administrator or data storage [1].

The main purpose is for the majority of the system's members to validate the content of each block. The information in a block cannot be removed or changed once it has been entered and confirmed. Each block could be thought of as a piece of encrypted data. Anyone in the system can theoretically add data to the chain of blocks and see the data at any moment, but no one can edit the data without proper authorization. As a result, all the "blocks" work together to create a comprehensive and immutable history of the network's operations, which is shared with all system participants. When a block is approved, it is added to a chronological chain of other blocks, acquiring the name "blockchain" (Fig. 1). As a result, the blockchain is a chain that holds verifiable records of all transactions, documents, and other actions ever performed in the system. By utilizing newly created technology, the demand of

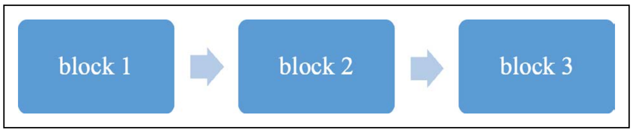

Figure 1. The formation of blocks [4].

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the construction industry would be met. These requirements could be filled by blockchain technology, despite it being a relatively new technology [2].

This technology consists of a distributed database of records, digital events, or a public ledger containing many transactions that are completed and shared among retention of workers. Getting rid of a third party as a requirement in any transaction is the aim of the blockchain technology. Instead, the majority of the system's participants, or nodes,-verify each transaction in a public ledger. Mutual trust has been shown in previous research to assist in smoothing the construction process that allows flexibility in the face of uncertainty, boost efficiency and maintain long-term relationships [2].

The popular crypto currency Bitcoin innovated blockchain technology, which allows digital information to be circulated without being duplicated or edited. Data is maintained in a central database that can be accessed from multiple locations in the traditional construction sector. The biggest concern is the security issue, as the transaction data could be tampered with by a hacker The blockchain technology, on the other hand, can be thought of as a shared database across a peer-to-peer network .In a set amount of time, transactions are grouped together into blocks and then added to a permanent chain. Once added to the chain, these blocks cannot be changed, making the transaction chain publicly verifiable and totally unhackable [3].

The main element of blockchain technology is trust. Participants do not need to have an established trust connection if they trust the blockchain itself, or if the building business or activities are carried out on a blockchain system [3]. Furthermore, blockchain technology facilitates information interchange by designating each project member as the owner of all information flowing during the project lifespan [2].

2. MATERIAL AND METHODS

In the Material and methods section, it was a collection of knowledge with regards to the blockchain operations. Furthermore, this tracking has been done by using the following terminology such as smart contract in blockchain operation, blockchain operations advantages and disadvantages and the effect of blockchain operation in the construction industry. For this section, there are only secondary sources. In other words, no raw materials were obtained for this research report. Firstly, this study includes an introduction section, which includes information and explanation of the relevant topic. Most of the articles obtained are recent and published within 2008-2021. Moreover, google scholar and academia were the main sources for obtaining these information and findings. Only articles were used to gather all of the information related to blockchain operation in construction management. Nearly over fifteen articles were checked and used for this study.

In recent years, research on blockchain applications and development in the construction industry has attracted a great deal of interest. A large number of review papers have recently evaluated and assessed blockchain research from diverse angles .One example for this, Jennifer Li and David Greenwood. [4] carried out a study on the built environment and construction sector related to blockchain. The findings suggest that blockchain has the potential to help digitization in the construction sector. A use case analysis and a complete literature review are also used to examine the application possibilities of blockchain in the construction industry, which was done by Perera in 2020. According to this study, it seems that blockchain has great potential in the construction sector. Hunhevicz and Hall. [4] have suggested the technical elements of blockchain scenarios and a decision framework is given to assist users in determining whether they require blockchain technology and which form to utilize. From 2017–2020, around 100 papers were published. Furthermore, they were examined to study the incorporation of blockchain, which led to progress and expansion. The outcome indicates that the extension of the blockchain conceptual model has nearly reached a plateau and that existing concepts will mature as attention turns to testing and improving earlier ideas in the future [4].

Hileman and Rauchs [5] claim that blockchain is made up of five components, such as cryptography, peer-to-peer, network, consensus mechanism, ledger, and validity rules. Moreover, these components contribute to the uniqueness of blockchain's quality. For example, cryptographic techniques are used to assure data secrecy and integrity in the event of a challenger. Cryptographic one-way hash function, symmetric key cryptography, or public key cryptography are a few examples of the variety of usages that are involved in cryptography techniques.

The peer to peer network is a peer-to-peer network that permits data sharing and peer discovery. In the event that not all participants are telling the truth, the consensus process regulates the ordering of transactions (adversarial environment). A ledger is a collection of transactions that are arranged into 'blocks' that are cryptographically linked. The eligibility rules are a set of guidelines used by the network to determine if a transaction is valid. Blockchain can reduce the amount of confidence necessary prior to a transaction, but they do not eliminate it entirely. Validators and/or operators are similarly trusted; in a well-configured environment, participants independently examine the system state and validate transactions [5].

A person can have their own bitcoin once its unique hash on the bitcoin has been signed. This can only be done after it has been sent to you by another peer. After the sending process, all the past signatures on your part can be checked. In order for all bitcoin's participants to resume the chain. Moreover, the ownership of the funds must be verified by the peers using the blockchain. Once the transaction has been inserted into the blockchain, it becomes irreversible. It's a shared transaction log ('ledger') that also functions as a timestamp server. The old-time stamp is included in any new timestamp, resulting in a perfectly trustworthy chain of events. The paper also introduces the proof of work system, which employs an algorithm to validate any operation and create a new blockchain [6].

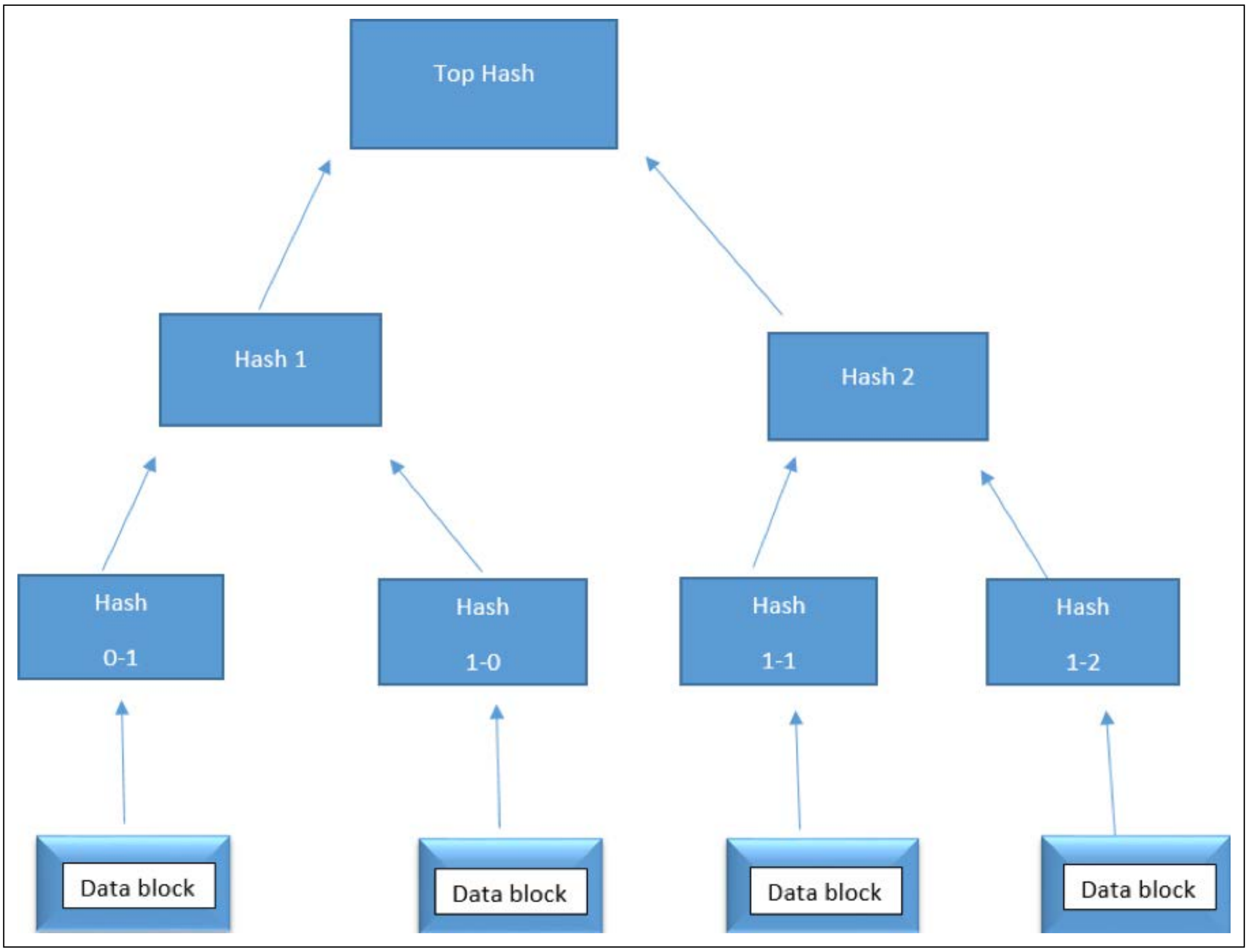

Figure 2. Merkle tree [7].

2.1. Hash Algorithm

This section is going to illustrate the significance of the hash algorithm operations.Peers must use a large amount of computing energy to obtain a similar hash when representing a block (as a SHA-256 hash). Then it's recorded in the ledger. For verification and continuity, nodes (i.e., people or computers) interact, especially when signing a block into the chain. In other words, the nodes must agree on the new block in the transaction. Even so, the POW (proof of work) is required to reach this agreement and to create and verify blocks. As a result, hacking Bitcoin is extremely costly due to the massive computing resources required by most block chains [6].

According to Shackelford and Myers. [6], it was suggested that there is a great consumption of the amount of energy used by the current blockchain designs to power up the algorithms (around 215 kWh with every transaction). In particular for validating and securing transactions, blockchain requires a great amount of processing power. It is considered that the bitcoin blockchain consumes more processing power (between 10 and 100 times) than combining all of Google's service farms.

2.2. Merkle Tree

Merkle Tree is demonstrated in the Figure 2 below. Based on Satoshi research. [6], all the transactions in Bitcoin and blockchain technology are summarized and used in the data structure. In addition, it is made up of many hashes, but it condenses them all into one while still being able to verify the data of each individual hash. It summarizes all transactions in a block, but each transaction in a block can still be checked. Because of this layout, the blockchain is smaller, requiring less CPU power to process and validate blocks. As a result, even the most basic devices can run a tiny blockchain and connect to it as blockchain nodes. In other words, rather than having every hash to join a Merkle Tree branch. The nodes (i.e devices) can do it. Moreover, Satoshi also explains how Bitcoin can enable data privacy to its users. Banks, for example, have the ability to reduce the number of transactions while being the only party with access to users' identities. However, while Bitcoin displays each transaction in actual time, users use a public key to identify one another in the network and a private key to access coins given to them. Their identity and transactions are thus secured.

2.3. Digital Signature

The digital signatures show the private key consists of randomly selected numbers that must be done in secret. For example, if one user wants to send something to another user, they need to use the private key to sign. Furthermore, across the blockchain, the message is sent and distributed.

The nodes then examine the memo to check that the transaction is legitimate. After the confirmation of the transaction, it is sent in a block that cannot be amended later The two key system is considered a fundamental and vital process [7].

Nonetheless, Nakamoto [6] emphasizes Bitcoin's (almost) non-hackable nature. For instance creating a chain to resemble an actual blockchain is useless because it is highly unlikely to form Bitcoin out of thin air. Therefore, the nodes will reject the misleading action automatically. Furthermore, the system incorporates secure channels, notably encrypted public channels.With the blockchain concept, the goal is to reduce broken trust digitally. When the need arises, blockchain may always refer to the unaltered data stored in public space. This procedure improves digital trust. Fraud and deception become more difficult as a result of this exposure. It is a hybrid of old technologies that have been around for a while. Cryptography and payment, for example, are forms of cryptocurrency. It represents values (for example, payment via a token) that, when combined, establish a totally new principle of cryptocurrencies [7].

Cryptocurrency combines the concept of money, the ability to send and receive money online, and the ability to trade safely using a token. For example, Bitcoin was created to disseminate the Bitcoin cryptocurrency, but it now clearly has a much greater capability [8].

Matter of fact, blockchain technology is the secret weapon driving cryptocurrency's sharp increase. Bitcoin demonstrated to the world what blockchain technology is capable of. It stirred up a monetary revolution, discussing the merits of cryptocurrency. As a result, the fundamental technology (blockchain) that powers bitcoin separates from the currency and is used for a variety of other purposes. In the last decade, this innovation has opened the way for numerous block-chain-based solutions Smart contracts are an example of a blockchain-based solution that integrates applications to the blockchain [9].

2.4. Main Components of a Block

As it is indicated in Figure 3, each block is made up of coded hashes that group together time-stamped transactions. Since the order is fundamental, the transaction must be entered in the order in which it occurs. The hash is determined by the current transaction and the hash of the previous transaction [10].

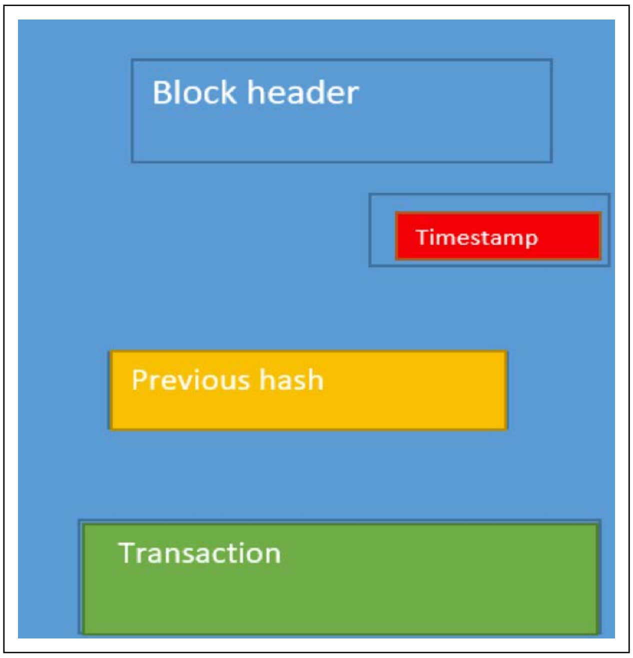

Figure 3. Main components of a block [11].

2.5. Nodes

The hashes are inspected by the nodes to ensure that a transaction has not been altered. A node-approved transaction is composed into a block. Each block makes reference to (and holds the information from) the preceding block, allowing the blocks to take part in the Blockchain [10].

Blockchain is extremely valuable because, as it expands across multiple computers, each computer (node) can have its own copy of the blockchain .Furthermore, because peers communicate directly with one another, any blockchain-related information is kept and passed on. Therefore, data is transmitted rapidly via the network. Besides, blockchain upgrades itself each 10 minutes, it is a very safe system. The blockchain is transformed into a database, with every node having access to the chain. As a result, it is practically impossible to forge a block because it must be validated by other nodes. Because it is encrypted and decentralized, blockchain security is unquestioned. Even though there are thousands of these nodes scattered around the world, trying to grab (or imitate) the system requires enormous computer power [4].

In general, Blockchain is a transaction ledger that instantly affirms itself. A single node (or computer) does not have any authority over the data. However, they can confirm the ledger without the use of intermediaries to regulate or try to control it [12].

There is a lot of debate concerning public versus private blockchain. Public blockchains, on the one hand, entail cryptocurrencies (such as Bitcoin) that allow Peer to Peer operations. Moreover, tokens are required in it and in the peer to peer network, it has its own set of rules. With the usage of private cloud infrastructure, blockchain based application can be used by private blockchains that functions and operates on it [13].

2.6. Smart Contract

In the construction industry, there has been an issue with the method of payment. For example, payment delays and the cost included to resolve all the issues. Therefore a solution to these problems that the construction industry faces is smart contracts. With the usage of smart contracts, the element of trust will be triggered in the process of exchange of money, any transactions and assets or anything valuable that will happen between stakeholders. As a result, smart contracts became a game-changer for the construction sector. Since it has transformed from document procedures into data procedures. Smart contracts are built on a set of rules; therefore, if all parties agree on these rules then it will enforce these rules for the completion of the contract. Moreover, the implementation of a smart contract in blockchain provides trust in the transaction. Since, the enforcement of the contract is automated. For instance, clients can buy products or services directly from providers by paying a deposit at the time of ordering. The remainder of the payment can be sent to the suppliers in an automated process after the products are delivered to the site. Therefore, smart contracts manage and initiate all of this [2].

2.7. BIM

Construction projects can be replicated in a multi-dimensional digital model, which offers various advantages from the start of the project through its completion. Building Information Modeling (BIM) is the term for this technique. The building supply chain treats BIM differently, which has an impact on the quality of the finished product. By integrating BIM with the construction supply chain, the activities of the construction process, as well as data for facilities management, may be improved during the design, operation, and post-construction stages [14].

3. DISCUSSION

This section seems that most of the researchers have agreed upon the fact that blockchain will enhance trustworthiness among workers and immensely reduce fraud and corruption because of the transparency which blockchain technology provides. In addition many researchers stated that this transparency is viewed as a disadvantage regarding blockchain operation. Some articles provided profound details regarding the components of the blockchain technology while other articles briefly explained them. Later on in the result section, which was conducted in a construction company, the statistics support the researchers' findings.

The construction sector has been blamed for its slow adaptation to any new changes. However, this disadvantage has not prevented the construction industry from finding other methods (internet and IT) from improving its management process. Similarly, these improvements have increased the level of competitiveness. There will be new construction material, better qualification for the employees and access to the international market [11].

According to Tekreeti [12], there are many procedures and processes that have control over the construction field and the management field, which includes third entities and intermediaries. However, this will be an obstacle for any changes because of this dependence. For instance, a project which entails a construction of a new bridge between two different cities. Firstly, a contract should be prepared and it will be announced that the project is looking for contractors. The construction company that is interested and has the capability of the job would demonstrate the essential documentation (involves other parties). Then the bids will be evaluated and signing of the contract is needed. The execution of the work cannot be completed without certain documents such as descriptive report, budget and work plan. All this documentation is presented during the bidding process. After that, everything that was mentioned on paper should be executed on site. Therefore, the work is carried out. Finally, the bridge construction is completed and delivered to the government or any other client with specific documentation. This example of the bridge shows the long process of any construction project procedure. In addition, it involves a great number of intermediaries like the government, subcontracts and so on. As a result, blockchain operations are looking forward to making these kinds of processes less tedious.

According to PMBOK (stands for project management body of knowledge), it defines the application and tools needed to connect the beginning and the end parts of the project. This includes the scope of the project, required work, how to manage the stages and check over the work. Moreover, this is applicable in nearly all construction management projects [13].

In construction management, the following phases are applied such as planning, design and construction etc. However, every stage is carried out by itself. For instance, some design sketches need to be changed because of an error but there is a misunderstanding in the communication between the designers and contractors. Therefore, the architect cannot make any effective changes in the design. There are some delays that occur at the construction site; for instance, the constructors need to wait until the architect completes the sketch so they can carry out their tasks [14]. Therefore, LCM (Life cycle management) combines all the phases of management together and the concerned parties can be involved. In that way, time and cost can be used effectively. In addition, it makes sure all communications are open and shared. This is where blockchain plays an important role and creates great changes to construction management [15].

Since blockchain communication is transparent, it is a decentralized system (many points of entry). In other words, all the parties are involved in full transparency. Even though the communication is transparent, it does not mean that everyone can be included. The communication is permitted to assigned employees. Therefore, the entire communication is considered secure. Not only is the communication secured, but also the data transfer because it is quite impossible for any external influence to hack into the management process. The reason behind this is the cloud storage systems which are secured; it reduces the risks because of the project manager interference. Project managers can ensure everything is on the right path by using this blockchain technology. Blockchain operations limit discussions to project issues and transmit them; therefore, it keeps the project focused, efficient and reduces mistakes. Project manager has great control over all the information. Since he or she can access this information and make any necessary changes. All the transactions can be handled efficiently by the blockchain. For example, Briq is a construction fintech company that works on one modern platform that connects all transactions and operations on a construction data cloud. In that way, all involved parties can easily use this system, which is provided by Briq. Moreover, many databases contain a ledger. Each ledger is a sealed copy and cannot be modified in any way. It was found that in the construction sector a lot of data is lost due to handovers that occur in the industry which is 95% of all this lost data. However, with the new sophisticated technology which is blockchain, we can see great horizons between blockchain's impact on the construction sector and management. Firstly, both the time of the transactions and number of intermediaries will significantly decrease. In other words, hiring any service or product directly from the company regardless of its location. The data can be used to find the best firm for various projects and the use of smart contracts would make the transaction easier. Furthermore, 'own payment method' could be a specialized payment procedure for certain sectors. To put it in another way, cryptocurrencies could be implemented as a method of payment for transportation, energy, insurance and other transactions [16].

Smart contracts enable computerization of legal binding forms and printed material; as a result, it decreases the cost and speeds up the delivery. Moreover, smart contracts are activated once the pre-set tasks are finished. Therefore, it grants permission for monitoring the stages and identifies responsibilities to the necessary parties. In addition, it demonstrates all the occurring events in the process (Like construction of a building) [14].

A reputation ledger, for instance, might track subcontractors deliverables and serve as a point of reference during the hiring process, thus blockchain can assist in this. This functionality makes it simpler to oversee the building process and find trustworthy subcontractors for a project [16].

This will be beneficial to manage projects afterwards, in regards to redesigning and following the rules. Corruption and fraud can be totally prevented in the construction process because the project material can be followed on the blockchain. Moreover, communication and findings of the information can be extremely effective with certain firms and people with the assistance of the record. Furthermore, payments are made quickly and the transactions would appear anywhere [16].

Smart contracts get rid of intermediaries and provide great improvement for the technology. Therefore, by diminishing the number of intermediaries, blockchain can provide better transparency. Since the status and the history of the transactions would be visible to anyone. However, the information stored in the blockchain can never be tampered with so it will be obvious which employees are hired, reason behind hiring them, date of hiring and how many were hired. Moreover, blockchain operations can tremendously affect the management process positively. Since it allows tracking the data, it decreases the time of delay for receiving and sending documents and increases the effectiveness of the decision-making procedures [12].

4. RESULTS

In this section, it will show some of the outcomes made in the United Arab Emirates regarding the application of the blockchain in the construction company. A construction company in the United Arab Emirates has applied the blockchain operations. Based on the answers obtained from the questionnaire of the methodology section, the following results were found. This questionnaire targeted upper management, executive-level managers, owners and board members [12].

Based on the questionnaire (regarding the decision making done for the blockchain operations), the following outcome was obtained

- It turns out that the IT staff have the highest percentage which is 47%
- Top managers in this construction company make up the second highest percentage which is 30%
- Comparing with the other sectors, the second highest is the top management
- In addition, finance has a low percentage which is 8%

Regarding the investment made to have blockchain operations in the company

A relatively high percentage responded that the investment in the blockchain technology in their company made above 5 million dollars.

- Only 1% stated that there is no investment
- In general, most of the respondents suggest that blockchain operations have great investment strategy and it is crucial for the organization

In regards, whether blockchain operations are relevant and important to the construction management. These are the following outcomes

- More than half of the respondents (53%) suggest that blockchain has some degree of relevance in their project.
- Majority of the respondents seem to find the blockchain technology a relevant component for their organization

5. CONCLUSION

Blockchain operations seems to be a very interesting topic and quite recent technology. Based on all the articles that were reviewed, the most liked idea was its non-hackable feature. Since the hash function in the blockchain is very similar to one's fingerprints and it's also related to the previous hash. In addition, the block that carries the information cannot be changed unless the majority of the people approve. Moreover, the system of how the blockchain works is fascinating and it can be implemented in other technologies such as BIM and smart contracts.

One of the main advantages of this blockchain technology in the construction sector would be collaboration. Since blockchain is implemented in BIM, many architects, contractors and other engineers can have an easy way of communication with each other. Many articles have mentioned these aspects will help in the reduction of the cost and mistakes.

In addition, cost is also another major factor in civil engineering. Based on these articles, blockchain technology would be of great assistance to reduce cost. Since, the third parties are eliminated in the blockchain operations and there are few administrative contracts. Therefore, the cost would significantly decrease.

In the project phase, the blockchain combines all the project stages together and the communication is open. It seems that this is crucial in management in order to avoid any delays or mistakes in the construction industry. The concept behind smart contracts seems intriguing that it is a digital form of contracts and the best part is that it reduces the paperwork. It seems that these kinds of paperwork will become obsolete in the near future. Technology has been evolving each day and it's changing many aspects in our world including the construction industry. It is surprising to know that technologies such as blockchain could be incorporated in the construction sector. As many people believe that civil engineering has ordinary procedures that will not change. For example, construction of houses or bridges has certain traditional steps to be followed. However, this blockchain operation can change the perception of the construction sector and innovate it. Many buildings, theaters, bridges and so on have been constructed for thousands of years even before blockchain operations. However,construction companies should implement this technology because we can use these technological benefits to our advantage and change the perspective that the construction industry is always behind in technology.

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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