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CONTENTS

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Research Article

Determination of exterior material in sustainable buildings by value engineering method according to LEED criteria

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ABSTRACT

Factors such as the rapid depletion of natural resources and environmental pollution enable us to understand the importance of sustainability better today. With the introduction of the concept of sustainability into the construction sector, the design of buildings according to the environmentally friendly "Green Building" approach has come to the forefront, and various certification systems have been developed. Due to these certification systems, various building materials must be used in buildings. However, since many materials are on the market, it is a problem which materials should be preferred according to the green building criteria. Although there are various approaches in this regard, the value engineering method is ideal as it considers both the criteria the materials must meet and their costs. Value Engineering is the teamwork to analyze the building properties, systems, equipment, and material selections while considering the costs to perform the necessary performance, quality, reliability, and essential functions. In this article, a method on how to choose a value-based, sustainable material was proposed, and as a case study, a product that can be used as an exterior cladding material of a building using LEED criteria, which is used for providing certification for sustainable green buildings, was selected. Initially, a value engineering team was formed. This team determined the product's qualities based on LEED criteria and the eight material alternatives that can meet these qualities. Subsequently, value analysis was conducted, and the highest-value exterior coating material was determined.

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1. INTRODUCTION

The construction industry produces structures by bringing together many stakeholders. Hundreds of stakeholders, from the designer to the manufacturer, from the equipment manufacturer to the end user, can work in great harmony to produce structures of the desired quality without exceeding the targeted budget and within the specified time [1]. However, this may not always be possible. When the aim is to reduce the cost, the quality often decreases with the cost. Similarly, when it is necessary to shorten the duration, the cost increases, or different risks arise. In addition, each stake-

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holder's expectation of the final product to be obtained may differ. The contractor will want to make more money, the engineer will want to obtain a safe and economic structure, the architect will want to make it look aesthetic, and the end user will want to live in a high-quality and comfortable living space. In this case, everyone will be satisfied if each stakeholder's request is fulfilled optimally. So how can this satisfaction be achieved? Today, many methods are used to achieve this goal. One of the most effective and practical of these methods is Value Engineering. Value Engineering is a systematic team effort to choose the lowest cost among the alternatives that can be solved to meet the stakeholders' demands and criteria for a product produced, a service provided, or an existing problem [2]. Team members are composed of people affected by the relevant problem and qualified to solve the problem.

The biggest problems experienced today are decreased resources and environmental pollution [3]. As in every field, similar problems are experienced in the construction sector [4–6]. In order to leave a habitable environment for the next generation, resources should be recycled and reused, and products should be obtained with the least amount of waste [7–9]. The construction sector is vital in deteriorating the ecological balance by using natural resources and energy consumption. Notably, 40% of the energy and 25% of the water consumed worldwide are spent on building construction or during their use [10]. In this context, sustainability has gained significant value in the construction sector, and various construction projects are built sustainably [11, 12]. Sustainable buildings, seen as green buildings in the construction sector, are evaluated with the criteria determined in advance by various global evaluators [13].

Sustainability can be described as the ability to be permanent. The concept of sustainability is used in many fields and sciences today. It is frequently used in ecological science. The global concept of sustainability introduced to the global public was formed thanks to the report "Our Common Future," published in 1987 by the World Commission on Environment and Development within the United Nations. This report defines sustainability as follows; "It is the ability to make development sustainable by providing the daily needs of nature without jeopardizing its ability to respond to the needs of future generations" [14]. Since the concept of sustainability is comprehensive, many people define it as per their understanding. However, they all have one common point in defining it: not using resources unlimitedly while creating a healthy environment and living spaces without harming the ecology.

Green buildings are environmentally friendly buildings designed for the most efficient use of natural resources. As a result of the measurements made, sustainability, green building, and environmental protection issues have become more critical, with the realization that the most significant share in the deterioration of global warming and environmental balance that causes climate changes in the world belongs to the construction sector. The building sector has developed green building projects that are compatible with nature, can use energy effectively, and aim to protect the health of people living and working in them with certification systems [15].

In this study, while designing a sustainable building project, an exemplary application was made for selecting the building's exterior cladding material according to the LEED certification system criteria using the value engineering method. First, an experienced value engineering team consisting of all stakeholders who were relevant to the problem was formed. This team researched which criteria an external (façade) cladding material must meet according to the LEED certification system and subsequently determined the criteria. Then, by conducting market research, they determined the products that could meet these criteria and obtained the technical features that demonstrated in what capacity these products could meet the determined criteria. However, since the importance given by each stakeholder to each criterion will not be equal, the stakeholders have scored and ranked the criteria according to their expertise. As a result, the benefit of each product was calculated by performing a value analysis. The value was calculated by dividing the benefit values determined for each alternative product by the unit costs of the products, and the product with the highest value was determined as the solution to the problem.

2. INTERNATIONAL GREEN BUILDING CERTIFICATION SYSTEMS

It is known that residential buildings constitute the majority of the world's energy consumption. An important aspect that causes significant energy waste in these buildings is that they are produced with conventional construction technology and inefficient consumption habits. The construction sector, which has an essential role in increasing global warming, causing climate changes, and leading to the reduction of energy resources in the world, has started to develop an innovative understanding of the concept of green building, which is a product of the construction concept that is compatible with nature, sustainable, environmentally friendly, and can use natural resources efficiently in order to reduce these adverse effects. Certification systems based on specific criteria have been developed for buildings to have green building characteristics. The most common certification systems developed and implemented by different countries are BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design), DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen e.V.), IISBE (International Initiative for Sustainable Built Environment), Greenstar (Environmental Rating System for Buildings), Casbee (Comprehensive Assessment System for Built Environment Efficiency) [16].

In this study, especially the features of this certification system will be mentioned since the exterior coating material will be selected in line with the LEED certification system criteria as an application.

2.1. LEED (Leadership in Energy and Environmental Design)

LEED certification can be used for all types of buildings, including existing buildings, commercial interiors, schools and homes, new buildings under construction, and buildings that have undergone significant renovations. Studies of LEED systems in a neighborhood, retail, and health system are in the pilot phase. To date, 41.8 million square meters of construction area have dealt with the LEED system. LEED is a points-based system, and each building project earns LEED points to meet specific green building criteria. Projects in the seven LEED credit categories must meet specific prerequisites and earn points. It has three grades: silver, gold, and platinum. Regional loans are another feature of the LEED Certification system and recognize the importance of local conditions in determining the best environmental design and construction practices. The distribution of scores is based on strategies to increase energy efficiency and reduce CO_2 [17].

3. VALUE ENGINEERING METHOD

The perception that the concept of value creates in most people is the price, which is the monetary equivalent of the product. However, value is not a concept that can only be measured by cost and price. The highest value is the value that can safely perform the desired functions at the desired time and place and meet the basic quality need with the minimum possible total cost. The actual value of a product comes only from comparing its quality and cost with another product that performs the same functions. Value Engineering (VE) is the technique of generating cost-cutting ideas by focusing on the functions of products without compromising the characteristics of a product desired by the customer and prolonging the product development process. Analyzing the functions determines whether the product or service provides the desired quality level and compliance with customer expectations. In order to meet customer expectations, if necessary, functions deemed not to be needed as a result of function analysis can be removed from the process, or new functions can be added. Value, which is the criterion for customer selection, is a phenomenon that becomes evident due to the quality of the product. A product or service designed and produced to expectations is found valuable and high quality by the customer [18].

VE does not take the objectives of the contractor, owner, or user involved in the construction process individually as an objective. By balancing all these, the goals to be determined work to achieve the whole. The impact of each component to be included in the process, such as the project's objectives, cost limitations, construction technique, materials, and equipment, should be estimated by collecting the necessary information in advance. The more information we have before starting the project, the more chance we have to be in control of goals, cost, quality, and completion date. DM objectives can be itemized as follows [19]:

- Avoiding unnecessary costs
- Using money, materials, and human resources efficiently and effectively
- Reducing construction time by using time effectively
- Improving quality
- Ensuring construction safety
- Ensuring the longevity of the structure
- Revealing staff skills through psychological techniques such as teamwork, creativity, and adaptation
- Identifying functions that contain and do not contain a value for the customer, adding the necessary (valuable) ones to the process, removing the unnecessary (worthless) ones from the process

Value engineering is used to solve many different problems. In the Croatian highway project where the method was applied, a total of $43,000,000 and 12 months of time savings were obtained from value engineering studies. Thus, 6% financial savings and a 17% reduction in project duration were achieved for the contractor company [20]. In the study by Mahdi et al. [21], value engineering was used to apply the four most frequently used techniques: soil replacement, preloading, vertical drains, and the construction of dikes to rehabilitate soft clay existing on highways under construction in Egypt. In the study conducted by Brahmane and Bachhav [22], value engineering was used to shorten the construction time of construction projects. In his publication, Atabay [23] applied value engineering to select the filling material between the shoring wall and the structure. In a study prepared by Taher and Elbeltagi [24], they developed a model to choose the best alternative among sustainable building designs with various criteria they determined, using Building Information Modeling (BIM) and Value Engineering. This model is based on developing a 5-D BIM model that examines the energy efficiency of a building design. In a study conducted by Gunarathne et al. [25], a model integrating the concepts of Value Engineering and sustainability was developed to improve project values in constructions built in Sri Lanka. Both quantitative and qualitative research approaches were used in the study. Albarbary et al. [26] used sustainability and value engineering integration for environmentally friendly concrete production in their study. Suliyanto [27] determined the criteria necessary to build a green bridge and applied value engineering in green bridge construction with the help of these criteria. Abdulaziz Almarzooq et al. [28] applied the value engineering method to the project to reduce the cost of energy use while building a new hospital building.

3.1 Job Plan in Value Engineering

One of the most critical differences distinguishing value engineering from traditional cost reduction methods is its application within the framework of a Job Plan. A Value Engineering Team is created for and implements this job plan. The application of Value Engineering starts with determining the scope and content of the project being worked on, then alternatives are produced to solve the identified problem, the alternatives produced are evaluated, and a solution is proposed at the end. The method used to do all these, that is, to implement value engineering, is known as a job plan. The job plan ensures that all the elements that will play a role in the realization of the project work together, and the team strives to meet the project owner's requirements at the optimum cost. The Job Plan consists of 5 steps, and each step has questions that need to be answered [29]:

Step 1: Information Gathering
- What functions should be provided?
- What are the costs of these functions?
- What are the values of these functions?
- Which functions must be performed?

Step 2: Creativity and Idea Development
- What else can this function do?
- How else can this function be performed?

Step 3: Evaluation
- Can each new idea perform functions?
- How can every idea be changed to provide the function?

Step 4: Developing Recommendations
- How to implement new ideas?
- Can all needs be met?
- What would the cost be?
- Does it contribute to value in terms of cost of use?

Step 5: Presentation/Completion
- What are the better features of the new idea than the old one?
- What are the pros and cons of the existing suggestions?
- What is needed to implement the proposal?

The Value Engineering Team completes the job plan by seeking answers to these questions, and thus the problems are solved from a value-based perspective.

3.2. Functional Analysis

The functional analysis seeks answers to the following questions [30]:
- What is it? In the analysis of complex products or processes, explaining the connection of each part to the whole can provide advantages in practice.
- What does it do? Functional identification of the product is made.
- How much does it cost? Information about the cost of each part/component must be available. High-cost elements can be analyzed first.
- What is the value of the basic functionality provided? It is aimed to fulfill the function with minimum cost.
- How is the primary function provided as an alternative? The ideas put forward should be evaluated together with their costs.
- What is the cost of the alternative? The alternatives decided are evaluated in terms of cost. Evaluation can be completed by:
  - o Comparison with a standard that provides a similar function
  - o Comparison to a similar physical-looking product
  - o Comparison with a product with similar processes in its production
  - o Dividing into functional areas that are simple enough to be comparable to commercial products that can perform similar functions
  - o Determining the quantity and cost of the material required to perform the function
  - o Destruction, creation, and perfection
  - o First, realize creative thinking and identify costs for new ideas

3.3. Value Calculation

In value engineering, the value of a product can be formulated in the following ways [31]:

Value = Entitlement/Cost (1)

Value = Customer Satisfaction/Cost (2)

Value = (User's Initial Impact + Benefit from the product)/(Initial Cost + Life-cycle costing) (3)

Value Analysis (VA) of each alternative is performed by determining the values of the products, processes, and services after the functional evaluation. The high-value alternative is determined as the product, process/service that can be applied and used.

4. SELECTION OF EXTERIOR CLADDING MATERIAL IN SUSTAINABLE BUILDING

The material should be preferred for coating the exterior of a building designed according to LEED certification criteria. Many coating materials on the market are available for this purpose. It was decided to make a value-oriented selection on which of these should be used. For this purpose, a team of four people with material, application, value analysis information, and also the end-user was formed. The members of the value engineering team consist of a civil engineer with 13 years of application experience working in a company that provides sustainable building design and consultancy services, an architect with 15 years of projecting experience working in the same company, a contractor, as well as a project owner who receives services from this company. A team of four stakeholders was sufficient for this study. However, the types and numbers of stakeholders will vary if the problem is more complex and involves different specializations. There may be additional members who are not directly involved in the team but provide support from outside for the calculations that need to be made. The team first determined the qualifications the materials should fulfill in line with the essential criteria specified in the LEED certification, considering the customer's requests.

The value calculation will determine the selection of the building material to be used as an exterior coating. The value shall be defined as the ratio of a product's suitability (benefit) to the economic burden it imposes on the user.

Value = Benefit (Suitability for use)/Economic burden (4)

Suitability for use (Benefit) = Importance x Satisfaction level (5)

Importance; is the value obtained by distributing the 100 total points or perceived by the customer to the qualifications specified in the product specification.

Satisfaction level; is a value that indicates how satisfied the customer is with the specified qualities of each product. It is found by digitizing between 1 and 10.

4.1. Determination of the Qualifications of Materials

The qualifications of the materials determined by the value engineering team are as follows:

- Use of local materials
- Recycling/Reusability
- Material life
- Energy efficiency
- Cost

The cost criterion will not be used in the benefit (function) calculation but will be used in the value calculation. The value engineering team has researched accessible exterior cladding materials that can meet these criteria, and eight alternatives have been determined with the help of brainstorming methods, etc.

4.2. Determination of Exterior Cladding Material Alternatives

- Aluminum: It is an accessible substance to find and access. It is about three times lighter than iron and is almost as durable as steel. Its pure form is much softer. It is non-magnetic and has high electrical and thermal conductivity. It can be quickly processed as hot and cold. It can be drawn and beaten well. It is non-toxic, non-flammable, and can be used without paint. It resists weather conditions, food, chemical liquids, and gases. It is much more active with hydrochloric acid and alkalis [32].
- PVC (Polyvinyl chloride): PVC is a polymer produced from oil (natural gas) and salt in petrochemical plants. PVC has good thermal insulation. The ignition temperature is high. It has a good insulation feature, and it is recyclable. It also prevents cutting trees and thus helps global sustainability [33].
- Glass: Provides heat and sound insulation and a wide field of view in buildings. Resistant to climatic conditions. It is stylish and aesthetic [34].
- Wood: It is a natural building material suitable for health. It provides heat and sound insulation. Moreover, it is 100% recyclable. Lightweight, aesthetic, additional treatments are required to protect from pests such as sun and insects. It is earthquake resistant [35].
- Fiber-cement: The word meaning in the literature is fiber-reinforced cemented board. Thanks to its flexible structure, it is environmentally and human-friendly, suitable for various architectural plans and textures, can be used in various climatic conditions and can be easily applied [36].
- Ceramic: It is unaffected by weather conditions, suitable for energy efficiency conditions, fire resistant, integrated, safe in earthquakes, has high application speed, and is functional and practical [37].
- Precast: It is very resistant to external factors. Its heat and good permeability are low and comply with fire regulations. Since the casting is done in the factory environment, the product quality and artistry can be controlled productively. Since precast equipment can be reused hundreds or even thousands of times, the time and equipment required for the mold are saved [38].
- Siding: It is resistant to heat and water. Fuel savings can be achieved as it provides pretty good insulation. It does not require paint, does not rot, and does not get insects. It is aesthetic and washable [39].

4.3. Limit Values of the Qualifications of the Materials

The limit values for the determined qualification criteria of the materials were found by investigating the technical characteristics of the selected exterior coating material types (Table 1). The determined alternative products are produced and applied by many different companies in the market. As far as possible, the technical features of the relevant products on the web pages of these companies were examined. Since the product features of some companies could not be accessed from the web pages, various communication tools were utilized, interviews were conducted, and information about their products was obtained. As a result of all this research, it has been found that although the material life, heat transfer coefficients, and reusability properties of alternative facade coating products specified in the technical specifications of each company are close to each other, they differ. Since some companies reinforce their products with various additives, differences have been observed in the product characteristics of each company. In order to avoid being based on a single brand, the average value of the relevant characteristics of each product was taken and is shown in Table 1.

Similarly, through research, it was determined whether the products were locally made. Since the application prepared here is a sample study, such a method was followed to not depend on a particular company. However, the products/brands intended to be selected and implemented in an actual project should be identified when an actual application occurs. Thus, the technical characteristics of that product are used in the problem as exact values. The cost values were taken from the 2022 Construction and Installation Unit Prices list published by the T.R. Ministry of Environment, Urbanization, and Climate Change [40]. The prices in the table are the

Table 1. Limit values of the qualifications of the materials

Qualification / Material	Material life (average year)	Energy efficiency (heat transfer coefficient) (w/mK)	Local material	Recycling/reusability	Cost (TL/m²)
Aluminum	130	0.16	50%	70%	1.277,23
PVC	30	0.23	60%	80%	714.90
Glass	200	0.04	100%	100%	6.176,87
Wood	80	0.20	100%	90%	880,00
Fiber-cement	40	0.18	50%	90%	605,01
Ceramic	180	0.96	80%	100%	260,25
Precast	60	0.44	60%	70%	2.824.82
Siding	20	0.22	60%	60%	963,19

Table 2. Determination of the order of importance of materials with nominal group technique

Value engineering team / Qualification	Architect	Civil engineer	Contractor	End user	Total	Sequence no
Energy efficiency	4	4	4	4	16	1
Material life	3	3	2	3	11	2
Recycling/reusability	2	2	3	2	9	3
Local material	1	1	1	1	4	4

Table 3. Importance ranks and percentages of qualifications with the priority matrix method

	Energy efficiency	Material life	Recycling/reusability	Local material	Total	%	Sequence no
Energy efficiency		1	1	1	3+1	40	1
Material life	0		1	1	2+1	30	2
Recycling/reusability	0	0		1	1+1	20	3
Local material	0	0	0		0+1	10	4
					10	**100**	

finished costs of each exterior cladding material, including 1 m² of craft. Life cycle repair costs are not taken into account in this example. The life span of the buildings varies depending on their quality, but it is around 50–60 years on average. It can be seen that some of the exterior cladding materials discussed have a longer life than the building's life. These features are not limited to the life of the building, and it is assumed that its longevity will contribute to its usability in recycling.

4.4. Order of Importance and Percentages of Qualifications

In Value Engineering, customer requests and demands are prioritized as much as possible. Customers' requests constitute the qualities that the solution to the problem must meet. However, the importance and priority of these qualities may vary according to customer expectations. Before proceeding to value analysis, different methods can be used to determine the customers' and value engineering team's ideas and priorities. This study used Nominal Group Technique and Priority Matrix Methods for this purpose.

4.4.1. Nominal Group Technique

The process of scoring the qualities, determined by brainstorming or another method by the value engineering team, in order of importance and ranking the values obtained by adding these scores is called the nominal group technique. Thus, the importance given by each stakeholder to the qualities is taken into account (Table 2).

4.4.2. Priority Matrix Method

In the Priority Matrix Method, the value engineering team compares qualifications with each other in pairs, and 1 point is given to the more critical and 0 points to the less important. The score of each qualification is summed and expressed as a percentage (Table 3).

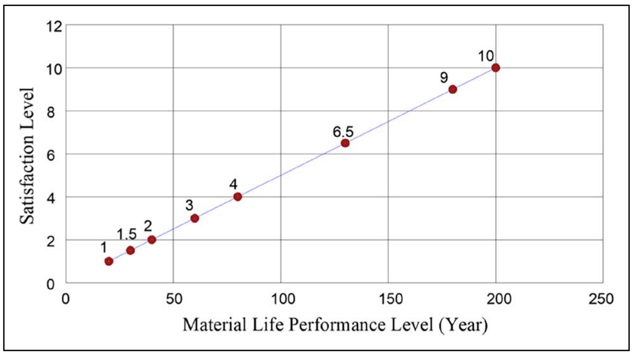

Figure 1. Material life performance – Satisfaction level graphic.

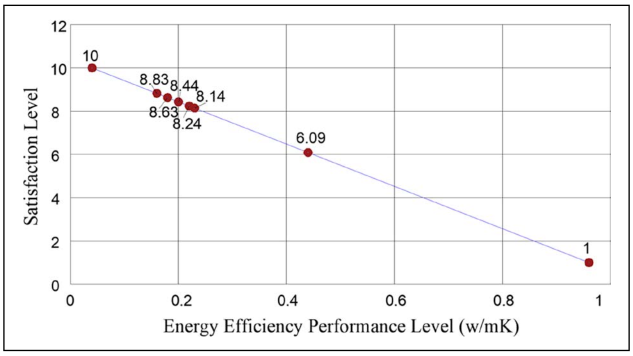

Figure 2. Energy efficiency performance – Satisfaction level graphic.

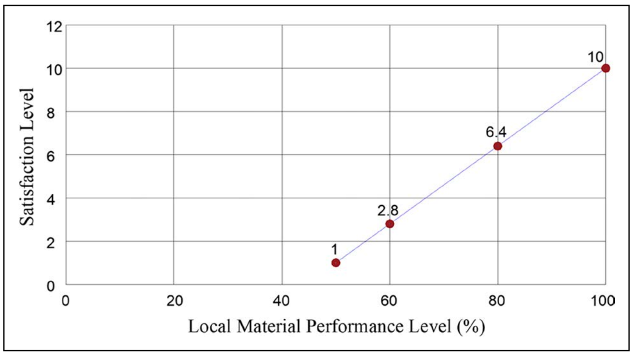

Figure 3. Local material performance – Satisfaction level graphic.

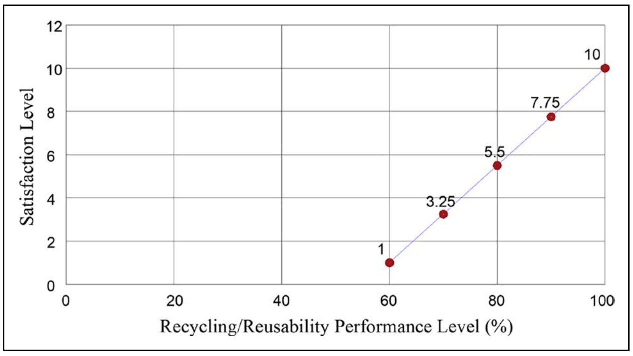

Figure 4. Recycling/Reusability performance – Satisfaction level graphic.

4.5. Satisfaction Levels of Materials

The level of satisfaction is a value for each product that indicates how satisfied the customer is with the specified qualities. It is determined by scaling from 1 to 10. When determining the satisfaction level, a graph shows the performance level of the materials on the horizontal axis and the satisfaction level on the vertical axis. The satisfaction level of the material with the lowest performance is taken as 1, the satisfaction level of the highest material is taken as ten, and a line is drawn. The satisfaction levels of other materials are determined according to their performance levels from this graph. This graph is drawn again for each qualification value. Satisfaction levels were determined for Material Life in Figure 1, Energy Efficiency in Figure 2, Local Material in Figure 3, and Recycling/Reusability performance levels in Figure 4.

4.6. Importance of Qualifications

The importance of exterior cladding materials is found by distributing the previously calculated importance percentages of each quality at the rate that the materials meet the performance of that quality.

For example, if the importance of aluminum for material life quality value is calculated;

Material Life quality value of aluminum: 130 years

Percentage of importance determined by the value engineering team for Material Life qualification value: 30%

Total Material Life qualification values of all materials: 130+30+200+80+40+180+60+20=740

In this case, the significance value corresponding to the ratio of aluminum to meet the total Material Life is calculated as 30x(130/740) =5.27.

All other Significances are calculated similarly. While it is more important that all other qualities are of high value except for the Energy Efficiency qualification value, it is more important that the energy efficiency qualification value is lower. Therefore, the importance of Energy Efficiency should be found with the inverse ratio when calculating the importance.

4.7. Qualification/Function Matrix

The Qualification/Function matrix was used to calculate the benefits of the qualifications of each exterior cladding material (Table 4). The importance and satisfaction levels corresponding to the qualification values for each exterior coating material were previously determined. After these are written in their places in Table 4;

Benefit = Importance x Satisfaction Level (5)

The benefits of all materials regarding qualification values are calculated with this formula. By adding these benefit values, each material has a total benefit. If desired, Function Benefit can also be obtained by adding the benefits of each qualification value for all materials.

Table 4. Qualification/function matrix

Material	Qualification	Energy efficiency	Material life	Recycling/reusability	Local material	Total
Aluminum	Importance	5.27	7.24	0.89	2.12	15.52
	Satisfaction level	6.5	8.83	1	3.25	19.58
	Benefit	34.26	63.93	0.89	6.89	**105.96**
PVC	Importance	1.22	2.96	1.07	2.43	8.51
	Satisfaction level	1.5	8.14	2.8	5.5	17.94
	Benefit	1.83	29.09	3.00	13.37	**47.29**
Glass	Importance	8.11	15.80	1.79	3.03	28.73
	Satisfaction level	10	10	10	10	40
	Benefit	81.11	158	17.9	30.30	**287.31**
Wood	Importance	3.24	3.62	1.79	2.73	11.38
	Satisfaction level	4	8.44	10	7.75	30.19
	Benefit	12.96	30.55	17.90	21.16	**82.57**
Fiber-cement	Importance	1.62	3.79	0.89	2.73	9.03
	Satisfaction level	2	8.63	1	7.75	19.38
	Benefit	3.24	32.71	0.89	21.16	**58**
Ceramic	Importance	7.30	0.66	1.43	3.03	12.42
	Satisfaction level	9	1	6.4	10	26.4
	Benefit	65.7	0.66	9.15	30.30	**105.81**
Precast	Importance	2.43	2.64	1.07	2.12	8.26
	Satisfaction level	3	6.09	2.8	3.25	15.14
	Benefit	7.29	16.08	3.00	6.89	**33.26**
Siding	Importance	0.81	3.29	1.07	1.82	6.99
	Satisfaction level	1	8.24	2.8	1	13.04
	Benefit	0.81	27.11	3.00	1.82	**32.74**
	Function's benefit	**207.20**	**358.13**	**55.73**	**131.89**	**752.95**

4.8. Value Calculation

Value of each exterior cladding material alternative;

Value = Benefit (Suitability for use)/Cost

formula, and thus it was determined which material was suitable for use in terms of value engineering (Table 5)

As a result of the value calculation, it was concluded that it would be appropriate to use the "Ceramic" material with the highest value (0.407) among the alternative exterior coating materials discussed.

Table 5. Value calculation for material selection

Material	Benefit	Cost (TL/m^2)	Value
Aluminum	105.96	1.277,23	0.083
PVC	47.29	714.90	0.066
Glass	287.31	6.176,87	0.047
Wood	82.57	880,00	0.094
Fiber-cement	58	605,01	0.096
Ceramic	105.81	260,25	**0.407**
Precast	33.26	2.824.82	0.012
Siding	32.74	963,19	0.034

5. CONCLUSION AND RECOMMENDATION

In this study, the exterior cladding material was determined using the Value Engineering method based on the LEED criteria in line with the sustainability principle of the structure to be built.

First, the problem was clearly revealed, and then a four-person Value Engineering Team consisting of people who may be interested in solving the problem was formed. In line with the LEED certificate, this team conducted a study on what the expectations may be from a product that can be the exterior coating material of a sustainable structure by brainstorming and other methods; hence, expectations, which are the criteria, were determined from the products. Subsequently, the alternative products that could meet these criteria were investigated, and eight products were determined. In order to determine to what extent these products could meet the determined criteria, their technical characteristics were researched, and these characteristics were digitized in the form of a scale.

Value Engineering tries to fulfill the wishes of the customers and all stakeholders involved in solving the problem at the optimum rate. For this reason, the criteria determined by the team were scored, and thus the ranking of importance and percentages of each criterion was identified. In order to perform Value Analysis, each product's satisfaction levels and importance were calculated, and its benefits were defined. The values of each product were estimated with the help of benefit and unit costs, and thus the material with the highest value was determined. Value Engineering chooses the alternative with the highest value as the solution to the problem. This study selected "ceramic" as the most valuable product.

Ceramic facade coating system is a vital coating material preferred in interior and exterior facades due to its features such as being easy to install, resistant to impacts and abrasions and all weather conditions, low water absorption, stain-free, having a large number of colors and size options and low maintenance-repair cost as a result of all these factors (although not taken into account in this application). Ceramic cladding systems prevent moisture formation due to the continuous air circulation within themselves. Joint gaps between the panels provide natural ventilation behind the facade. It is a natural material that complies with energy efficiency requirements, is fire-resistant, is safe from earthquakes, and has a high application rate [41].

Despite all these features, ceramic exterior cladding material cannot be claimed as the most environmentally friendly product. If the aim were to determine only the most environmentally friendly product, only the technical characteristics of the products would be considered, and the product that met the most desired criteria would be selected directly. Value engineering may require a product to meet different requirements, as well as the primary purpose, among the criteria it must meet when selecting a product. In addition, since the team members prioritize these criteria, each criterion contributes to the problem to a certain extent. In value engineering, the goal is to choose the least costly of the alternatives that can solve a problem. If the chosen alternative does not satisfy the selected team due to the calculations, it should not be involved in the problem from the beginning. In the study conducted here, there may be a more environmentally friendly product than ceramic. However, the value obtained when the benefit of each product is calculated by taking into account the determined criteria such as importance, satisfaction levels, etc., and divided by its unit cost, has led to choosing the "ceramic" coating material, which is among the alternative solutions, assuming that it is also among the environmentally friendly products. In other words, an optimization has been made.

Value Engineering does not offer the lowest-cost product as a solution. The goal is not just to cut costs; customer and stakeholder requests are also significant. Therefore, it proposes a value-based solution, not a cost-based one. The Value Engineering Method can be used to evaluate projects on a macroscale or to solve a problem related to the minor function of a project.

One of the essential things to remember is that the solution to this type of problem is not always the same. The fact that the Value Engineering team consists of different specializations, criteria, and preferred alternatives will also change the solution.

As a result, this study was prepared as an example for similar choices to be made. Only the construction costs were considered in this example, but also considering the life cycle costs would be ideal. For those who want to do similar studies later, it is also recommended to consider the life cycle costs.

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.

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Research Article

Comparative evaluation of mechanical performance of steel slag and earthen granular aggregates

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ABSTRACT

The diminishing quantity of natural resources has resulted in a search for alternative materials. Reusing industrial by-products, such as steel slag, provides opportunities for sustainable highway construction practices due to the valuable space they occupy and the potential environmental impacts when they are stockpiled. In this paper, the mechanical suitability of steel slag as an unbound highway aggregate is investigated, and its performance is compared with that of traditional graded aggregate base (GAB) materials. In order to compare the behavior, three steel slag samples with different aging properties and five aggregate samples from different quarries were employed. The results indicate that resilient moduli and permanent. Deformation characteristics of steel slag are comparable with those of traditional aggregates and can replace when used as a base or subbase course.

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1. INTRODUCTION

Stockpiling large quantities of steel slag, a by-product of steel production, has become an issue over the years as the practice takes valuable space in urban areas and may result in the leaching of undesired compounds into surface waters or groundwater [1, 2]. Thus, alternative applications for the use of steel slag need to be evaluated. Steel slag constitutes approximately 15% of 1 ton of steel produced, and in 2021 was estimated to total 190–280 million tons globally and 9 million tons in the United States [3]. Using steel slag in various applications, such as clinker cement aggregate or recycling in iron-making applications, has been extensively studied [4–11]. In addition, using steel slag in highway applications has been a very good research topic due to the consumption of larger volumes of the material [12]. Investigated the use of electric arc furnace (EAF) steel slag as an unbound granular aggregate for low-volume roads and showed that steel slag might have California Bearing Ratio (CBR) values up to 200%, and its resilient modulus is much higher than those of traditional aggregate materials. Various studies [13–16] evaluated the performance of EAF slag when used as an asphalt aggregate and showed that the mechanical performance of steel slag was comparable to that of natural aggregates. Ameri et al. [17] mixed steel slag with virgin aggregate and indicated that steel slag enhances the

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quality of cold-in-place-recycled asphalt mixtures. Maghool et al. [18] evaluated the mechanical and environmental impacts of EAF steel slag when used on highways and found that, especially when blended with a fine-grained material, EAF slag would have excellent mechanical characteristics to be used as a base layer.

Steel slag has high CaO and MgO content due to the composition of the fluxing agents used to purify the material, which results in the formation of calcium hydroxide (Ca(OH)2) upon reacting with water which ultimately causes volumetric expansion [19–21]. Past studies by Ozkok et al. [22] assessed the success of different mitigation methods, such as bitumen coating, bathing steel slag in either Fe(III), Al(III), or PO4(-III), and mixing steel slag with an alum-based drinking water treatment residual (WTR), and showed that WTR amendment proved to be the most effective method. However, Ca release was also reduced by about 50- 70% for the other methods. Steel slag can also be mixed with WTR to reduce the ultimate swelling potential [23] significantly. Similarly, studies conducted by [1, 2] revealed that when encapsulated by a clayey soil layer and/or by the presence of a clayey natural subgrade, both trace metal leaching and swelling potential of water treatment residual (WTR) treated basic oxygen furnace (BOF) steel slag are mitigated.

In order to evaluate the potential use of steel slag in highway base applications, a definition of its structural stability through resilient modulus tests is necessary. The test provides an essential input parameter for the pavement design, aligned with the mechanistic-empirical pavement design guidelines (MEPDG) to design flexible pavements [24]; however, high constant stresses are usually not applied on the materials for a very long period during the test, while they are being exposed to such stresses during their service life. Thus, permanent deformation tests are generally performed on unbound granular aggregates to determine their plastic deformation (rutting) potential [25–28].

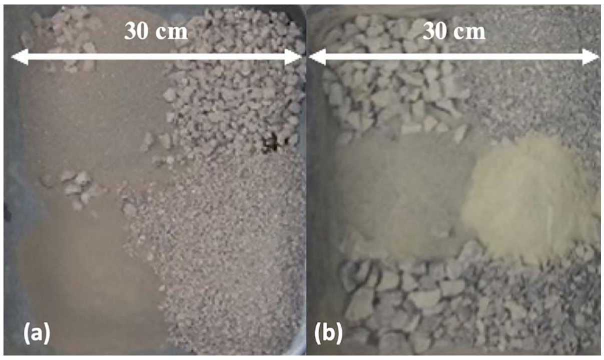

Figure 1. Materials used in this study **(a)** Steel Slag; **(b)** GAB Material.

The main goal of this study was to evaluate the stiffness and plastic deformation characteristics of steel slag and to compare them with those of graded aggregate base (GAB) materials. For this purpose, laboratory resilient modulus and permanent deformation tests were conducted on pure steel slag and GAB samples. In order to study the nonlinear behavior of steel slag and GAB materials, the model recommended by mechanistic-empirical pavement design guidelines (MEPDG) was employed. Furthermore, permanent deformation tests were performed on specimens with up to 10,000 load repetitions to determine the steel slag's plastic strain and compare its performance with natural aggregates.

2. MATERIALS

Three steel slag (S) materials with different aging properties (i.e., six months (S6M), one year (S1Y), and 2+ years (S2Y)) and five different graded aggregate base (GAB) ma-

Table 1. Gradation properties of the materials tested

Material	Gravel (%)	Sand (%)	FC (%)	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_u	C_c	Passing from 2-mm sieve (%)	Passing from 0.42-mm sieve (%)
S6M	35	53.5	11.5	4	0.65	0.07	57	1.5	46	25
S1Y	22.3	68.6	9.1	2.5	0.64	0.08	31	2	53	25
S2Y	20.7	67	12.3	2.5	0.55	0.045	53	2.7	54	27
GAB1	58	36	6	9.8	1.6	0.1	98	2.6	32	17
GAB2	46.8	44.6	8.6	6.7	0.5	0.085	79	0.44	44	28
GAB3	61	33	6	10.1	2	0.15	67	2.64	30	19
GAB4	58	36.7	5.3	10.1	1.5	0.15	67	1.49	34	16
GAB5	56	36	8	10.0	1.2	0.09	111	1.6	30	15
AASHTO (UL)	45	47	8	NA	NA	NA	NA	NA	NA	NA
AASHTO (LL)	65	35	0	NA	NA	NA	NA	NA	NA	NA

Note: S: Steel slag, GAB: Graded Aggregate Base, FC: Fines Content. NA: Not available. Cu: Coefficient of uniformity Cc: Coefficient of curvature, UL: Upper Limit, LL: Lower Limit. Values outside of the AASHTO Limits are in bold.

Table 2. Physical and chemical properties of the materials tested

Material	Physical properties						Chemical properties			
	Gs	I_P (%)	w_{opt} (%)	$\gamma_{dry\text{-}max}$ (kN/m^3)	USCS classification	AASHTO classification	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)
S6M	3.46	NP	10	23.9	SW-SM	A-1-b	11.48	4.10	36.45	32.84
S1Y	3.45	NP	11	22.5	SW-SM	A-1-b	12.18	3.68	35.93	32.42
S2Y	3.45	NP	13.5	22.2	SW-SM	A-1-b	11.65	3.60	37.12	32.41
GAB1	2.77	NP	5.8	23.9	GW	A-1-a	60.9	13.3	9.43	2.93
GAB2	2.79	NP	4.2	23.9	GW	A-1-a	44.1	3.04	1.57	26.8
GAB3	3.01	NP	5.3	24.8	GW	A-1-a	47.7	15.6	11.0	11.9
GAB4	2.68	NP	4.7	23.0	GW	A-1-a	11.9	1.95	0.85	31.7
GAB5	2.79	NP	5.2	23.4	GW	A-1-a	2.36	0.70	1.31	29.3

Note: Ip: plasticity index, Gs: specific gravity NP: non-plastic, wopt: optimum moisture content, γdry-max: maximum dry unit weight.

terials were included in the testing program (Fig. 1). The GAB and S materials were collected from different quarries in the eastern part of the United States and tested in the laboratory. Both materials contained coarse and non-plastic fine fractions. The gradation properties of the materials are provided in Table 1, whereas the index properties are given in Table 2.

The fines fraction of GAB and S are 5.3–8.6% and 9.1–12.3% by weight, respectively. Gradation properties of all three steel slag materials exceed the AASHTO M147 upper level for base aggregates. However, it should be noted that those specifications were developed for traditional GAB materials, and no specific limits were set for steel slag. The unit weight of GAB materials varies between 2.68 and 3.01 and agrees with the values reported by [29, 30]. The higher specific gravity of the slags as compared to earthen aggregates can be attributed to their higher Fe2O3 content (35.93–37.12% versus 0.85–11.0, Table 2), and previous studies reported comparable specific gravities for steel slag samples [31, 32]. GAB materials utilized in the current study were classified as A-1-a according to AASHTO, while the S materials were classified as A-1-b [33].

Slag particles' bituminous coating (BC) was achieved using an asphalt binder PG-64-22. The physical properties of the asphalt binder can be found in [34]. The asphalt binder (Gs= 3.45) is solid at room temperature and is viscous fluid at 90°C. Steel slag particles were mixed with 4% by-weight asphalt binder following the procedures outlined in [34].

Figure 2. Resilient modulus test setup.

3. METHODS

3.1. Resilient Modulus Test

The resilient modulus test is usually performed to obtain soil stiffness under confining stress and a repeated axial load. All the resilient moduli tests were performed by AASHTO T-307, a protocol for testing highway base and subbase materials [35]. The loading sequences used in the resilient modulus test are presented in Table 3. A vibratory compactor was used to place all GAB and S specimens in split molds with a diameter of 152 mm and a height of 305 mm per ASTM

Table 3. Testing sequences used for materials in this study (AASHTO T-307)

Sequence no	Confining pressure	Maximum deviatoric stress	Cyclic stress	Constant stress	No of repetitions
0 (Conditioning)	103.4	103.4	93.1	10.3	500
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

Table 4. Resilient modulus and permanent deformation test results

Material	SM_R (MPa)	Fitting parameters			R^2	εplastic (%)
		k_1	k_2	k_3		
S6M	94.8	442.80	1.324	-0.522	0.988	0.041
S1Y	184	1182.63	0.797	-0.374	0.987	0.039
S2Y	98.4	522.76	1.077	-0.396	0.990	0.055
GAB1	186	1096.53	0.983	-0.489	0.980	0.077
GAB2	249	1594.21	0.864	-0.487	0.988	0.043
GAB3	87	406.20	1.114	-0.135	0.987	0.066
GAB4	130	765.36	0.950	-0.426	0.979	0.078
GAB5	117	647.50	0.995	-0.354	0.996	0.060

Note: S: Steel slag, GAB: Graded aggregate base, SMR: Summary resilient modulus.

D 7382. All materials were compacted in six layers at their optimum moisture contents and maximum dry unit weights.

A Geocomp LoadTrac-II loading frame and associated hydraulic power unit system was used to load the specimens (Fig. 2). A conditioning stage was performed on the specimens before actual test loading under the same confining and axial stress of 103 kPa for 500 repetitions. The confining stress was constrained between 20.7 and 138 kPa during the loading stages, while the deviator stress was raised from 20.7 kPa to 275.8 kPa with 100 repetitions at each step. Resilient modulus 5.0 software was used to keep track of the loading sequence, confining pressure, and data acquisition. External linear variable displacement transducers (LVDTs) with a measurement capacity of 50.8 mm were utilized to measure the deformations. In order to obtain the resilient modulus for each load sequence, the average moduli from the last five cycles of the corresponding sequence were calculated. The following model in the Mechanistic-Empirical Pavement Design Guide (MEPDG) [36, 37] was used to calculate the resilient moduli:

$$M_R = k_1 \times P_a \times (\frac{\theta}{P_a})^{k_2} \times (\frac{\tau_{oct}}{P_a} + 1)^{k_3} \quad (1)$$

where M^R= resilient modulus; k_1; k_2, and k_3 are constants; θ = bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$) ; P_a = atmospheric pressure. τ_{oct} is octahedral stress depending on the principal stresses acting on the sample and calculated as follows:

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \quad (2)$$

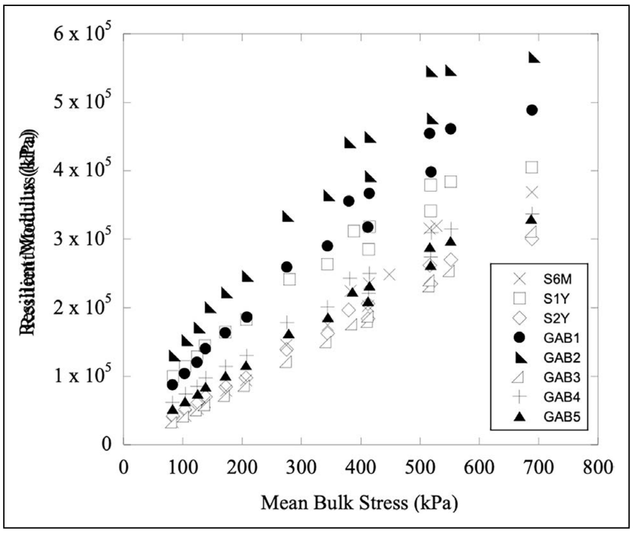

Figure 3. Resilient moduli of GABs and steel slags at different loading sequences.

The resilient modulus data at a bulk stress of 208 kPa computed by National Cooperative Highway Research Program 1-28A was named the summary resilient modulus (SM_R) ([38]). The resilient modulus test results are summarized in Table 4 and Figure 3.

3.2. Permanent Deformation Test

In order to obtain the plastic strain characteristics of the specimens, a battery of permanent deformation tests was performed by AASHTO T-307 ([35]). The samples were subjected to the same preconditioning steps; however, after the preconditioning stage, the specimens were subjected to 10,000 load repetitions under 103.4 kPa confining pressure and 206.8 kPa deviator stresses in order to measure the permanent deformations. Permanent deformation tests were terminated after 10,000 load repetitions were completed or a plastic strain of 5% was reached.

4. RESULTS

4.1. Resilient Modulus Test

The results of the resilient moduli test for all samples are presented in Figure 3 and Table 4. There is a near-linear relationship between bulk stress and resilient modulus, as observed in earlier studies [24, 27, 39–43]. The data in Figure 3 and Table 4 indicate that the SM_R of steel slag (S) is comparable to those of GAB materials. The SM_R values obtained for steel slag samples agree with the findings of [12] but are slightly lower than those reported by [44]. However, it should be noted that the latter study used an empirical equation to obtain M_R from the laboratory CBR test results. Although the steel slag samples have a lower gravel fraction, higher fines content, and higher optimum moisture content, their resilient moduli remained within the range of resilient moduli of traditional GAB materials. This phenomenon might be due to their relatively higher angularity and roughness [12, 24], even though such measurements were not made in the current study [45] reported that the resilient modulus of steel slag is significantly dependent on deviator stress, and the fine fraction of steel slag may be responsible for the observed behavior. No apparent correlation exists between the aging period and resilient modulus since the maximum and minimum SM_R was observed for S1Y and S6M, respectively. However, Table 4 indicates that the highest unit weight results in the lowest SM_R, agreeing with the findings of [46].

Table 4 indicates that all k_3 values are negative and vary between -0.135 and -0.522, most probably because the granular materials used in this study are affected by bulk stress [24]. Furthermore, the results show that the resilient moduli values depend on the bulk stress level applied. At the lower bulk stress levels (100–500 kPa), the minimum and maximum M_R were computed for GAB2 and GAB3, respectively, while at the higher bulk stress levels (600 700 kPa), the minimum M_R was calculated for S2Y.

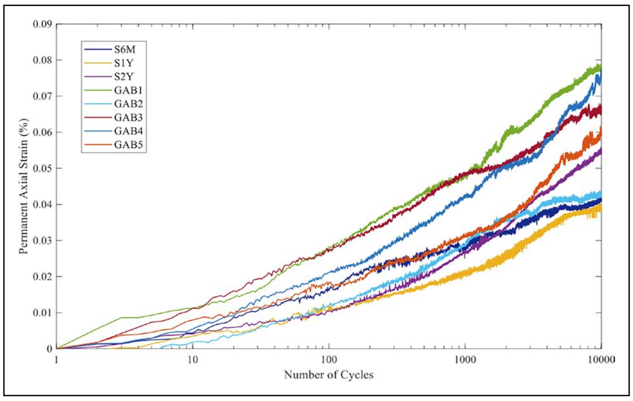

Figure 4. Permanent strains of the GABs and steel slags.

4.2. Permanent Deformation Test

Table 4 and Figure 4 show the plastic strain of all materials used in the current study. GAB1 has the maximum plastic strain (0.078%), whereas S1Y has the minimum plastic strain (0.039%) after 10,000 repeated loading cycles. In general, steel slags yield lower plastic strains when compared with the GAB materials (ε=0.039-0.055 versus 0.043-0.078), suggesting a better performance for the slags under a specific load for the long term. Upon subjecting to 10,000 repeated cycles of loading, GAB4 shows the maximum plastic strain (0.078%), whereas GAB2 has the minimum plastic strain (0.043%) among the GABs tested, which may be attributed to the gravel and acceptable content of these two GABs (Table 1). GAB4 has a relatively higher gravel content (58% versus 46.8%) and lower fines (5.3% versus 8.6%) than GAB2, resulting in a larger void ratio for GAB4. The large voids between the particles and lack of fines may have resulted in more significant deformation during repeated loading [47].

5. CONCLUSIONS

A series of laboratory tests were conducted to study the resilient modulus and permanent deformations of a steel slag material and to compare the measured values to those of natural aggregates. In addition, the swelling potentials of pure slag, as well as Bitumen-coated slag particles were determined in accelerated swelling tests. The following conclusions can be drawn from the findings of this study:

- Resilient moduli of steel slag with different aging properties were comparable to those of traditional graded aggregate base materials. Although the tested steel slag samples have lower gravel fraction, higher fines content, and higher optimum moisture content, the SM_R of steel slag samples remained within the range of values for graded aggregate base materials.
- In general, steel slag materials yielded lower plastic strains as compared to GAB materials. These results show that steel slag performs better than GAB under a specific load for the long term.
- All three steel slag materials with different aging properties exceeded the 0.5% swell limit set by ASTM D 2940 at seven days.
- The aging process did not seem to influence the ultimate swelling of steel slags, contrary to findings reported in past studies. Surface area and fines content may be the dominant factors for Ca-release potential and measured swelling ratios.
- Even though the mechanical test results showed that steel slags could be potentially used instead of earthen aggregates, the pollution and pH characteristics of steel slags must be evaluated in the laboratory and field.

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ETHICS

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

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

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Research Article

Assessment of iron tailings as replacement for fine aggregate in engineering applications

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ABSTRACT

This study evaluated the suitability of iron tailings as fine aggregate replacements for engineering applications. This is necessary to find economic usage for the enormous amount of waste from Itakpe mines. The physical properties of specific gravity, bulk density, moisture content, particle size, fineness modulus, and mechanical properties in terms of compressive strength, compaction factor, flexural strength, and relative density of the concrete made with iron tailings were determined. World Health Organization (WHO) standard methods for examining water and wastewater were used to analyze water used for curing the concrete cubes and beams to ascertain toxicity. The result shows the workability of concrete made with 50% iron tailings within the standard limit. The compressive strength at 28 days for 0% to 100% percentage replacement increases from 10.1N/mm^2 to 15.3N/mm^2. Therefore, replacing sand with the iron filling will improve the compressive strength of any concrete. The flexural strength analysis shows that the iron tailings concrete beam increases the flexural strength from 15N/mm^2 to 16.9N/mm^2 from 0 to 100% at 28-day curing. There is also a linear relationship between the flexural strength and the density of the iron tailing concrete. The pH and Alkalinity tests of the water used to cure the iron tailing concrete indicate that the curing water's alkalinity was high (20.883 to 40.75) with a pH range of 12.1-12.4. This shows that using iron tailing will not harm the durability of the resulting concrete. The iron tailings are suitable for acceptable aggregate replacement up to 75% without negatively altering the mechanical properties of such concrete.

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INTRODUCTION

Mining activities involve the separation of valuable minerals from the surrounding waste rocks, which often litter the vicinity of the mine, where they remain unsightly features in the natural landscape [1]. Iron-ore tailings are waste materials obtained in the Iron ore mine after the extraction of Iron from the ore. The Iron tailings are alkaline in nature with a pH value of 7.0-8.5, unfit for farming and making the land barren. It is, therefore, necessary to permanently dispose-off unwant-

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ed or unused materials or find an alternative usage for these wastes. The disposal of the mine tailings continues to burden the mining industries and the general public regarding economic and environmental health, respectively. Pollution concern is also one of the main issues for the mining industry. Therefore, the need to get environmentally friendly and sustainable disposal methods. After successful disposal of the tailings, there is also the need to monitor and manage the tailings site [2]; prevention of erosion, development of acid mine drainage (AMD), and dam failures must be ensured [3, 4]. They can also release toxic and heavy metals into the environment. The industries are therefore confronted with mine and post-disposal costs, which deplete substantial profit from their production. There are pretty several iron ore mining sites in Nigeria and worldwide. Concrete, on the other hand, is a construction material that is valuable and widely acceptable. One of concrete's significant constituents is fine aggregates that have recently experienced cost escalation. This, in turn, has increased the cost of concrete and made the cost unfriendly to the construction industries and other stakeholders. There is, therefore, a dire need to source for an alternative. Waste rocks such as tailings are abundant and can be utilized for this purpose. This will reduce groundwater pollution caused by leachates from the heaps of iron ore tailings and reduce the overall cost of concrete production. Tiwari et al. [5] predicted that the advancement in concrete technology could reduce the consumption of natural resources and energy sources and lessen the burden of pollutants on the environment if wisely utilized. They considered the feasibility of using Iron Ore Tailing (IOT) as a partial replacement for sand (or Fine Aggregate). This research has assessed the possibility of partially replacing fine aggregates with iron ore tailings.

MATERIALS AND METHODOLOGY

The primary materials employed in this research were iron tailings, sharp sand, 19 mm granite aggregates, water, and cement. Samples of iron tailings were collected from the final tailings dump in the beneficiation section of the National Iron Ore Mining Company (NIOMCO) in Itakpe, Kogi State, Nigeria. In contrast, 19 mm granite aggregates were collected from Zibo Quarry in Ijare Ondo State, and sharp sand was collected from the Bonvick block industry in Akure Ondo State. Samples of sharp sand were replaced with 15%, 25%, 50%, 75%, and 100% of IOT denoted as T15, T25, T50, T75, and T100, respectively, while the control sample (100% sharp sand) was denoted as T0. The samples were subjected to various tests, as highlighted below.

Uniaxial Compressive Strength: This was carried out to know the maximum compressive strength capacity of iron tailings at 0, 15, 25, 50, 75, and 100% as an acceptable aggregate replacement, which could sustain under a gradually applied load of compressive stress without fracture. The compressive strength test used a concrete cube of 100 X 100 X 100mm. The concrete cube was made and cured in water for seven days, 14 days, 21 days, and 28 days. They were removed after the specified time for crushing. Compressive strength was calculated by dividing the maximum load by the original cross-sectional area of a specimen by the provision of ASTM [6]. The mixed proportioning of the materials used for the compressive strength test is shown in Table 1.

Flexural Strength: This was carried out to know the maximum bending stress capacity of iron tailings at 0, 15, 25, 50, 75, and 100% as acceptable aggregate replacement. The flexural strength test was conducted using a concrete cube of 500 X 100 X 100 mm. The concrete cube was made and cured in water for seven days, 14 days, 21 days, and 28 days. They were removed after the specified time for testing. Flexural strength was calculated by dividing the maximum load by the original cross-sectional area of a specimen by the provision of ASTM [7].

The mix proportioning of the materials used for the flexural strength test is shown in Table 2.

Toxicity Test: This was done on the curing water from day seven till day twenty-eight by carrying out Alkalinity, pH, and Hardness tests in order to ascertain no seepage of heavy metals in the iron tailings concrete cubes and beams when it is used in water structures like reservoir and well rings which was done relatively to WHO [8].

Table 1. Mix proportioning by mass of materials used for the compressive strength test

S/N	Percentage Replacement (%)	Cement	Sand	IT	Granite
1.	0	9.63	19.30	0	38.52
2.	15	9.63	16.40	2.90	38.52
3.	25	9.63	14.47	4.83	38.52
4.	50	9.63	9.60	9.70	38.52
5.	75	9.63	4.80	14.50	38.52
6.	100	9.63	0	19.30	38.52

Key: IT means Iron tailings.

Table 2. Mix proportioning by mass of materials used for the flexural strength test

S/N	Percentage Replacement (%)	Cement	Sand	IT	Granite
1.	0	20.8	41.60	0	83.20
2.	15	20.8	35.36	6.24	83.20
3.	25	20.8	31.20	10.40	83.20
4.	50	20.8	20.80	20.80	83.20
5.	75	20.8	10.40	31.20.	83.20
6.	10%	20.8	0	41.60	83.20

Key: IT means Iron tailings.

PROPERTIES OF THE RESEARCH MATERIALS

Characterization and Chemical Analysis of the Iron Ore Tailings

Sample Digestion: Samples of iron tailings were digested by adding 1g with 10 ml mixture of HNO_3 and HCl. The mixture was after that heated for 15mins by the open-air method. A color change from blackish-grey to pale yellow was noted. On cooling, decantation was done (to separate the filtrate from the residue) then the filtrate was added to aqua reagent solution (HNO_3 and HCl). Distilled water was diluted to the required volume of 100 ml by ASTM [9].

X-ray Fluorescence Analysis: It involves the emission of characteristic secondary X-rays from a material that has been excited by being bombarding it with High-Energy gamma rays, commonly designated an electric lamp-like device emitting ultraviolet radiations or black light. The concentration of heavy metals in the iron tailings, including Pb, Ni, Cd, and Ti, was examined to ensure that the materials were non-hazardous per ASTM [10].

RESULTS AND DISCUSSION

Bulk Density and Specific Gravity Tests: The bulk density of iron tailings (2121.9 kg/m^3) is higher than that of the sharp sand (2118.3 kg/m^3). Samples of iron tailings used have an average specific gravity of 4.13 compared to the specific gravity of sharp sand (2.97). This high specific gravity can be traced to iron content since its density is more significant than sand. Therefore, concrete cubes and beams made with the tailings are expected to have high specific gravity with high strength and less possibility of deformation resulting from external loads [11].

Particle Sizing: The particle size analysis of the iron tailings samples is shown in Figure 1. The iron ore tailings sample is of a high coarse and high medium grains size and 30% fines in terms of its structure in granular form. This is responsible for the increased compacting density of the iron tailing obtained. Figure 2 also shows the particle size analysis of the sharp sand samples. Similarly, the sharp sand is of a high coarse and high medium grains size and 27% fines in its structure in granular form resulting in its high compacting. The two figures indicate iron tailing to be well-graded while the sand is uniformly graded.

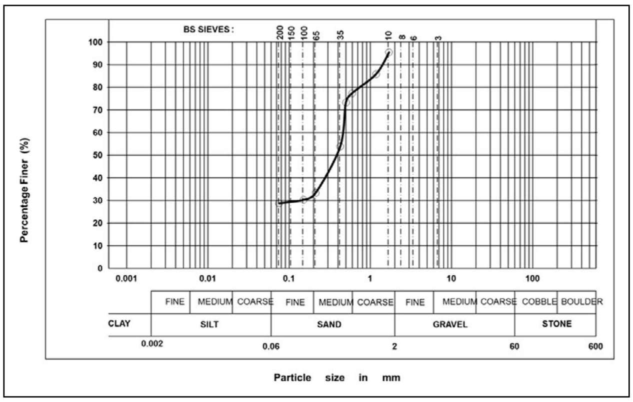

Figure 1. Particle Size and Texture of Iron Tailings.

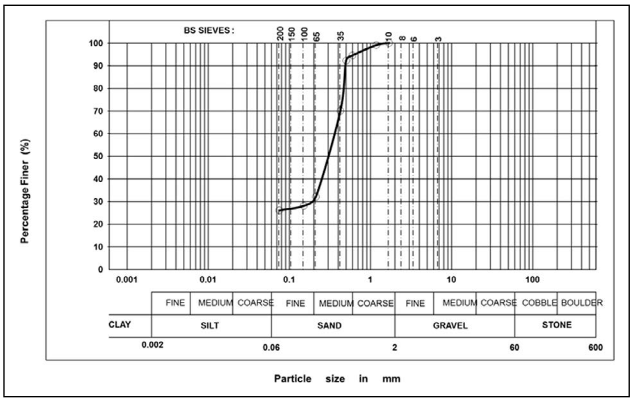

Figure 2. Particle size and Texture of Sharp Sand.

Fineness Modulus: The fineness modulus of the iron tailings is shown in Table 3. This result shows that the material used lies within fine and medium sand grains suitable for making satisfactory concrete cubes and beams in accordance with ASTM [12].

Coarse Aggregates: The aggregate impact value (AIV) and specific gravity of granite used in this study are 19.1 % and 2.73, respectively. This makes the granite aggregate competent as an Aggregate Impact Value of 19-21% is desired [12].

Table 3. Fineness Modulus for Aggregates of different Sieves Sizes

Aperture size	Sharp sand	Iron Tailings	15%	25%	50%	75%
1.8 mm	0	0	0	0	0	0
1.7 mm	0.02	22.8	3.44	5.72	11.41	17.11
1.18 mm	4.5	47.7	10.98	15.3	26.1	36.9
600 microns	22.8	42.2	25.71	27.65	32.5	37.35
500 microns	11.2	20.6	12.61	13.55	15.9	18.25
425 microns	111	97.7	109.01	107.68	104.35	101.03
212 microns	189.8	102.4	176.69	167.95	146.1	124.25
150 microns	20.2	15.3	19.47	18.98	17.75	16.53
75 microns	10	7.5	9.63	9.375	8.75	8.125
pan	130.48	143.8	132.48	133.81	137.14	140.47
	500	500	500	500	500	500

Curing Water: The potency of hydrogen ion concentration, an average of total alkalinity test, and hardness test of the water sample used for curing every seven days of crushing test done by WHO's Drinking water standards (2008) is presented in Table 4. The results show an increase in the alkalinity of the curing water from 20.883 to 40.75mg/l and hardness from 209.023 to 297.025mg/l. This implies that the reaction releases hydrogen iron as the end product when iron tailing partially replaces sand. This benefits concrete durability [13].

Chemical Analysis of Iron Tailings

Table 5 shows the chemical analysis of iron ore tailings. Metals that are toxic when in contact with environmental media, such as lead, nickel, cadmium, and titanium, were analyzed but were found below the detection limit, which differs entirely from the chemical composition analysis carried out by (Shettima et al., [14], other elements like copper were analyzed. They were not detected in the iron tailings. This makes the tailings environmentally friendly when partially replaced or entirely replaced in construction works as there cannot be fear of seepage of toxic heavy metals, which are inimical to healthy living into the ecosystem due to its usage.

Table 4. The pH, total alkalinity, and hardness of the water sample for curing every seven days of crushing test

Water Sample @	pH	Total Alkalinity (mg/l)	Hardness (mg/l)
7 Days	12.1	20.833	209.023
14 Days	12.3	21.85	219.145
21 Days	12.3	29.84	229.231
28 Days	12.4	40.75	297.025

Cement Test

Fineness and Soundness Test: The cement used had a fineness percentage of 9.89 and a soundness value of 5.6. These value (fineness and soundness) shows that the cement used is not adulterated, as adulterated cement will have a fineness and soundness percentage that will exceed ten percent (10%). This is the ability of a hardened cement paste to retain its volume after setting to assert if it has not been subjected to delayed destructive expansion due to the presence of excessive free lime or magnesia.

Consistency, Initial and Final Setting Time Test Result: The Setting time of a Lafarge cement used in this study was done by the ASTM [15].

Workability Test: Table 6 shows the workability tests (compaction and slump tests) results for fresh concrete made with different aggregate replacement mixtures. The workability decreases with an increase in Iron tailings which is very different from the research done by Owolabi [1] because of the post-beneficiation tailings used in this study.

The compressive strength replacement for the various concrete mixes made from the partial replacement of the fine aggregates with iron tailing is shown in Figure 3. The compressive strength at 28 days for 0% to 100% percentage replacement increases from 10.1N/mm^2 to 15.3N/mm^2. The same trend of increment in the compressive strength was also observed for all the remaining curing days. There is an improvement in the compressive strength for all the

Table 5. Chemical analysis of iron tailings (ppm)

Element	Fe	Mn	Zn	Ca	Na	K	Ni	Pb	Al	Si
Amount	622	1.92	0.39	1.59	5.66	0.66	0.01	0.21	0.0008	0.0014

Table 6. Workability classification

Replacement with IOT	Compaction Factor	Slump (mm)	Workability Classification
0%	0.96	98.0	Medium
15%	0.97	70.0	Medium
25%	0.92	90.0	Medium
50%	0.94	85.0	High
75%	0.94	80.0	Medium
100%	0.87	85.0	Medium

curing days considered and the percentage of iron tailing (IOT) replacement considered. The sharp increase at 75% replacement of sharp sand with iron tailings could be because iron tailings are more resistant to compressive force than sharp sand. After all, the result was consistent on all the days. This indicates that fine aggregates can be replaced with IOT without impairing the compressive strength of such concrete. This was also similar to the result obtained by Arum and Owolabi [13].

Figure 4 shows the flexural strength of cast beams. The results follow the same trends for all the curing days. A reduction is noticed at seven days and 14 days of curing, while at 21 days and 28 days of curing, the flexural strength at 75% replacement of the IOT shows comparable results. The higher flexural strength obtained at 75% indicates that iron tailings are more resistant to bending than sharp sand. This is in line with the fundamentals of reinforced concrete properties. However, for flexural strength stability, the percentage replacement of the fine aggregates with the IOT should not exceed 75%.

The result of the density of the Beams used for Flexural strength is presented in Figure 5. The result is similar to the flexural strength obtained in Figure 4. This is an indication that there is a linear relationship between the flexural strength of any concrete and its density. The flexural strength depends on the concrete's density, as Figure 6 shows that the higher the density, the higher the bending stress of the casted beams and satisfies the null hypothesis.

Results of Toxicity Test

The chemical composition of iron tailings is non-acidic, as the suspected harmful elements were analyzed and found beyond the detection limit. Also, the potency of hydrogen in the iron tailings had normal basicity, average hardness value, and World Health Organisation alkalinity standard for portable water achievable, making it portable for drinking. The negative toxicity result makes it highly environmentally friendly. Thus, suitable for industrial and commercial construction purposes.

Figure 7 shows the pH of the curing water used for curing the concrete at 7, 14, 21, and 28 days. Using IOT will reduce the pH of the concrete, as shown in Figure 7. The pH of the curing water increases with age. This can be attributed to the reaction of the Iron tailing with the other constituents of the concrete.

Figure 8 shows the average alkalinity values of the iron tailings curing water sample casted cubes and beams at 7, 14, 21, and 28 days. The curing water at seven days has a normal alkalinity of 20.8 mg/l, while at 14, 21, and 28 days gives good normalized caustic bases values of 21.85, 29.84, and 40.75 mg/l, making the water drinkable as the normal drinkable water alkalinity should be between 20 – 200 mg/l. The alkalinity increases with curing days.

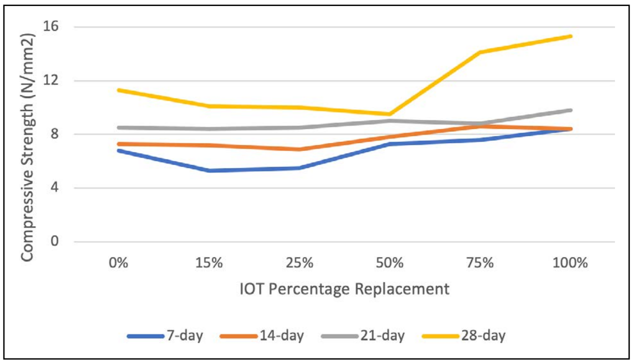

Figure 3. Compressive Strength of iron tailings concrete cubes.

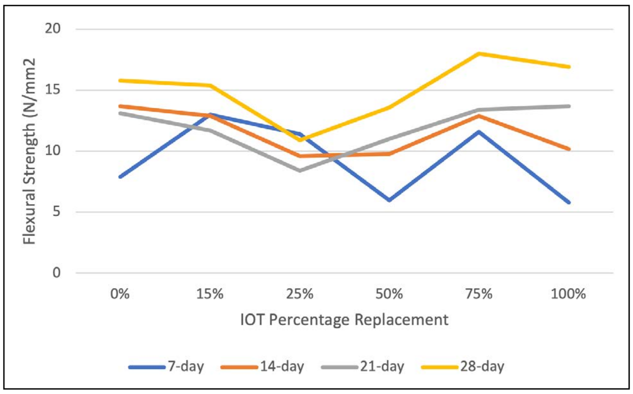

Figure 4. Flexural Strength of casted Beams.

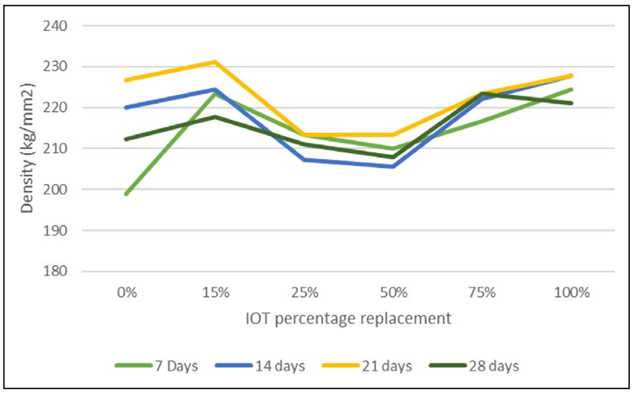

Figure 5. Density of the beams used for flexural strength.

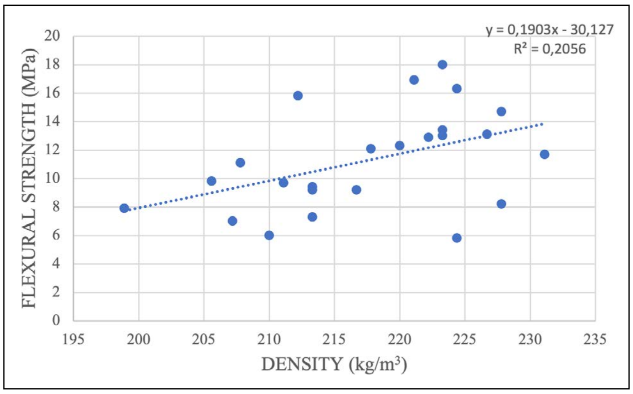

Figure 6. Relationship between density and the flexural strength of the casted Beams.

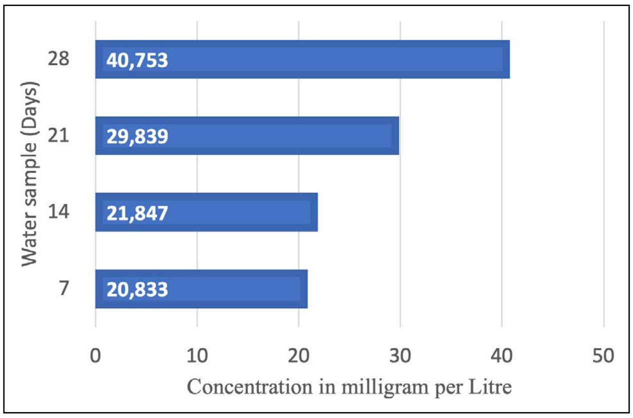

Figure 8. Alkalinity of the curing water at 7, 14, 21, and 28 days.

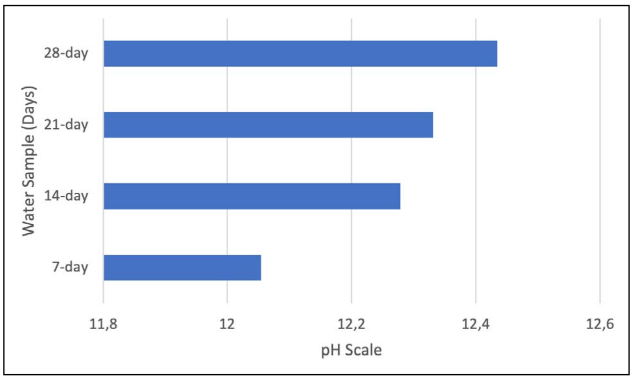

Figure 7. The pH of Curing Water on Different Days.

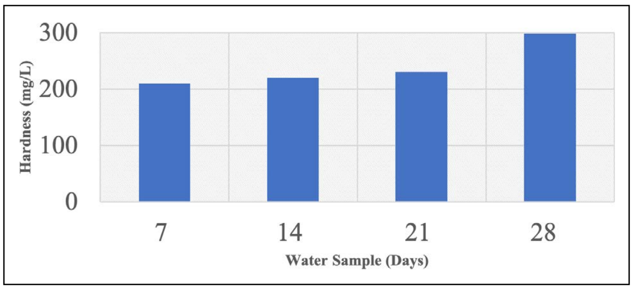

Figure 9. Hardness of curing water sample for seven, fourteen, twenty-one, and twenty-eight days.

Figure 9 shows the hardness values of the curing water sample of the iron tailings cast cubes and beams for 7, 14, 21, and 28 days. The hardness of the twenty-eight days curing water was higher at 297.03 mg/l than the twenty-one, fourteen- and seven-day water samples with 229.23, 219.15, and 209.02 mg/l, respectively. There is an increase in the alkalinity.

CONCLUSION AND RECOMMENDATION

This research has shown that iron tailings can successfully replace river sand as fine aggregates without compromising the compressive strength and the flexural strength of such concrete when the iron tailings are available as waste without a reasonable means of disposal. It was indicated that when 75% of it is blended with 25% river sand, the resulting concrete can have a strength value of about 7% higher than the strength of concrete produced with 100% river sand fine aggregate. The research also showed that the highest strength with iron ore tailings resulted when 100% iron tailings were used as the acceptable aggregate content. This compressive strength value is 15.3N/mm^2 in this research. The alkalinity of the curing water shows that using the iron tailings will not impair the durability of such concrete if used in reinforced concrete. There is a relationship between the density and the flexural strength of concrete beams cast; thus, the higher the density, the higher its bending stress.

The iron tailings can be used to construct water structures like reservoirs and well rings without any fear of the seepage of toxic elements, making it environmentally friendly.

ETHICS

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

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

PEER-REVIEW

Externally peer-reviewed.

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Research Article

Synthesis of macrocyclization cyclophanes and their metal complexes, characterization and antimicrobial activity

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ABSTRACT

Due to their chemical properties, cyclophane-type compounds constitute an interesting organic chemistry class. In the structure of all cyclic compounds, macrocyclization is the most critical issue for high-efficiency synthesis. Especially with a small cyclophane structure, the experimental steps are more complicated than with a prominent cyclophane structure. In this manuscript, three different material groups were applied to synthesize silver cyclophane compounds for smart drug properties. In the first material group, 5,6-dimetil-1H-benzo[d]imidazole (1) and 2,6-bis(chloromethyl)pyridine (2) were reacted to form 5,6-dimethyl-1-((6-((5,6-dimethyl-1H-benzo[d]imidazole-1-il)methyl)pyridine-2-il)methyl)-1H-benzo[d]imidazole compound (3). In the second material group, ethyl 2-bromoacetate (4) reacted to different nitrogen atoms of the cyclophane compound to form a symmetric carbene compound, which is water-soluble (5). In the third material group, the silver (I) and palladium (II) metal complexes were synthesized due to the reaction with silver(I) oxide (6) and palladium (II) chloride (7). Antimicrobial activities of the carbene compounds and silver and palladium complexes (5, 6, and 7) were investigated against bacteria and fungal in more detail. Silver (I) complex (6) shows an antimicrobial agent when mixed with microorganisms, such as Gram-positive, Gram-negative, and fungal, but this property has not been observed in the palladium (II)-carbene complex (7).

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1. INTRODUCTION

Cyclophanes are heterocyclic compounds that combine a benzene ring and a chain that can form a bridge between two non-adjacent positions of the aromatic ring. More complex derivatives, including many aromatic units and bridged compounds, have been synthesized in literature [1, 2]. Cyclophanes are the most well-known and studied compounds inside organic compounds [3, 4]. Different methods were used to form more stable and well-designed compounds in the ring closure step.

Cyclophane compounds have attracted the attention of chemists in recent years and have led to the develop-

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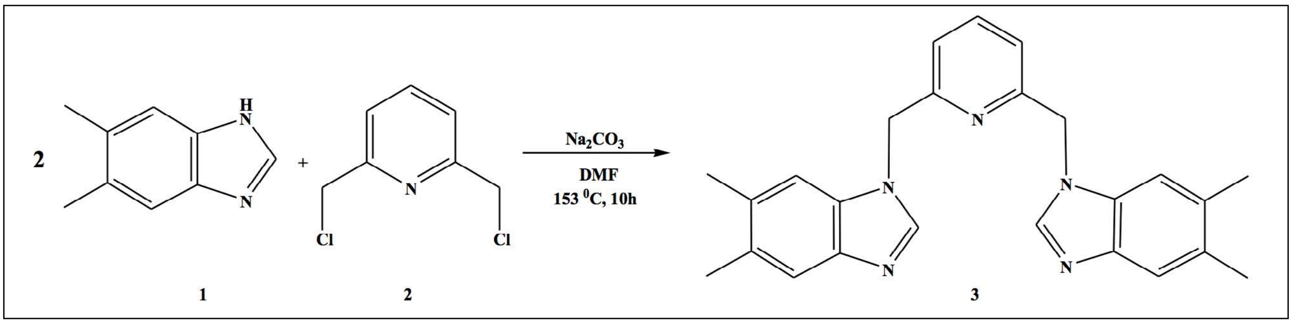

Figure 1. Synthesis ways of macrocycocyclic compounds.

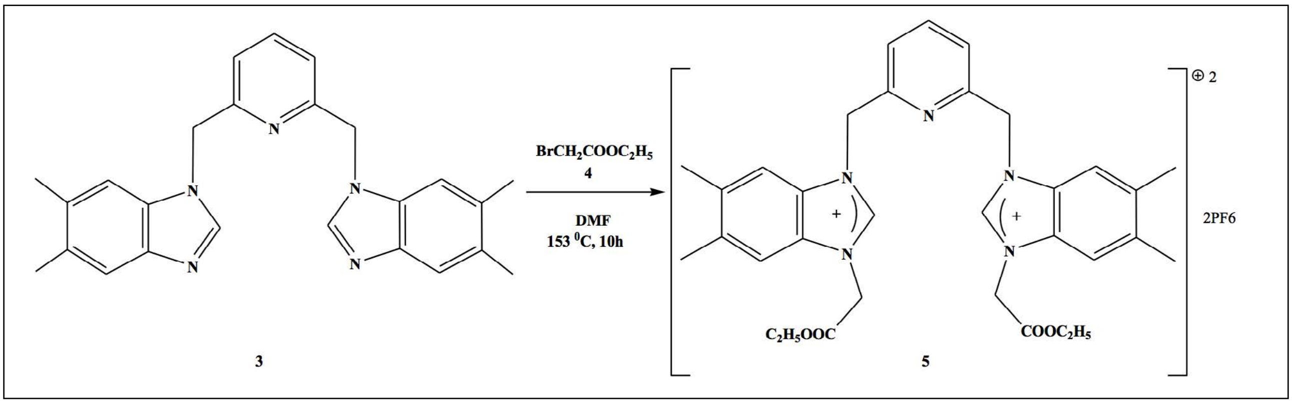

Figure 2. Synthesis methods of carbene compounds.

ment of synthesis methods for chemical reactions [5]. The first cyclophane compound, metacyclophane [6], was synthesized at the end of the 19th century (Fig. 1). The development of cyclophane chemistry began with the scientists Brown and Farthing [7]. The multilayer compounds were obtained as bridged purchased compound 1 (Fig. 2) [8, 9]. Compounds were characterized by different methods to understand bent and contracted benzene rings in the layered structures [10]. In addition, metal complexes were synthesized from 5,6-dimethylbenzimidazolium-linked cyclophane. The critical parameters of these compounds have been obtained as catalytic activities and high stability [11–13].

Chelated palladium (Pd), platinum, and nickel o-cyclophane complexes are highly stable materials. In Heck-type reactions, this stability and other geometric effects contribute significantly to the catalytic activity of o-cyclophane Pd(II) complexes [14]. The synthesis method of 5,6-dimethylbenzimidazolium-linked cyclophanes is similar to the synthesis method of other imidazolium salts [15, 16].

The silver (Ag) metal and silver salt compounds have been used for antimicrobial activity [17]. The synthesis and structural analysis of 5,6-dimethylbenzimidazolium-linked cyclophanes and their metal complexes are investigated in the literature. The antimicrobial activity of silver(I) carbene complex with water-soluble properties on some types of bacteria has been reported [18, 19].

As a result, three different material groups were applied to synthesize silver cyclophane compounds for innovative drug properties. Moreover, this article studied the antimicrobial activities of the carbene compounds and silver and palladium complexes against bacteria and fungi.

2. MATERIALS AND METHODS

2.1. Materials and Measurements

2,6-bis(chloromethyl)pyridine ($C_7H_7Cl_2N$≥99.00%), 5,6-dimetil-1H-benzo[d]imidazole ($C_9H_{10}N_2$≥99%), ethyl bromoacetate ($C_4H_7BrO_2$≥98%), deuterium oxide (D_2O≥99.95%), deuterated chloroform ($CDCl_3$≥99.80%), N,N'-dimethylformamide (DMF≥99%), ethanol (C_2H_5OH≥99%), potassium hexafluorophosphate (KPF6≥99%), sodium carbonate (Na_2CO_3≥99%), hexane (C_6H_{14}≥99%), ethyl acetate ($C_4H_8O_2$≥99.50%), silver(I) oxide (Ag_2O≥99%) and palladium(II) chloride ($PdCl_2$≥99%) were purchased in different companies. Gram-negative, Gram-positive bacteria, and fungal strains were used for antimicrobial tests.

2.2. Instrumentations

In this study, Nuclear magnetic resonance spectroscopy (^{1}H-NMR, ^{13}C-NMR, Varian As 300 mercury), Fourier transform infrared spectroscopy (FT-IR, ATI Unicam 1000), Four-point probe (Qiatek, FFP 4), Thermogravimetric analysis (TGA 400, Perkin Elmer EXSTAR 6300), melt-

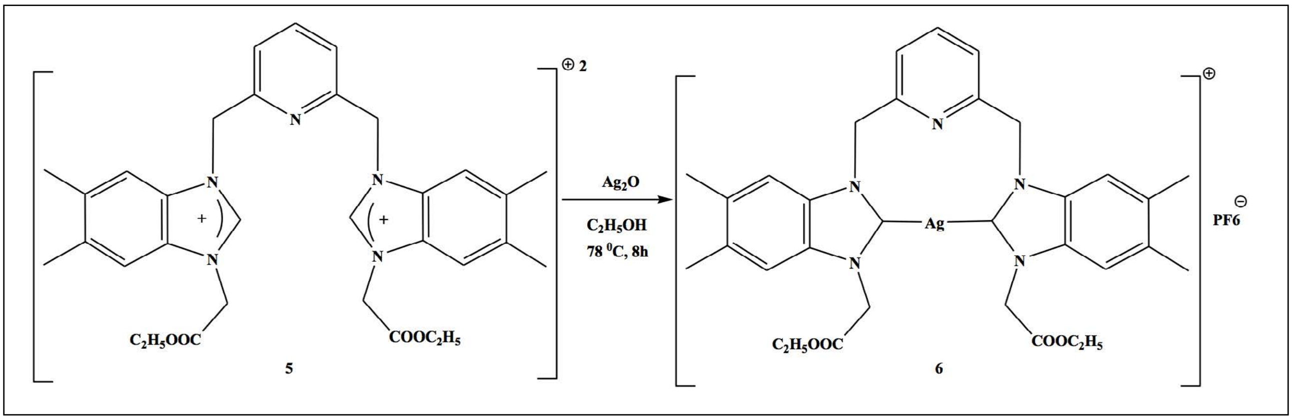

Figure 3. Synthesis ways of silver (I)-NHC complexes.

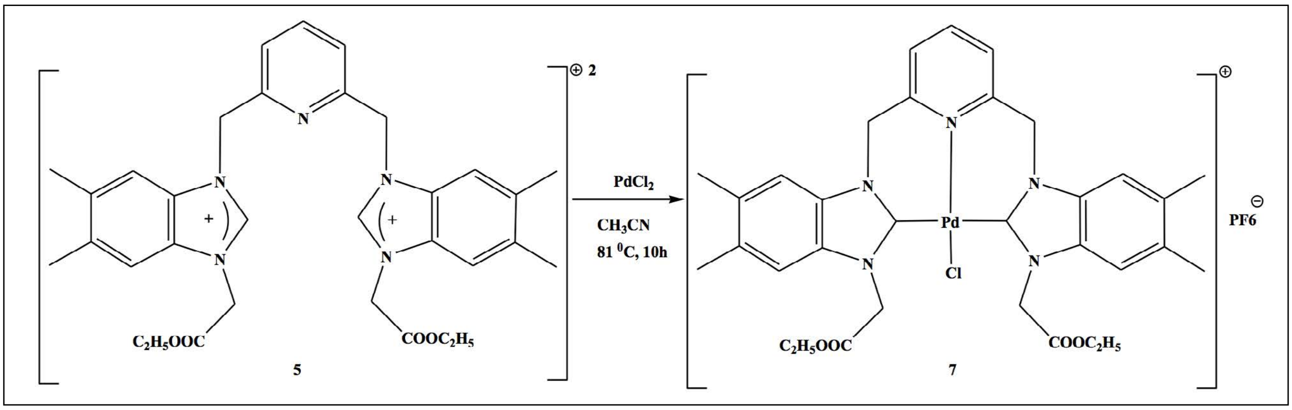

Figure 4. Synthesis ways of palladium(II)-NHC complexes.

ing point analysis (Electrothermal-9200), X-ray diffraction (XRD, Malvern Panalytical Empyrean), elemental analysis (Leco True Spec Micro), and Mass analysis (Shimadzu LC-MS/MS 8040) were used in different steps of the characterization methods.

2.3. Antimicrobial Activity

The antimicrobial activity of compounds 3, 5, 6, and 7 was measured in an agar dilution medium. In this experimental setup, the McFarland scale was set to 0.5. Ampicillin was used as a bactericide, and DMSO was used as a stock solution. The antimicrobial activities of these compounds were measured in Tryptic Soy Broth standards (TSB) at 37°C for 24 h. Viability values at 600 nm were measured by comparing 24 and 48-h for the incubation period. The Clinical laboratory standards institute was conducted for antimicrobial tests [20].

2.4. Synthesis Methods of N-Heterocyclic Carbenes

Heterocyclic carbene molecules were obtained with ethyl bromoacetate and cyclophane compound, which is water-soluble azolium salt of a symmetrical structure. Carbene compounds are ionic compounds that dissolve in water. These molecules' chemical and physical properties were comparatively examined in the literature. They are characterized by Four-point probe conductivity, ^{1}H-NMR, ^{13}C-NMR, FT-IR, TGA, melting point measurement, and XRD, as shown in Figure 1, 2.

2.5. Synthesis Ways of Metal Complexes

Silver (I)-NHC (6) and Pd (II)-NHC (7) complexes were obtained by the interaction of Ag_2O and $PdCl_2$ compounds with carbene compound 5, respectively. (Fig. 3, 4).

3. RESULTS AND DISCUSSIONS

3.1. FT-IR Measurements

FT-IR analyses of synthesized compounds 3 and 5 were examined for functional groups in their chemical structures, as given in Table 1.

In the FT-IR analysis of compounds of 3, the -C-H stretching of the CH_2 and CH_3 groups were obtained as 1000 and 838 cm^{-1}. -C-H stretching of the aromatic structure of 5,6-dimetil-1H-benzo[d]imidazole was given as 2944 cm-1. The cyclic ring structure of the imine group (-C=N:) was referred to at 3384 cm^{-1}. Additionally, the carbonyl of the acetate group (-C=O) showed a sharp peak at 1615 cm^{-1} for

Table 1. FT-IR peaks of compounds 3, 5, 6, and 7.

Compound name	υ(CH_3-CH_2) (alkane) (cm^{-1})	υ(C=C) (alkane) (cm^{-1})	υ(CH_2) (alkane) (cm^{-1})	υ(C=O) (carbonyl) (cm^{-1})	υ(NH_2) (amine) (cm^{-1})
3	949 834	1690 1455	2921 2852	–	3404
5	1000 838	1562 1458	2944 2854	1615	3384
6	1000 838	1486 1378	2915	1716 1596	3166 2916
7	1000 838	1378	2885	1736 1599	3155 2855

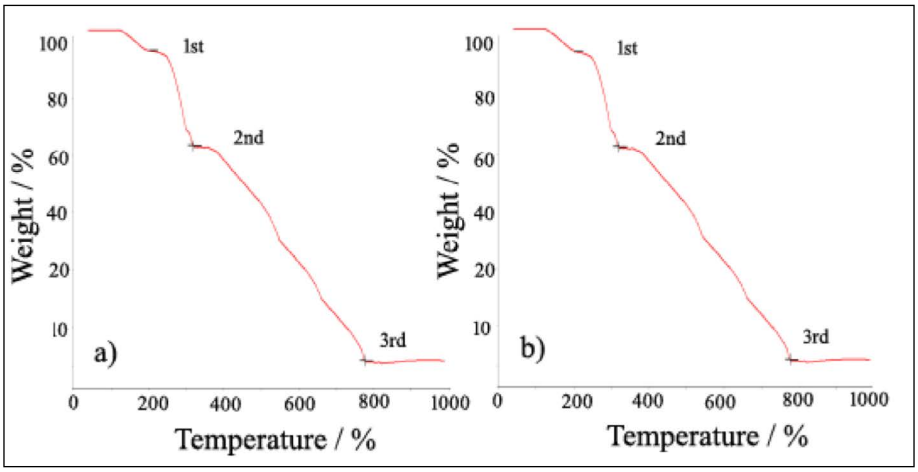

Figure 5. TGA graph compound of **(a)** 6 and **(b)** 7.

the compound of 5. The carbonyl of the acetate group was given at 1716 and 1596 cm^{-1}, and the cyclic ring of the imine group at 3166 and 2916 cm^{-1} for compound 6. In addition, the carbonyl of the acetate group was given at 1736 and 1599 cm^{-1}, and the cyclic ring of the imine group at 3155 and 2855 cm^{-1} for compound 7.

3.2. Thermal Gravimetric Analysis of Metal Complexes

Thermal gravimetric analysis (TGA) measurements of synthesized silver and palladium-containing metal complexes are presented in Figure 5. Depending on the weight loss of the complexes, organic and inorganic parts were distinguished from each other. This weight loss takes place in three steps. In the 1^{st} step, the moisture of water molecules was removed from the molecules at temperatures between 101 and 399°C. In the 2^{nd} step, there is a weight loss between 400 and 510°C, depending on the carbonization of the metal complexes. In the 3^{rd} step, the carbonization of the organic part in the metal complexes continued at the temperature between 510 and 795°C. In addition, the highest weight loss occurred in the last step (Fig. 5).

3.3. XRD Analysis

XRD measurements of synthesized compounds were obtained in the 2θ=10-100°. Three different peaks were determined for compounds 3 and 5 and four for 6 and 7. For the silver and palladium complexes, three different characteristic peaks correspond to their complexes. Comp. 3; 001; 11.95, 002; 17.71, 003; 75.95, comp. 5; 001; 10.85, 002; 26.59, 003; 46.20, comp. 6; 001; 8.67, 002; 13.19, 003; 13.84, 004; 48.39, comp.7; 001; 8.17, 002; 12.38, 003; 13.34, 004; 49.68, respectively. The compounds were composed of crystalline Ag(I) and Pd(II) metals (Fig. 6). The synthesized carbenes contain C, N, and H as organic elements forming the main skeleton. Hexafluorophosphate, chlorine ions, and silver and palladium metals are bound to this organic part in metal complexes. The XRD peaks obtained in this analysis method consist of the reflection planes of the complexes. The large peak chlorine ion was observed between 8-28°C, which might be bound to the organic structure. In addition, the nano-structured part of the carbenes was also observed in the environment [21].

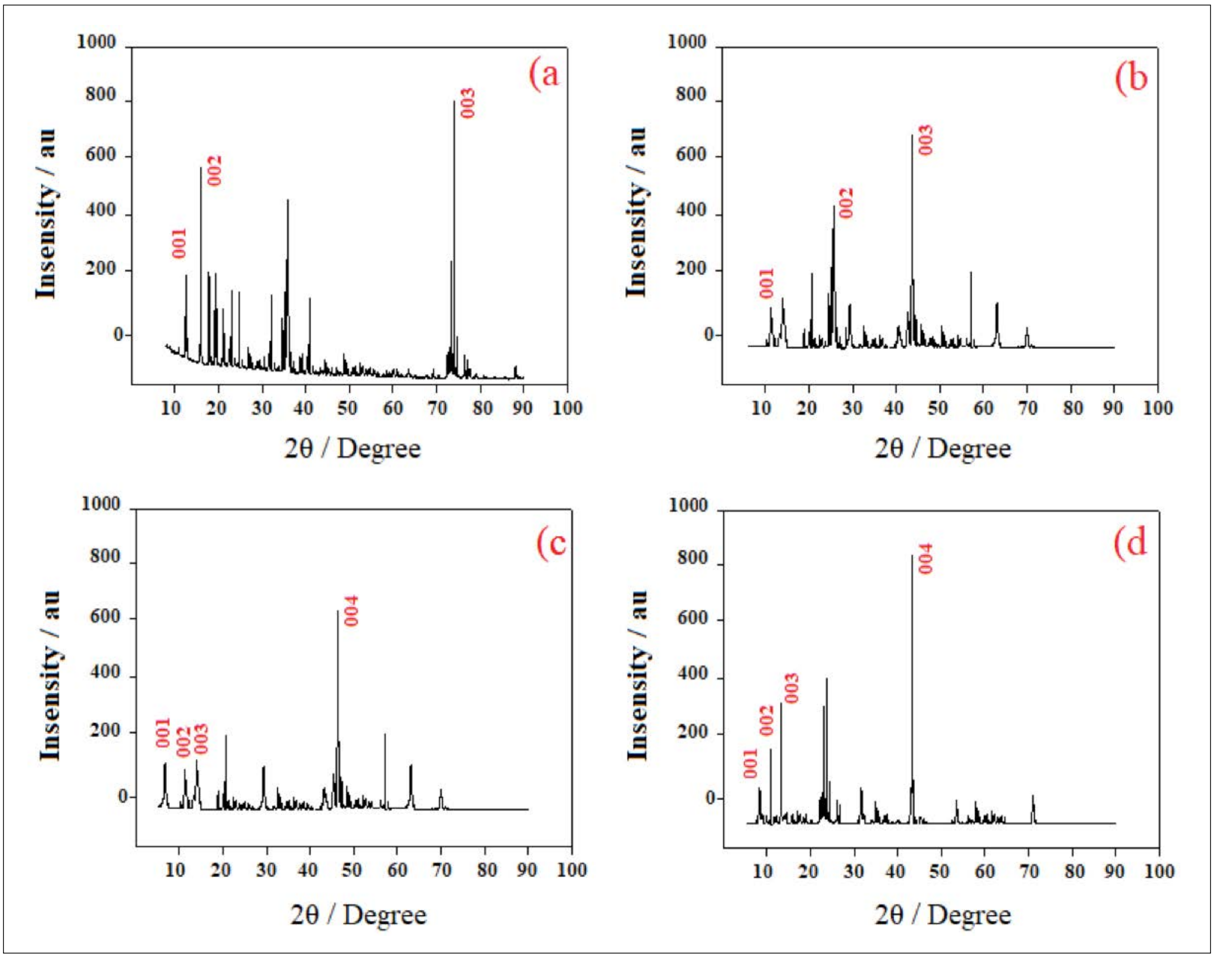

Figure 6. XRD peaks of comp. a) 3, b) 5, c) 6, and d) 7.

3.4. 1H-NMR and 13C-NMR Spectra

In the ^{1}H-NMR (300 MHz, D_2O) spectrum of compound (3) has signals at δ (ppm): 8.21 (s, 1H, *J*=11.7 Hz, for carbene), 7.45 (d, 2H), 7.21 (m, *J*=7.7 Hz, 2H), 6.99 (m, *J*=9.4 Hz, 2H), 5.66 (s, *J*=8.1 Hz, 4H), 2.22 (s, *J*=10.7 Hz, 12H). In the ^{13}C-NMR (75.5 MHz, D_2O) spectrum of compound (3) has signals at δ (ppm): 137.8 (C=C), 112.9 (C=C, for aromatic), 120.9 (C=C), 59.0 (NCH_2), 19.8 (CH_3), 152.5 (C=C), 130.1 (C=C, for aromatic), 128.0 (C=C, for aromatic).

In the ^{1}H-NMR (300 MHz, D_2O) spectrum of compound (5) has signals at δ (ppm): 9.28 (s, 1H, *J*=9.4 Hz, for carbene), 7.13 (d, 2H), 7.50 (t, *J*=7.4 Hz, 2H), 6.70 (d, *J*=9.5 Hz, 2H), 5.50 (m, *J*=6.8 Hz, 6H), 3.91 (s, 4H), 4.43 (t, 4H). 2.30 (s, *J*=10.8 Hz, 12H). In the ^{13}C-NMR (75.5 MHz, D_2O) spectrum of compound (5) has signals at δ (ppm): 147.20 (NCN, for carbene), 112.93 (C=C, for aromatic), 137.87 (C=C), 120.91 (C=C), 59.03 (NCH_2), 19.87 (CH_3), 152.52 (C=C), 130.15 (C=C, for aromatic), 128.05 (C=C, for aromatic), 48.93 (CH_2), 57.54 (CH_2).

In the ^{1}H-NMR (300 MHz, D_2O) spectrum of compound (6) has signals at δ (ppm): 7.85 (s, 1H), 7.52 (d, *J*=8.2-8.3 Hz, 4H), 7.41 (d, *J*=10.0-10.1 Hz, 2H), 5.52 (t, *J*=8.6-8.7 Hz, 4H), 5.10 (t, *J*=9.2-9.3 Hz, 4H), 3.88 (t, 6H), 2.65 (m, *J*=7.5 Hz, 12H), 1.46 (t, 6H). In the ^{13}C-NMR (75.5 MHz, D_2O) spectrum of compound (6) has signals at δ (ppm): 193.3 (NCN, for carbene), 134.3 (C=C, for aromatic), 112.9 (C=C), 122.0 (C=C), 72.7 (NCH_2), 59.1 (CH_2), 63.2 (OCH_2), 19.8 (CH_3), 172.1 (C=O), 154.9 (C=C), 138.1 (C=C, for aromatic), 130.1 (C=C, for aromatic) ppm.

In the 1H-NMR (300 MHz, D_2O) spectrum of compound (7) has signals at δ (ppm): 8.02 (s, 1H), 7.64 (d, 4H), 7.41 (d, *J*=6.6-6.7 Hz, 2H), 5.52 (t, *J*=9.5 Hz, 4H), 5.10 (t, *J*=7.8 Hz, 4H), 3.88 (t, *J*=9.8-9.9 Hz, 6H), 2.58 (m, *J*=5.4-5.5 Hz, 12H), 1.88 (s, *J*=5.4-5.5 Hz, 6H). ^{13}C-NMR (75.5 MHz, D_2O) spectrum of compound (7) has signals at δ (ppm): 176.7 (NCN, carbene), 134.3 (C=C, aromatic) 112.9 (C=C, aromatic), 122.0 (C=C, aromatic), 72.7 (NCH_2), 59.1 CH_2), 63.2 (OCH_2), 19.8 (CH_3), 13.9 (CH_3), 172.1 (C=O), 154.9 (C=C, aromatic), 138.1 (C=C, aromatic), 130.1 (C=C, aromatic) ppm.

3.5. Four-Point Probe Conductivity Measurements

Solid-state conductivity measurements of compounds 3, 4, 5, 6, and 7 were measured by a Four-point probe instrument. All materials were pressed into pellet forms using the pellet machine. The highest conductivity was obtained as $3.96\times10^{-}$

Table 2. MIC values of comp. (3, 5, 6, and 7) for bacterial resistance in antimicrobial tests

	MIC (µg/mL)				
	Gram-negative bacteria		Gram-positive bacteria		Fungal
Samples	*Escherichia coli*	*Listeria monocytogenes*	*Staphylococcus aureus*	*Bacillus cereus*	*Candida albicans*
3	84.95	86.52	79.95	78.65	81.23
5	72.65	71.32	70.62	72.36	69.38
6	0.01	0.02	0.02	0.02	0.01
7	55.61	54.68	46.38	47.96	41.64

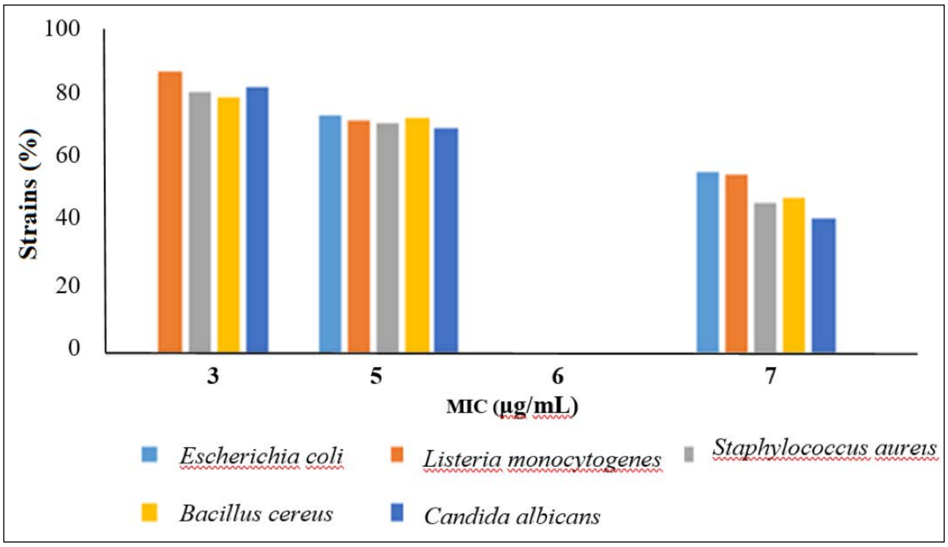

Figure 7. Compounds 3, 5, 6, and 7 were used against bacterial resistance in antimicrobial tests.

6 S/cm for compound 5. The other conductivity results are 5.76×10^{-7} S/cm, 2.17×10^{-6} S/cm, 5.94×10^{-7} S/cm, and 1.31×10^{-6} S/cm for compounds of 3, 4, 6, and 7, respectively. Pd(II)-NHC complex is more electrically conductive than Ag(I) due to the easy electron transfer from valance and conduction bands [22].

3.6. Antimicrobial Activities

The antibacterial activity measurement of four compounds was tested on four different bacteria and one yeast species. The results of the tests are separately given in Table 2. The antimicrobial activities of Ag(I) and Pd(II)-NHC complexes have shown that they have a relatively broad spectrum of antimicrobial activity [23, 24]. The silver complex of comp. 3, 5, 6, and 7 showed inhibitory effects against four different bacteria (*Escherichia coli* O157: H7 (ATCC 25922), *Listeria monocytogenes* (ATCC 19115), *Staphylococcus aureus* (ATCC 25923), *Bacillus cereus* (ATCC 11778) and a type of mushroom (*Candida albicans* (ATCC 10231). On the other hand, they had a very low inhibitory effect on different properties of bacterial species and fungal. Compared to the sulfamethoxazole drug, it has much lower antimicrobial activities. Complex six is effective against bacteria and fungal even though the stated absorbance measurements have some statistical flaws [25, 26]. The absorbance values were added for informational purposes even though the other synthetic compounds 3, 5, and 7 did not exhibit the anticipated inhibitory effects on the target bacteria (Fig. 7).

The tested compounds have a MIC range of 5 to 100 µg/mL. Compounds 3 and 5 were found to have similar activities against Gram-positive and Gram-negative bacteria, and fungal (Fig. 7). These results contained useful information for synthesizing NHC compounds with high antimicrobial activity. The efficiencies of synthesized carbenes and complexes of Ag(I)-NHC (6) and Pd(II)-NHC (7) were evaluated against antimicrobial agents [27].

4. CONCLUSIONS

The symmetric structure of the NHC ligands (3, 5) and NHC complexes containing the new pioneer (6, 7) were synthesized in this study. Many characterization techniques were used, such as FT-IR, ^{1}H-NMR, ^{13}C-NMR, TGA analysis, XRD spectroscopy, and Four-point probe conductivity measurements. As a result of comparing the XRD results of the calculated compounds with the results of a similar cyclophane, the structures were confirmed.

Complexes 6 and 7 have shown transitions of $^{1}A_{1g} \rightarrow {}^{1}A_{2g}$, $^{1}A1g \rightarrow {}^{1}B_{1g}$, and $^{1}A_{1g} \rightarrow {}^{1}E_{g}$, respectively. The absorbance values observed at 285, 315, and 297 nm represent the transition charge transfer from NHCs to the Ag^{+} and Pd^{2+} ions by UV-vis spectrophotometer. According to the results of the electronic spectrum, the synthesized silver complex has a linear geometry coordinated with the ligand of the central Ag^{+} ion. In contrast, the synthesized palladium complex has a square planar geometry coordinated with the ligand of the central Pd^{2+} ion.

In this study, when the Ag(I)-NHC complex (6) is compared with other compounds (3,5,7), they have shown higher antimicrobial activity even at much lower concentrations. According to the findings, compounds containing silver ions have antimicrobial agent properties. Complex six's lowest microbial inhibition concentration (MIC) values were measured as 0.01 μg/ml for Escherichia coli and Candida albicans, respectively. The Ag(I)-NHC complex (6) showed higher antimicrobial activity than the carbene compound and Pd(II)-NHC complex (7).

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ETHICS

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

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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Research Article

Thermal conductivity, abrasion resistance, and compressive strength of end-of-life tire aggregate incorporated concrete

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ABSTRACT

Recycling end-of-life tires is a global problem that requires an urgent solution. Storing and preserving these tires is a challenge that delays facing potential problems instead of solving the problem. In this context, recycling waste tires without harming the environment and at low costs has been the focus of many researchers. For several decades, the possibility of grinding these tires to aggregate size for concrete and substituting them with natural aggregate has been the subject of research by scientists working in this field. In this regard, this study aims to experimentally investigate the influence of waste rubber aggregate on some engineering properties of concrete, such as ultrasonic pulse velocity-based quality assessment, abrasion resistance, thermal conductivity characteristics, and mechanical performance, namely, compressive strength. Another significant side of the study was establishing a statistical relationship and correlation between the w/c ratio and substitution level of waste rubber aggregate and the experimental outputs. The experimental study indicated that the waste rubber aggregate decreased the concretes' compressive strength, but it improved the thermal conductivity characteristics and abrasion resistance of the concretes manufactured in this study. On the other hand, the statistical analysis revealed that the input parameters have meaningful effects on the engineering properties of the concretes, and there is a strong correlation between these properties.

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1. INTRODUCTION

Waste materials considered obsolete and/or unwanted materials are substances free from some production steps or domestic activities, such as commercial, agricultural, industrial, or mining operations. According to the United Nations Environmental Protection Agency, waste materials are handled in two classes: hazardous and non-hazardous. Hazardous waste materials, including chemicals, substances obtained from by-products of commercial production processes or heavy metals, and household items that are inactive and removed from the house, can potentially harm

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the environment or the health of living creatures. However, idle materials that have the potential to be reused and/or recycled may be considered non-hazardous waste materials.

The Tire Manufacturers Association states that when used correctly, idle tires do not lead to any environmental problems. However, it is also stated that when it comes to misuse, waste tires can harm the environment and health. Therefore, despite the fact that they do not pose a hazard in their current condition, idle tires can be considered hazardous waste because of the release of high amounts of toxic gases, heavy metals, and mineral oil when burnt. In addition, due to the shape they have, these tires can host many rodents and flies by holding water in the areas where they are stored and become a home for reptiles. This situation may not only negatively influence human health but also deteriorate the natural habitat in such regions.

China, European Union countries, the United States of America, Japan, and India, produce the majority (about 88%) of waste (scrap) tires worldwide. Compared to Japan (about 91%) and the United States (about 89%), the European Union countries (about 96%) are the most developed regions in the world in terms of recycling and/or recovery of idle tires [1]. Since rubber tires take a long time to naturally biodegrade, their reuse or recycling is an urgent matter of concern [2, 3]. Within this scope, various recycling or reuse methods have been developed and proposed to recycle these idle tires. For that purpose, the recycling of end-of-life tires is carried out by five methods: retreading method, energy recovery, pyrolysis technique, product recycling, and material recycling.

Retreading replaces the worn outer part of the tires, consisting of treads and grooves, with a new one, which is used to extend the life of the tires. However, due to their weak structure, about 85% of car tires are generally not suitable for retreading, while truck tires are more suitable for this process than car tires because they are better maintained and have a more substantial structure. If the tires are not found suitable for retreading recycling method, they become waste material that needs to be disposed of and recycled by another method. Reducing waste tires by incineration is the most accessible, practical, and profitable method, as it provides high heat energy (a relatively higher calorific value than coal) [4]. Tire-derived kilns can be widely used in the cement industry, as the clinker production kiln requires a temperature higher than 1200 °C, which ensures complete combustion of all tire components.

Moreover, the use of shredded tires is also allowed in these kilns [1]. Although this fuel is widely used in clinker kilns in the cement industry because it increases the thermal efficiency of steam boilers and kilns when burned together with coal, it can also be used as fuel together with ground rubber wastes in thermal power plants, industrial boilers, and paper, pulp, iron, and steel factories [1, 5]. However, because of the release of high amounts of toxic, dangerous, and polluting gases, burning waste tires is prohibited or restricted by law in many countries [6, 7].

Another method used to recycle end-of-life tires is pyrolysis, which simultaneously and irreversibly changes the chemical composition and physical phase of organic matter through thermochemical decomposition by breaking down chemical bonds at high temperatures under non-oxidative conditions [8]. In this context, the waste tire is converted into valuable components such as pyrolysis oil, carbon black, and hydrocarbon gas through the pyrolysis method. Using end-of-life tires in the manufacture of tire derivative products is another recycling method for idle tires. In this context, although each company recycles idle tires in a different area, these may be generally categorized as traffic-related products, sidewalks, paving stones, greenways, pathways, paving, sports field surfacing and playground paving materials, mat, synthetic turf, accessibility (wheelchair) ramps, animal care products, landscaping, and rubber mulch, and siding material. Recycling end-of-life tires in the form of crumbs and chips as an inexpensive filling material can also be considered in this context. For that purpose, waste tires are mechanically ground to obtain the tire chips and crumb rubber in a required size using different ways [9].

On the other hand, since recycling, as mentioned above, is either not environmentally friendly, costly, or does not produce a sustainable solution, it has encouraged people to look for alternative ways to reuse or recycle idle tires. In this sense, using idle tires in various forms in civil engineering projects with a wide application area and a sizeable industrial volume is an effective and environmentally friendly way of getting rid of these tires. Considering the amount of ready-mixed concrete (160 million tons in Türkiye, 620 million tons in Europe [10], approximately 4.4 billion tons in the world [11] – for 2019) and asphalt roads (46 million tons in Türkiye and 300 million tons in Europe [12], 375 million tons in the U.S.A. [13] – for 2017) produced around the world, it can be said that using waste rubber tires in these two sectors of civil engineering will be a very practical, environmentally friendly, and the innovative way [14, 15]. Raw materials from natural reserves are not unlimited; therefore, complying with the waste hierarchy, also known as the three Rs of solid waste management (Reduce-Reuse-Recycle), is essential to create a sustainable life [16].

Over the past decade, studies on rubber-substituted (or rubberized) concretes have shown that rubber substitution adversely affects concrete's mechanical properties. In this context, it was stated that the most effective parameters on the mechanical properties of concrete are rubber aggregate size, substitution level, and the water-to-cement ratio of concrete [17, 18]. Gupta et al. [19] and Lv et al. [20] reported that increasing the waste tire aggregate replacement level caused a regular decrease in

Table 1. Chemical compositions and physical properties of Portland cement

Chemical compositions (%)											Physical properties	
CaO	SiO_2	Fe_2O_3	Al_2O_3	SO_3	MgO	TA	L.I.O.	I.S.	Cl^-	FL	Specific gravity	Blaine fineness (m^2/kg)
62.8	19.0	4.7	4.0	2.6	1.73	0.45	2.63	0.68	0.01	1.31	3.15	374

TA: Total alkaline (Na_2O+0.658K_2O); LIO: Loss in ignition; IS: Insoluble residue; FL: Free lime.

compressive strength. Similar findings were reported by Güneyisi et al. [17] and Gesoğlu et al. [18], not only for compressive strength but also for flexural strength. The decrease in flexural tensile strength of concrete at different levels of substitution has also been reported by Su et al. [21] and Mohammed and Adamu [22]. In addition, studies have revealed that after the 30% substitution level, the integrity of the concrete is seriously lost, porous concrete is obtained, and its mechanical properties are lost at severe rates. Güneyisi et al. [17] incorporated waste tire aggregate at 50% and observed a 75% decrease in flexural strength, while Lv et al. [20] reported a similar decrease at a 100% waste tire replacement level. Also, Güneyisi et al. [17] reported a more than 80% reduction in compressive strength at a 50% waste tire replacement level. In this context, since waste tire aggregate in concrete production seriously deteriorates the mechanical performance, it is important to investigate the use of such concretes in manufacturing non-bearing elements, especially as insulation material, rather than for structural purposes.

For this reason, this study mainly aims to examine the effect of the use of end-of-life tires as aggregate (hereupon named waste rubber aggregate) at various replacement levels on the engineering properties such as compressive strength, abrasion resistance, thermal conductivity, and ultrasonic pulse velocity of concretes produced at various water-to-cement ratios. Various water-to-cement (w/c) ratios and waste rubber aggregate substitution levels were considered experimental parameters.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, the binding material used in the production of rubberized concrete was Portland cement (CEM I 42.5 R) with a specific gravity of 3.15 and a Blaine fineness of 374 m^2/kg. The chemical compositions and physical properties of this cement procured from ÇİMSA are presented in Table 1.

In all concrete mixtures produced within the scope of the study, river sand was used as fine aggregate, and basalt crushed stone in two different sizes was used as coarse and medium aggregates. The results of the sieve analysis of fine, medium, and coarse aggregates with the specific gravity values of 2.73, 2.79, and 2.78, respectively, are given in Figure 1. Besides, the fineness modulus of the river sand was 1.9, and the 24-hour water absorption value was 0.70%, while the 24-hour water absorption value of both the medium and coarse basalt crushed aggregates was 0.65%.

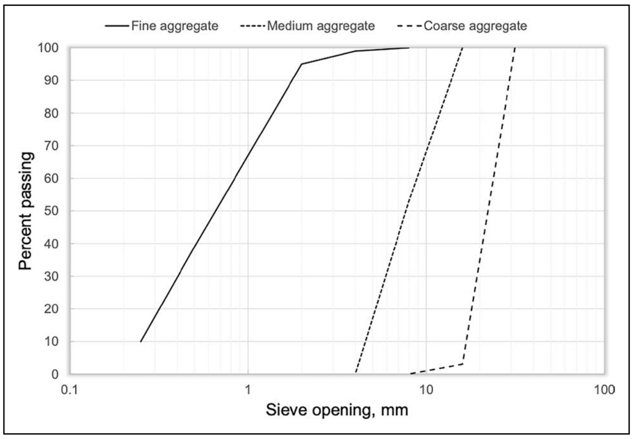

Figure 1. Sieve analysis results of natural aggregates.

Table 2. Technical properties of MasterGlenium 51

Properties	
Material's structure	Polycarboxylic ether based
Appearance	Brown - liquid
pH value	6–7
Alkaline content (%)	≤3.0 (by weight)
Chlorine ion content (%)	≤0.1 (by weight)

The aggregates obtained from end-of-life tires constituting the main theme of this study are rubber pieces called crumb rubber (Fig. 2a) and tire chips (Fig. 2b), which are obtained during the preparation of the surface of the tires for the recapping during the treading of the old tire with a mechanical scraping tool. The specific gravity of the crumb rubber replaced with the fine aggregate was 0.91, and the specific gravity of the tire chips substituted for the medium and coarse aggregates was 1.01. Both tire aggregates had a 24-hour water absorption value of 0.

In order to achieve the desired workability performance in concrete mixtures, a superplasticizer with the commercial name of "MasterGlenium 51" produced by B.A.S.F. construction chemicals was used. Its specific gravity was 1.07, and the other technical properties are given in Table 2.

Figure 2. High-resolution photos of **(a)** crumb rubber and **(b)** tire chips.

Table 3. Mixture proportions of concretes (kg/m^3)

Mix ID	Cement	Water	Natural aggregate			Rubber aggregate		Superplasticizer
			Fine	Medium	Coarse	Crumb	Chips	
PC|35	550	192.5	674.6	603.2	429.3	0.0	0.0	5.50
RC|35-10	550	192.5	604.7	540.7	384.8	23.4	38.8	6.05
RC|35-20	550	192.5	535.3	478.7	340.7	46.6	77.2	6.60
RC|35-30	550	192.5	463.4	414.4	294.9	69.1	114.6	7.15
PC|45	450	202.5	701.2	627.0	446.3	0.0	0.0	2.70
RC|45-10	450	202.5	628.7	562.2	400.1	24.3	40.3	3.15
RC|45-20	450	202.5	556.7	497.8	354.3	48.4	80.3	3.60
RC|45-30	450	202.5	482.2	431.2	306.9	71.9	119.2	4.05
PC|55	350	192.5	748.5	669.3	476.4	0.0	0.0	1.05
RC|55-10	350	192.5	671.3	600.3	427.3	26.0	43.0	1.40
RC|55-20	350	192.5	594.7	531.8	378.5	51.7	85.8	1.75
RC|55-30	350	192.5	515.5	461.0	328.1	76.9	127.5	2.10

2.2. Mixture Proportions and Concrete Production

Concrete manufactured within the scope of the present study was designed at 0.35, 0.45, and 0.55 w/c ratios and cement dosages of 550 kg/m^3, 450 kg/m^3, and 350 kg/m^3, respectively. In this way, three w/c ratio-based concrete mixture series were designed, and in each concrete series, the natural aggregate was replaced with waste rubber aggregate at the substitution levels of 10%, 20%, and 30%, and hence, three rubberized concrete series were designed from each w/c ratio. It is well-known that incorporating waste rubber aggregate into concrete and increasing its content deteriorates some characteristics of concrete. In general, especially after the 30% substitution level, it is stated that the waste rubber aggregate significantly worsens concrete performance. For this reason, although recycling waste rubber as aggregate in concrete production was intended, in this study, up to 30% substitution was considered to achieve some mechanical performance.

On the other hand, the conventional concrete used for structural applications is usually produced at a w/c ratio of 0.55. In the present study, the aim of using w/c ratios of various levels is to monitor the impact of rubber replacement on average, moderately high, and high-strength concretes of common use. Thereby, 12 concrete mixtures, three of which were plain and nine of which were rubberized, were manufactured in the current study. The exact mix proportions of both plain and rubberized concretes are presented in Table 3. The superplasticizer contents given in the last column of Table 3 were designated during the manufacturing by trial and error to achieve the plastic consistency in each mixture. Besides, in the Mix ID column of Table 3, the P.C. and R.C. are used to abbreviate the plain and rubberized concrete, respectively, and the numbers following these abbreviations represent the w/c ratio and rubber aggregate substitution level, respectively. For instance, the concrete mixture represented with the I.D. of R.C. |55-20 was produced at a w/c ratio of 0.55 and a waste rubber aggregate substitution ratio of 20%, while that represented with the I.D. of P.C. |45 was manufactured completely with natural aggregate at a w/c ratio of 0.45.

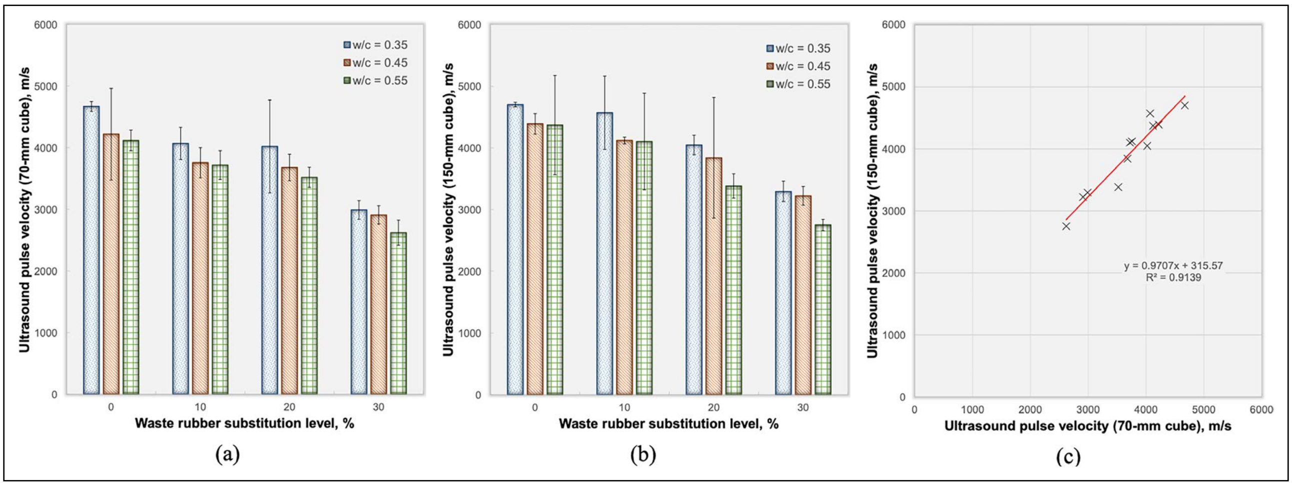

Figure 3. Variation in U.P.V. values of concretes regarding waste rubber substitution levels: **(a)** measured on 70-mm cube, **(b)** measured on 150-mm cube, and **(c)** relationship between U.P.V. values measured on 70-mm and 150-mm cubes.

In the present study, all concrete mixtures were manufactured using an electrical revolving pan mixer having a capacity of 20 liters and following the same mixing process and sequence since the consistency and homogeneity, accordingly, strength development of concretes are significantly affected by the production process. For this reason, first of all, the natural and waste rubber aggregates and cement were put into the mixer, and the mixer was allowed to be rotated until the homogeneous mixing of dry ingredients was achieved. Subsequently, the just mixed water and superplasticizer mixture was slowly poured onto these homogeneously mixed dry ingredients. After the water-superplasticizer mixture was completely added, the mixer continued to be rotated for 5-6 minutes to obtain a homogeneous concrete mixture.

Immediately after the concrete production was completed, the slump test was performed, and then three 150-mm cubic samples were taken for the compressive strength test, and three 70-mm cubic samples were taken for the Böhme abrasion and thermal conductivity coefficient (T.C.C.) tests. Since the ultrasonic pulse velocity (U.P.V.) test is a non-destructive test method, it was measured on the same samples taken for compressive strength and Böhme abrasion tests before they tested for compressive strength and abrasion resistance. All the samples were taken by compacting with a vibrator and kept in a laboratory condition for 24 hours, and then water curing was applied till the test day.

2.3. Methods

In the first stage of the testing program, the nondestructive tests, ultrasonic pulse velocity, and thermal conductivity coefficient were carried out on the samples. The instructions given in ASTM C597 [23] were followed while measuring the U.P.V. values of the concrete produced in the present study. The U.P.V. test was performed on both 70-mm and 150-mm cubic samples to examine the effect of size on the U.P.V. values of concretes. On the other hand, the thermal properties of concrete mixtures were determined using a thermal property analyzer called Hot Disk TPS 500 S, which measures the heat transmission coefficient with the hot disk method [24]. Before being tested, 70-mm samples are kept in an oven at 105 °C for 24 hours to become oven-dry. The hot disc sensor is placed between two oven-dry cube samples taken from the same mixture [25]. Afterward, the average T.C.C. of the cube samples, i.e., the concrete mixture, was determined by measuring with a thermal conductivity device. The compressive strengths of concrete mixtures produced in this study were measured concerning ASTM C39 [26]. The abrasion resistance of the concretes was measured using the Böhme abrasive wheel, and the instructions recommended in DIN52108 [27] were followed while conducting the test. All tests were performed on three samples and the results presented are average.

3. RESULTS AND DISCUSSION

3.1. UPV Results

The U.P.V. value, a powerful non-destructive testing method, gives an idea about the existence of cracks and voids in the concrete and the uniformity of concrete. The U.P.V. values of the concrete mixtures were measured on 70-mm and 150-mm cubic samples. In addition to assessing the concrete quality in terms of U.P.V. values, it was aimed to show how the specimen size influences the U.P.V. results. The variation in the U.P.V. values measured on 70-mm and 150-mm cubes and the standard deviation values are demonstrated in Figures 3a and 3b, respectively. The plain concretes produced in the present study at any w/c ratio had U.P.V. values of more than 4000 m/s for both 70-mm and 150-mm cubic samples. Among the concrete mixtures, the P.C. |35 has a U.P.V. value of more than 4500 m/s and is regarded as high-quality concrete [28]. In addition,

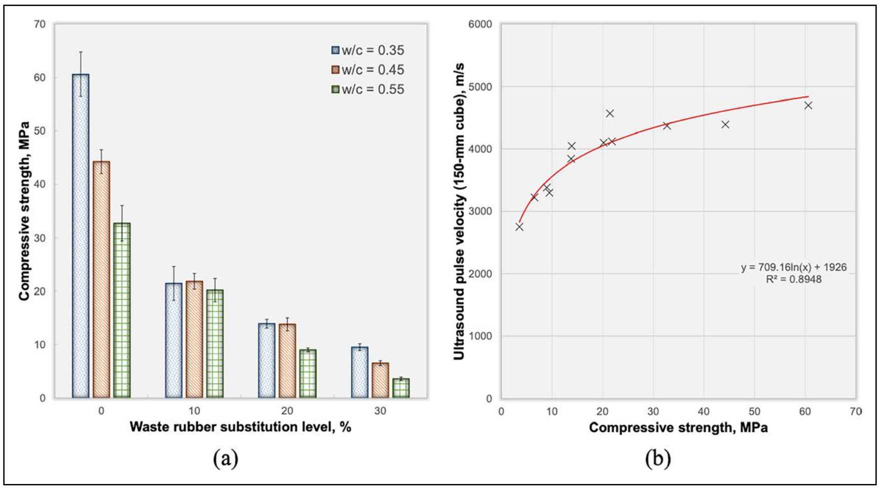

Figure 4. **(a)** Variation in the compressive strength of the concretes regarding the w/c ratio and waste rubber substitution level and **(b)** the relationship between the U.P.V. values and compressive strength of concretes.

the mixture named R.C. |35-10 had a U.P.V. value of more than 4500 m/s when measured on 150-mm cubic samples and a U.P.V. value of more than 4000 m/s and less than 4500 m/s when it was measured on 70-mm cubic samples.

However, the results revealed an adverse influence of waste rubber aggregate incorporation on the U.P.V. values of the concrete. It was observed that substituting the natural aggregate with the waste rubber aggregate resulted in systematical decreases in the U.P.V. values. The main reason behind this effect is the pores led by waste rubber aggregate particles. Since the U.P.V. measurement decreases with increasing the void content of the material, substituting the natural aggregate with the waste rubber aggregate and increasing the substitution level directly reduced the U.P.V. values due to the decrease in the concrete quality. In other words, the waste rubber aggregate particles create a porous structure in the concrete, thus reducing the density of the concrete. This increases the transition time of sound waves from the transmitting probe to the receiving probe. Therefore, the lowest U.P.V. values were measured on the concrete mixtures containing 30% waste rubber aggregate. Apart from the porous structures created by the waste rubber aggregate particles, the nature of these particles absorbs such ultrasonic waves and prevents their passage. This may also decrease the passage velocity of the ultrasonic waves from one probe to another. For these reasons, increasing the substitution level of waste rubber aggregate from 0% to 10% gradually dropped the concrete quality grade from high/good quality to good/poor quality, regarding the classification Feldman gave [29].

A similar reduction in the U.P.V. values of the concretes was observed when the w/c ratio was increased from 0.35 to 0.55. Of course, the porous structure in the cement paste is caused by the high amount of water content in the concrete produced by a higher w/c ratio. The porous structures in the cement paste of such concretes result in slow propagation of the ultrasonic waves, thus decreasing the U.P.V. values. Another significant finding achieved in the current study is the relationship between the U.P.V. values measured on the 70-mm and 150-mm samples. A linear relationship with a relatively high coefficient of determination value was achieved between the U.P.V. values of the 70-mm and 150-mm cubic concrete samples manufactured in the present study (Fig. 3c). When the figure is investigated, it would be seen that the measurement taken on the 150-mm cubes yielded higher U.P.V. values. This is directly related to the frequency and amplitude of the ultrasonic waves. Therefore, it was found that the larger size of the specimen yields a more precise U.P.V. measurement.

3.2. Compressive Strength Results

The variation in the 28-day average compressive strength regarding the w/c ratio and waste rubber aggregate substitution level and the standard deviation values are shown in Figure 4a. The 28-day average compressive strength of plain concretes produced at w/c ratios of 0.35, 0.45, and 0.55 were about 60 MPa, 44 MPa, and 33 MPa, respectively. This w/c ratio-dependent dramatic decrease in the compressive strength is an expected and known phenomenon. Similarly, it has been observed that the compressive strength of concrete systematically decreases as the waste rubber content increases. One of the important reasons why waste rubber aggregate decreases the concrete strength is that it creates a more porous and voided structure in the concrete. However, it should also be stated that the difference between the modulus of elasticity of the natural aggregate-cement paste phase and that of rubber aggregate particles plays a significant role in this impact. When compressive loads are applied to concrete, natural aggregate, and cement paste, which have a relatively similar modulus of elasticity, exhibit nearly similar strains, but the waste rubber aggregate from tires, which has a much lower modulus of elasticity than

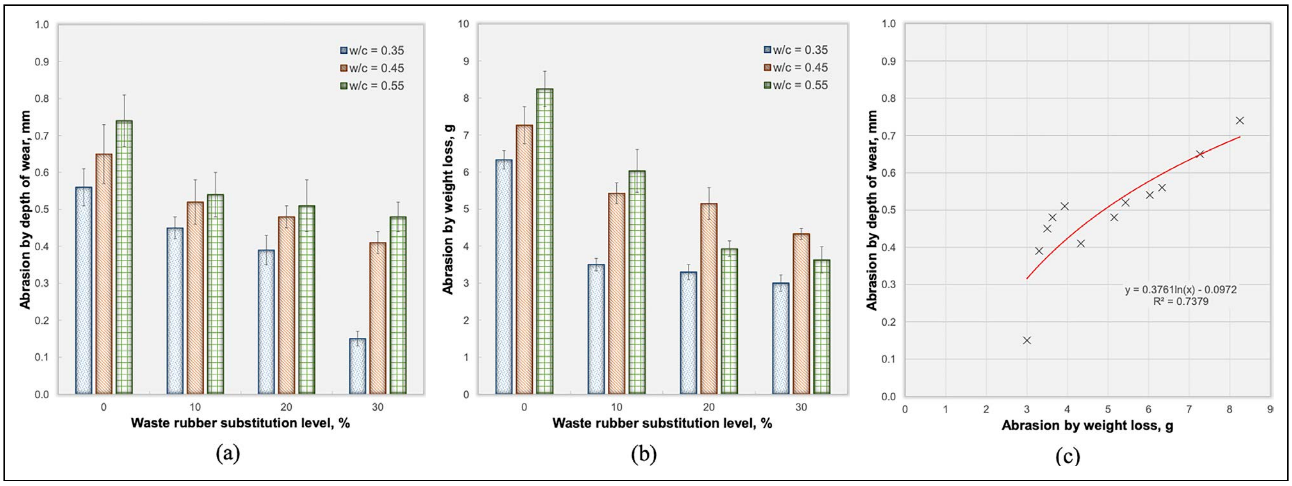

Figure 5. Variation in abrasion resistance of concretes with w/c ratio and waste rubber substitution levels in terms of **(a)** abrasion by the depth of wear, **(b)** abrasion by weight loss, and **(c)** the correlation between abrasion by the depth of wear and abrasion by weight loss.

both, shows more strain than natural aggregate and cement paste. Therefore, under loading, waste rubber aggregate particles behave as a void in the solid structure of concrete, and thereby, the concrete containing such material in its constitution will yield lower compressive strength. Besides, even though the substitution of waste rubber aggregate causes a severe decrease in the compressive strength of the concrete, it should be noted that it increases the ductility of the concrete based on the observations during the test. In addition, it should be noted that another main reason for the compressive strength decreasing effect of waste rubber aggregate is that the interfacial transition zone between cement paste and waste rubber aggregate is more significant than that formed between the cement paste and natural aggregate. Many scientists reported similar influences of waste rubber aggregate incorporation into the concrete in the literature. For example, Güneyisi et al. [17], examining the effect of waste rubber aggregate substitution level and water-binder ratio on compressive strength, reported that increasing the content of waste rubber aggregate systematically reduces the compressive strength and causes more than an 80% decrease in compressive strength for both water-binder ratios (0.4 and 0.6) at 50% substitution level. Also, Gupta et al. [19] and Lv et al. [20] reported that increasing the amount of waste tire causes a regular decrease in compressive strength. Therefore, using waste rubber aggregate after certain substitution levels does not allow concrete production for structural purposes.

Furthermore, since the U.P.V. value of concrete material is mainly related to its modulus of elasticity, and there is a strong relationship between the modulus of elasticity and mechanical properties of concrete, constructing a correlation between the U.P.V. and compressive strength can be accepted on this basis [30]. In this context, Figure 4b demonstrates the relationship between the compressive strength and U.P.V. values that were measured on 150-mm cubic samples of concrete produced in this study. A strong logarithmic correlation with a relatively high coefficient of determination value was established between the compressive strength and U.P.V. values of the concretes of the present study.

3.3. Abrasion Resistance Results

The abrasion resistance of the concretes manufactured in this study was determined using Böhme abrasive wheel test, and it was described in terms of abrasion by the depth of wear and abrasion by weight loss. In this regard, Figures 5a and 5b, respectively, show the variation in the abrasion by the depth of wear and abrasion by weight loss following the w/c ratio and waste rubber substitution level. In addition, to establish a relation between these two different abrasion descriptions, Figure 5c is presented. The lowest abrasion resistances using the depth of wear and weight loss were observed in the plain concrete mixtures (P.C. |35, P.C. |45, and P.C. |55). Among these mixtures, the lowest performance was seen in the concrete mixture produced at a higher w/c ratio. The abrasions in P.C. |35, P.C. |45, and P.C. |55 coded concretes using the wear depth were 0.56 mm, 0.65 mm, and 0.74 mm, respectively. A 30% increase in the abrasion by the wear depth was seen as the w/c ratio increased from 0.35 to 0.55.

On the other hand, the abrasions by weight loss for these concretes, respectively, were about 6.3 g, 7.3 g, and 8.3 g. A similar trend was also observed in the abrasions of the concrete mixtures when the abrasion by weight loss was considered. This is precisely related to the weak structure of cement paste formed at high w/c ratios. Weak cement paste tends to wear out quickly, while strong cement paste resists abrasion and holds together.

The results revealed that incorporating waste rubber aggregate into the concrete improved the abrasion resistance

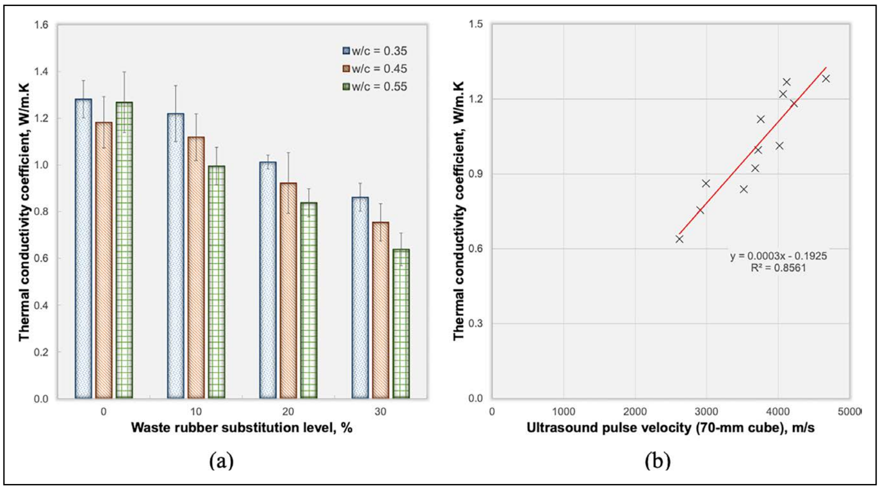

Figure 6. **(a)** Variation in the head conductivity factor of the concretes about the w/c ratio and waste rubber substitution level and **(b)** the relationship between the U.P.V. values and head conductivity factor of concretes.

of the concretes. When Figures 5a and 5b are investigated, it will be seen that the abrasions in the concrete mixtures in terms of both the depth of wear and the weight loss were enhanced as the waste rubber aggregate substitution level increased. There are two reasons for this situation: firstly, the soft nature of the waste rubber aggregate, and secondly, the light weight of the waste rubber aggregate compared to both cement paste and natural aggregate particles. The waste rubber aggregate particles, with their soft structure nature, exhibit higher abrasion resistance to the abrasive dust used in this test, and thereby, the concretes containing waste rubber aggregate yield lower abrasion values in terms of both the depth of wear and the weight loss. Besides, waste rubber, which usually wears very little, causes less mass loss due to its low unit weight when abraded. Gesoğlu et al. [31], who produced previous concretes containing waste rubber aggregate, also concluded that waste rubber aggregate positively affects the abrasion resistance of concrete. Likewise, in general, it has been reported in the studies available in the literature that waste rubber aggregate substitution improves the abrasion resistance of concrete [22, 32, 33].

On the other hand, Abdelmonem et al. [34] reported reductions of up to 47% in the abrasion resistance of concrete at 10%, 20%, and 30% in waste rubber aggregate substitution levels. Similarly, Bisht and Ramana [35] reported that using waste rubber aggregate at the level of 5% in concrete production reduces the abrasion resistance of concrete by 18%. Researchers who obtained such findings associated this situation with low adhesion between cement paste and waste rubber aggregate particles.

The relation between the abrasion by the depth of wear and abrasion by weight loss indicated a moderate logarithmic relationship between these two abrasion identification ways. By this correlation, it could be stated that using one of these abrasion descriptions, the abrasion resistance of concretes can be determined.

3.4. Thermal Conductivity Results

The variation in the thermal conductivity coefficients of the concretes according to w/c ratios and waste rubber aggregate substation levels is presented in Figure 6a. The results showed that the w/c ratio did not affect the thermal conductivity coefficients of plain concretes. However, a decrease in the T.C.C. of concretes and a noticeable effect of the w/c ratio on the T.C.C. of concretes emerged from incorporating the waste tire aggregate into the concrete. As the content of waste rubber aggregate increased, the thermal conductivity coefficient systematically decreased. By increasing the waste rubber aggregate substitution level from 0% to 30%, a decrease of 33% and 36% was observed in the T.C.C. of concretes produced at w/c ratios of 0.35 and 0.45, respectively, while a 50% reduction was seen for concrete produced at w/c ratio of 0.55. Considering the results of these experiments, it can be comprehended that the waste rubber aggregates, which reduce the T.C.C. of the concrete, have improving thermal insulation characteristics. The thermal performance properties of building elements in which waste rubbers were utilized were investigated in the study conducted by Argunhan [36]. According to the findings obtained from the test results, it was reported that the T.C.C. of the concrete produced using average aggregate was 2.075 W/m.K, while the T.C.C. of the concrete containing 30% waste rubber aggregate was 1.070 W/m.K. According to Medina et al. [33], concrete made entirely of crumb rubber-based aggregate had a much lower thermal conductivity value (0.27 W/m.K) than the reference specimen (0.65 W/m.K). Aliabdo et al. [37] obtained quantitatively similar findings, noting a thermal conductivity value of 1.45 W/m.K for traditional concrete and 0.96 W/m.K and 0.60 W/m.K for rubberized concrete with 20% and 100% rubber volume fractions, respectively.

Similarly, Turgut and Yesilata [38] reported that using rubber aggregate in concrete bricks improved thermal insulation performance by 11%, and Hall et al. [39] reported that using rubber aggregate at a 30% level led to a 28% reduction in T.C.C. This shows an inverse proportionality between the waste rubber aggregate substitution level and the T.C.C. of the concrete. This results from the rubber having a much lower T.C.C. than natural aggregate and the fact that the rubber aggregates form a porous structure in the concrete. The better thermal insulation performance of rubberized concrete can also be partly attributed to the rubber particles' hydrophobic properties and the rubber surface's inherent tendency to entrap air. Thus, porous structures are formed in rubber-containing concrete during concrete production as rubber exhibits an anti-wetting behavior, resulting in increased air entrapping within the concrete. The concrete containing more porous structures will also have a lower T.C.C. value.

On the other hand, the decrease in the thermal conductivity of concrete manufactured at a higher w/c ratio may be related to the porosity of the cement paste. The higher w/c ratio makes the paste phase more porous, resulting in higher thermal insulation performance of concrete. Therefore, it is also essential to investigate whether there is a relation between U.P.V., which indicates the integrity and porous structure of concrete, and thermal conductivity. In this context, the relationship between the T.C.C.s of concretes and the U.P.V. values measured on samples of the same size is shown in Figure 6b. As seen from the figure, there is a linear relationship with a relatively high coefficient of determination value between the T.C.C. and U.P.V. values of concretes. The standard error between the observed and fitted T.C.C. values determined by regression analysis was determined as 0.084, whereas that between the observed and fitted ultrasound pulse velocity values was computed as 238.6.

4. STATISTICAL ANALYSIS

The statistical evaluation of the experimental outputs obtained in the present study was based on general linear analysis of variance (GLM-ANOVA) and Pearson correlation coefficient analysis. The GLM-ANOVA aimed to illustrate the effectiveness of the input parameters like w/c ratio and waste rubber substitution level on the experimental outputs such as U.P.V., compressive strength, abrasion resistance, and T.C.C. In order to describe the effectiveness of the input parameters on the outputs, the analysis results were assessed based on a 0.05 level of significance (also known as P-value). In this way, it aimed to determine whether the input parameters are statistically essential parameters on the outputs; in other words, whether the experimental results of this study were obtained by chance or not were evaluated. On the other hand, the Pearson correlation coefficients were determined to show the correlation among all experimental variables, not only between the inputs and outputs. The results achieved from the GLM-ANOVA method are presented in Table 4, while that attained from the Pearson correlation coefficient analysis is given in Figure 7.

V	w/c	sl	UPV70	UPV150	f_c	A_{dw}	A_{wl}	TCC
w/c	1	0	-0.315	-0.352	-0.252	0.53	0.361	-0.321
sl	0	1	-0.895	-0.901	-0.877	-0.769	-0.813	-0.922
UPV70	-0.315	-0.895	1	0.956	0.845	0.549	0.575	0.925
UPV150	-0.352	-0.901	0.956	1	0.807	0.504	0.578	0.97
f_c	-0.252	-0.877	0.845	0.807	1	0.564	0.71	0.831
A_{dw}	0.53	-0.769	0.549	0.504	0.564	1	0.851	0.528
A_{wl}	0.361	-0.813	0.575	0.578	0.71	0.851	1	0.627
TCC	-0.321	-0.922	0.925	0.97	0.831	0.528	0.627	1

Figure 7. Correlation matrix of experimental variables (***V***: variables; ***w/c***: water-to-cement ratio; ***sl***: waste rubber aggregate substitution level; ***UPV70***: UPV values measured on 70-mm cubes; ***UPV150***: UPV values measured on 150-mm cubes; f_c: 28-day compressive strength; A_{dw}: Abrasion by depth of wear; A_{wl}: Abrasion by weight loss; ***TCC***: Thermal conductivity coefficient).

Considering the P-values given in Table 4, it can be stated that the input parameters like w/c ratio and waste rubber substitution level have a statistically significant influence on the experimental outputs of the present study. In addition, since the U.P.V. values were measured on two different-sized cubic samples, the effect of size on the U.P.V. results was also statistically assessed. It was revealed that the sample size also has statistical significance on the U.P.V. results; however, its contribution to variance in the experimental results is not as much as the other two input parameters (see the values given in the sequential sum squares column). Besides, when the contribution of the input parameters is considered, it will be seen that the waste rubber substitution level than the w/c ratio much more influenced the variance in the experimental results. Furthermore, in the last column of Table 4, the R-squared values of the statistical analysis of each experimental output are presented. These R-squared values are used to interpret the relationship of an output variable with one or more input variables by percentage. The results indicate a strong relationship between the output and input variables.

Table 4. Statistical analysis of experimental test results

Dependent variable	Independent variable	The sequential sum of squares	Computed F	P-value	Significance	R-squared
Ultrasonic pulse velocity	Sample size	258302	15.01	0.001	Yes	
	w/c ratio	902534	26.23	0.000	Yes	
	Substitution level	6842237	132.54	0.000	Yes	96.47%
	Error	292525	–	–	–	
	Total	8295598	–	–	–	
Compressive strength	w/c ratio	1110.6	13.69	0.000	Yes	
	Substitution level	13128.7	141.69	0.000	Yes	90.22%
	Error	1544.3	–	–	–	
	Total	15783.5	–	–	–	
Abrasion by the depth of wear	w/c ratio	0.068550	10.09	0.012	Yes	
	Substitution level	0.141667	13.90	0.004	Yes	91.16%
	Error	0.020383	–	–	–	
	Total	0.230600	–	–	–	
Abrasion by weight loss	w/c ratio	5.7726	7.80	0.021	Yes	
	Substitution level	23.3500	21.03	0.001	Yes	92.91%
	Error	2.2208	–	–	–	
	Total	31.3434	–	–	–	
Thermal conductivity coefficient	w/c ratio	0.051491	7.88	0.021	Yes	
	Substitution level	0.417699	42.63	0.000	Yes	95.99%
	Error	0.019597	–	–	–	
	Total	0.488787	–	–	–	

On the other hand, the relationship between all variables can be comprehended by interpreting the correlation values presented in Figure 7. The negative values in the figure show the inverse relationship between the compared variables, whereas the positive values indicate the direct relationship. In this context, it can be stated that there is a strong inverse relationship between the waste rubber substitution level and the experimental outputs. However, it should be stated that this negative correlation between the waste rubber substitution level and abrasion by the depth of wear and weight loss is just a mathematical demonstration. An increase in waste rubber substitution level decreases the abrasion by the depth of wear and weight loss, not abrasion resistance. Besides, it can be stated that there is a strong positive correlation between the T.C.C. and U.P.V. values.

Similarly, the correlations between the T.C.C. and compressive strength can be meaningful. The same conclusion can be made about the correlation between U.P.V. and compressive strength. However, the interaction between the compressive strength and abrasion resistance achieved in the current study is moderate.

5. CONCLUSION

Following the findings presented above, the following conclusions can be drawn:

- The waste rubber aggregate substitution level and the w/c ratio significantly influence the U.P.V. of concrete: U.P.V. decreased as they increased. Besides, the results showed that the U.P.V. values were size-dependent; however, a significant linear relationship was found between the U.P.V. values measured in different-sized samples.
- The results revealed that the waste rubber substitution with a level of 10% resulted in a severe strength loss; however, although reducing the w/c ratio led to a slight increase in the compressive strength, it cannot be considered a complete remedy for the negative influence due to waste rubber aggregate substitution. Instead of decreasing the w/c ratio, the pozzolanic materials may be included in producing such concretes to improve their strength characteristics.
- On the other hand, waste rubber aggregate incorporation improved the abrasion resistance of concrete. As expected, concretes produced at higher w/c ratios exhibited lower abrasion resistance.

- No significant effect of the w/c ratio on the T.C.C. of plain concrete was observed. However, when waste rubber aggregate was included in the concrete, it was noticed that the w/c ratio was effective on T.C.C.
- A statistically strong relationship was observed between the T.C.C. and U.P.V. values of the plain and rubberized concretes.
- The statistical analysis showed that the experimental parameters, such as the w/c ratio and the waste rubber aggregate substitution level, had a statistically significant effect on the studied properties.
- The Pearson correlation coefficient analysis achieved a strong inverse correlation between the waste rubber substitution level and the studied properties. Furthermore, it showed strong positive correlations between T.C.C. and U.P.V. values, between T.C.C. and compressive strength values, and between U.P.V. and compressive strength values.

ETHICS

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

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

PEER-REVIEW

Externally peer-reviewed.

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Research Article

Pattern and filament optimization for 3D-printed reinforcements to enhance the flexural behavior of cement-based composites

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ABSTRACT

Cement-based materials are the world's most widely utilized construction materials due to their high compressive strength. However, they need reinforcement to withstand direct or indirect tensile forces. This study evaluated the potential use of 3D-printed polymers as an alternative reinforcement in cement-based composites. Polyethylene terephthalate glycol (PETG), Polyamide (PA), and Acrylonitrile butadiene styrene (ABS) based triangular and honeycomb-patterned 3D-printed reinforcements were incorporated into cement-based composites, and their mechanical performances were compared under three-point flexural tests by considering both polymer and pattern type. Both triangular and honeycomb patterns enhanced flexural behavior. Considering all filaments, the honeycomb pattern was found more effective than the triangular one for increasing flexural strength, deflection capacity, and toughness up to 46.80%, 251.85%, and 77.66%, respectively. In the case of filament type, 3D-printed PA-type filament in a honeycomb pattern preserved flexural strength, enhanced deflection capacity, and increased flexural toughness with pseudo-deflection hardening behavior. 3D-printed honeycomb patterned reinforcements produced by PA have the opportunity to be used in the manufacture of cement-based composites.

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1. INTRODUCTION

Three-dimensional (3D) printing (also known as additive manufacturing (AM)) has been defined as the process of producing a 3D model product in which complex structures can be built using single or different raw materials. According to ASTM F2792-12 [1], AM was described as "a process of joining materials to make objects from 3D model data, usually layer upon layer". The 3D printing technology used metals, polymers, ceramics, concrete, food, living cells, and organs, while material forms included filaments, powder, paste, resins, and inks. In manufacturing objects, 3D printing technology

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has introduced the creation of customized geometry, the possibility of making changes and detecting errors before manufacturing a product, and effective cost management. Hull [2] applied for a patent in 1984 to produce 3D objects using stereolithography (SLA) technology. Steven Scott Crump filed a patent in 1989 for another 3D-printing technology, fused deposition modeling (FDM) [3]. 3D-printing techniques developed rapidly. After the mid-2000s, with the rapid development of household products and affordable prices, 3D technology has been in incredible demand. It has enormous potential for new product fabrication, prototyping, hybrid applications, and structural reinforcement. 3D printing technology for cement-based applications is now generating considerable attention.

Due to their low strength under tensile loads, cement-based construction materials need reinforcements such as steel reinforcing bars [4,5], polymeric and metallic fiber reinforcements [6], and various fiber types [7-8]. Başsürücü et al. [5] stated that the concretes incorporating long hooked-end steel fibers exhibited deflection hardening behavior, while the short straight steel fiber and polypropylene synthetic fibers incorporating concretes exhibited deflection softening. Zhang et al. [7] investigated the flexural behavior of engineered cementitious composites incorporating polyvinyl alcohol and polyethylene fibers and enhanced the flexural strengths by up to 247.2% compared to reference composite. Doğan et al. [8] studied concrete with carbon fiber incorporating recycled ferrochrome slag aggregate. They reported that reinforced concrete with recycled ferrochrome slag aggregate provides superior mechanical and electrical properties to regular concrete, providing lower production costs and energy savings. There has been a recent search for different products for more effective solutions. In literature, applications for 3D-printing with different materials such as bio-inspired polymeric reinforcement, composites, silica sol, ceramic, concrete, steel fiber, polypropylene synthetic fibers, and wax have been used [9,10]. Rosewitz et al. [9] examined the mechanical performances of their new design products in terms of flexural strength, flexibility, toughness, and compressive strength. When the literature is examined, it is seen that although there are significant changes in performance according to the characteristics of the reinforcement product, most of the products used as reinforcement products provide specific improvements on the concrete.

Studies on 3D-printed reinforcements for cement-based materials are limited. In the studies, metallic materials, Acrylonitrile butadiene styrene (ABS) reinforcement, Polyethylene terephthalate-glycol (PETG) structures, and Polylactic acid (PLA) were used as 3D-printed reinforcement materials for cement-based materials [5,6,11-18]. Xu and Šavija [11] tested both bending and tensile performances and achieved significant performance improvements. Shweiki et al. [12] printed PLA and PETG-based products as reinforcements and observed bending behaviors. PETG-reinforced samples showed better flexural behavior than PLA-reinforced samples in terms of ultimate loads and deformations, which was almost double, and the deformation of PETG samples at final loads was found to be three times that of PLA samples. Salazar et al. [15] investigated the use of 3D octet lattice structures made of PLA and ABS materials instead of steel reinforcement. Flexural test results showed that all truss-reinforced beams exhibit strain hardening up to peak load. In addition, multiple cracking and crack expansion were observed in the samples up to the peak load [15]. Xu et al. [16] used ABS-based octet lattice structures for reinforcement. They stated that the refined products did not meet the steady-state cracking criteria; however, they suggested increasing the strength of the reinforcement material by 40%. Santana et al. [18] studied composites reinforced with homogeneous or graded PETG structures and compared the PLA and PETG. Even though PLA natural polymer outperformed PETG in terms of mechanical properties, it lost around 50% of its tensile strength and elastic modulus after exposure to alkali solutions. The above studies have shown that the products generally used in 3D-printing technology have advantages and disadvantages against each other due to their material content.

The honeycomb structure's application fields have significantly increased since the discovery of its unique geometry. The honeycomb construction and its structural usage started in 1914 with a patent of Hofler and Renyi [19]. Honeycomb core's first use in the modern sense was carried out on aircraft in the 1940s to reduce weight and increase flight distance and payload. However, its usage areas are expanding rapidly. Due to the structural opportunities it offers, the honeycomb structure has been widely applied in a variety of fields, including mechanical engineering (e.g., to increase the heat storage efficiency in the solar collector [20]), architecture (to reduce the weight of structures, absorb vibrations and provide thermal and acoustic insulation) and aviation industry (to reduce weight and increase payload and flight distance). Habib et al. [21] conducted a simulation study on nine different honeycomb types and stated that the unit cell geometry and arrangement seriously affect the compression response of the honeycombs and ensure different energy absorption properties. Katzer and Szatkiewicz [14] printed the honeycomb geometry using ABS filament to reinforce the concrete beams. The F_{max} values in some specimens were equal from 74% to 98% of pure mortar; however, the reinforced mortar beam with H=20 mm and D=2.00 mm was equivalent to 184% of the pure mortar. In our previous pioneering work, honeycomb-shaped reinforcements of two different thicknesses (1 and 2 mm) with a combination of protrusions (flat and protruded) were produced by the use of PLA filament and used as reinforcement in cement-based composites [17]. Three-point bending tests were performed to determine the flexural behavior of these composites. The results showed that the flexural performance of composites changed depending on the thickness and protrusion combinations, and accordingly, the flexural strengths, deflection capacities, and toughness values ranged between 2.30-3.04 MPa, 0.045-0.588 mm, and 15.92-652.37 N.mm, respectively. The 2 mm thick and protruding specimens showed significant improvement in the spurious deflection hardening behavior, which is considered an essential criterion for performance improvement [17].

As seen from the literature, different designs and different products have been studied, and significant contributions have been made to the literature, but issues such as printing geometry or polymer type still need to be investigated. Based on the recent literature, it has been seen that the most common polymer types used in studies are PLA, PETG, and ABS. This study analyzes the possibility of using 3D-printed reinforcements as an alternative reinforcement element in cement-based composites. In addition to the literature, the effect on the performance of different designs of well-known geometries, such as triangles and honeycombs, and three different printing material types (PETG, ABS, and PA) are investigated. Therefore, triangle-patterned and honeycomb-patterned 3D-printed reinforcements were formed using PETG, ABS, and PA, added to the cement mortars as a reinforcement, and mechanical performances of cement-based composites were compared under three-point flexural tests by taking both printing geometries and polymer type into consideration.

2. MATERIALS AND METHODS

Cement mortars with a cement:aggregate: water ratio of 1:3:0.50 was prepared using CEM I 42.5 R type cement and micro silica powder below <400µm. The chemical, physical and mechanical properties of cement are given in Table 1. This combination is known as a reference mortar in TS EN 196-1 standard [22]. In this study, the mixture was modified by replacing micro silica sand with standard sand, and a superplasticizer of 0.1% of cement by weight was used to achieve proper workability for casting.

Due to the balance between strength and ease of printing, Table 2 shows the characteristics of the ABS and PA nylon. PETG and ABS are the most consumed materials in 3D printing, with good mechanical properties. Both materials have good shock resistance. The ABS is the plastic par excellence at the time of creating parts of all kinds in the industry. The ABS offers hardness, resistance to some chemical elements, rigidity, and stability at a high temperature like 100 °C. Since PETG has a certain flexibility, products with greater hardness and strength can be obtained. However, the ABS presents can be machined without deformation. PETG is more resistant to sun, rain, and cold and less prone to cracking deformations than ABS. The PA is more resistant to chemical products and has good impact resistance and low friction properties than the ABS. The ABS has better thermal conductivity properties than the PA. Three materials (ABS, PA, and PETG) being compared need similar extrusion temperatures, usually in the wide range of 210-260 °C. Two materials (ABS and PETG) being compared need similar extrusion temperatures, usually in the range of 230-260 °C. Compared to the ABS (1.04 g/cm³), the PA (1.14 g/cm³) has a higher density. The difference in density is about 9%. Blok et al. [23] compared the machinability and performance of four different filaments and stated that PA began to lose mass at about 100 °C and lost 7% of its mass at 300 °C,

Table 1. Chemical, physical and mechanical properties of cement

Chemical Properties (%)		Physical Properties	
SiO_2	17.62	Specific gravity	3.11
Al_2O_3	5.01	Blaine (cm²/kg)	3485
Fe_2O_3	3.17	Retaining on 90 µm sieve (%)	0.6
CaO	63.78	Retaining on 45 µm sieve (%)	17.4
MgO	0.97	Mechanical Properties (MPa)	
Na_2O	0.39	Compressive strength at two day	28.3
K_2O	0.77	Compressive strength at seven day	40.1
SO_3	3.10	Compressive strength at 28 day	49.9
Loss on ignition	2.48		
Cl-	0.006		
Insoluble residue	0.19		
Free CaO	1.09		

Table 2. Characteristics of the ABS, PA, and PETG nylon (Data obtained by manufacturer of filaments)

Feature	ABS	PA Nylon	PETG
Melting temperature (°C)	170-220	220	220-245
Printing temperature (°C)	210-250	230-250	230-260
Printing bed temperature (°C)	80-110	>110	80-90
Density (g/cm³)	1.04	1.14	1.27
Specific heat capability (J/g °C)	1.6-2.13	1.6	1.47-1.53
Thermal conductivity (W/m K)	0.128-0.187	0.25	0.162-0.225
Thermal expansion coefficient	Good	Very good	Good
Strength	Good	Very good	Very good
Flexibility	Medium	Very good	Good
Heat resistance	Good	Good	Medium
Cold resistance	Medium	Medium	Good
Water resistance	Medium	Good	Good
Chemical resistance	Medium	Very good	Good
Machinable	Very good	Good	Medium
Stiffness	Good	Medium	Good
Durability	Good	Very good	Good

ABS: Acrylonitrile butadiene styrene; PA: Polyamide; PETG: polyethylene terephthalate glycol.

while ABS lost less than 1% of its mass. Compared to ABS (1.04 g/cm^3), PETG (1.27 g/cm^3) has a higher density. The difference in density is about 20%.

Two different geometries, honeycomb, and triangle were used. In addition to these geometries, the protruding structure was created, and the protrusions were applied in the same direction. Honeycomb and triangular patterned reinforcements were designed with a thickness of 4 mm protrusions and printed by using the three types of filaments. These designs were selected based on the previous study of authors [17]. In addition, support pieces have been added at the bottom of the mesh to centralize the printed mesh in the mold for insertion into the mold. 3D schematics of reinforcement designs are presented in Figure 1.

The product idea is transformed into digital data employing CAD; multifunctional material systems with complex shapes are transformed into a CAD-guided 3D product; a virtual object is created, which is digitally sliced; layered data is transferred to a 3D printer; and finally, manufacturing of the model or product is printed with the 3Dprinter but at a slower rate than conventional polymer processing. The 3D-printed part with FDM has visible layer lines. However, the SLA has sharp edges, a smooth surface finish, and minimal visible layer lines. Therefore, FDM is more effective in adhering to concrete than SLA.

In the 3D-printing process, the ZAXE Z1 model 3D filament printer was used. Figure 2 shows the 3D printing process of the reinforcements and their printed versions. Figure 2a shows the step of reinforcement printing in the 3D printer. Support legs were added at six different points

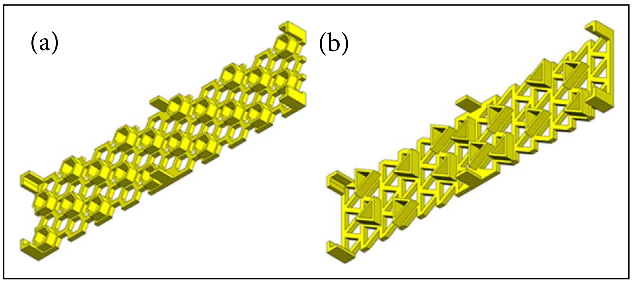

Figure 1. 3D schematics of reinforcement designs **(a)** Honeycomb patterned, **(b)** Triangular patterned

to keep the reinforcements at a certain level in the mortar. Three replicates of each design were produced for three replications. Figure 2b shows the PETG reinforcement products printed with a 3D printer.

PA filament was processed at 250 °C at 0.15 microns. Its high yarn structure makes it difficult to produce small micron sizes in ABS filament. Therefore, ABS nylon filament was processed at 240 °C at 0.3 microns. The PETG filament was processed at 0.1 microns and 245 °C. As a hybrid of the two materials, PETG is somewhat more heat resistant than PLA and a little bit stronger than ABS. FDM printing parameters for ABS, PA, and PETG specimens are given in Table 3.

First, 3D-printed reinforcements were placed into 40×40×160 mm steel molds. Then, the cement mortar was prepared in a laboratory-type mixer confirming with TS EN 196-1 [22] and filled into molds. Reference specimens and three specimens for each series were molded, and 21

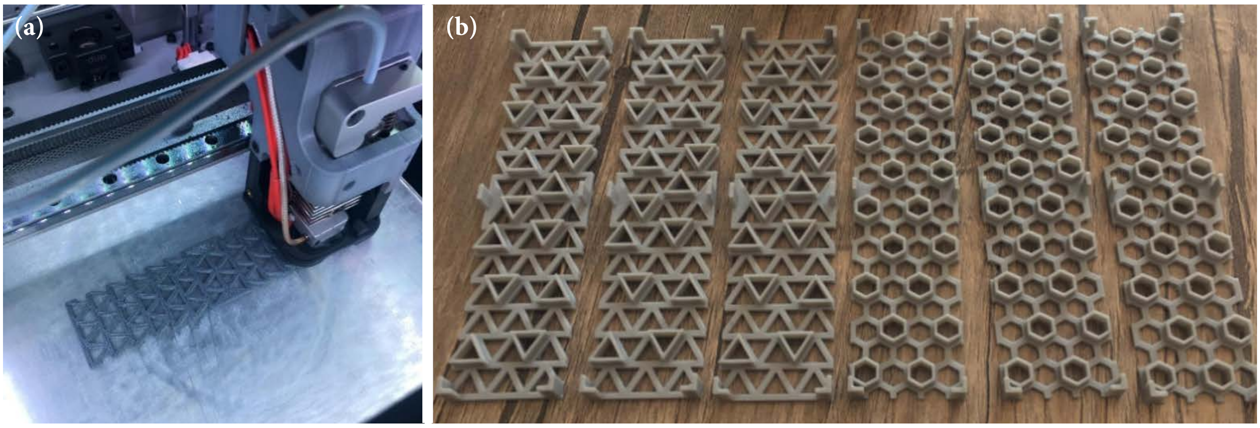

Figure 2. 3D printing of reinforcements and their printed versions. **(a)** The 3D-printing process of reinforcements, **(b)** 3D-printed triangular and honeycomb-patterned reinforcements (Photo of PETG reinforcements).

Table 3. FDM printing parameters for ABS, PA, and PETG filaments

Parameters	ABS	PA	PETG
Printing speed (mm/s)	50	10	60
Printing thickness (μ)	0.3	0.15	0.1
Infill density (%)	90	90	90
Diameter (mm)	1.75	1.75	1.75
Nozzle diameter (mm)	0.4	0.4	0.4
Nozzle temperature (°C)	250	240	245
Environment temperature (°C)	22	22	22
Bed temperature (°C)	100	90	70

Fused deposition modeling; ABS: Acrylonitrile butadiene styrene; PA: Polyamide; PETG: polyethylene terephthalate glycol.

specimens were obtained. Mechanical performances of specimens were determined under deflection-controlled three-point flexural tests with a loading rate of 0.5 mm/min. Load and deflection values were saved, and flexural load-mid span deflection curves were drawn for three specimens for each series.

During flexural loading, two prominent cases occur. The load gradually increases. When a crack is formed on the specimen, the load dramatically decreases. The stress calculated using this first cracking load is called the first cracking strength. At this critical moment, if the reinforcement in the cracked section cannot transfer the load, stress accumulation occurs on the reinforcement, and the reinforcement breaks, which is named as deflection softening behavior (Figure 3a). If the reinforcement in the cracked section effectively transfers the load to the uncracked sections, the load tends to increase, exceeds the load on the first cracking stage, and may create new cracks. This behavior is called pseudo-deflection hardening (Figure 3b). The maximum load value was determined and accepted as the peak load in the curves, and flexural strengths were calculated using these values. Corresponding deflection values to the peak loads were determined as deflection capacities. Finally, the area under the curve up to 1.5 mm deflection was calculated and named the relative toughness ($T_{1.5}$) (note that this value is the typical value obtained from all curves, which ensures a practical comparison).

The failure of 3D printed reinforcement was also investigated at the cracked sections of determined specimens using a digital optical microscope. Images were taken between 200-240x magnification levels, where the images became apparent, and results were discussed.

3. RESULTS AND DISCUSSIONS

3.1. Flexural Load – Mid-Span Deflection Curves

Flexural load – mid-span deflection curves of specimens are given in Figure 4. It was clear from the graphics that mechanical performances were remarkably enhanced by the use of 3D-printed reinforcements when compared to reference specimens. In general observation, it has been determined that using honeycomb reinforcing elements is more effective in increasing the flexural performance of composites than triangular patterns (Figure 4b-4d-4f; Figure 4c-4e-g). Detailed comparisons for mechanical parameters will be discussed in the following sections.

3.2. Flexural Strengths

The flexural strengths of composites are given in Figure 5. The dashed line in the graph represents the average strength of reference specimens. Since the reference specimens lacked reinforcement, they abruptly collapsed when the composites achieved their load-bearing capability. Their average bending strength was calculated as 1.84

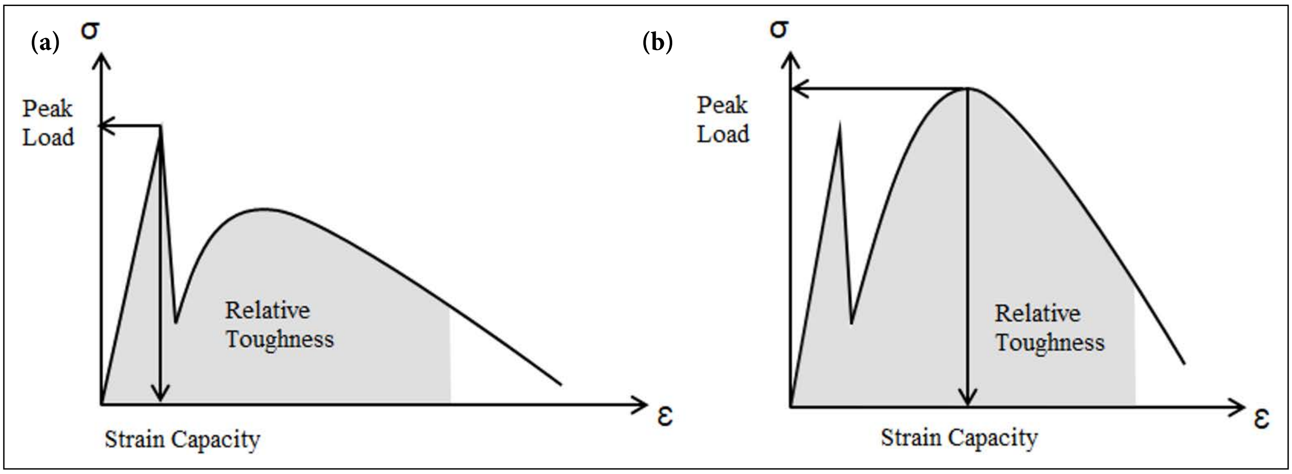

Figure 3. Curves of **(a)** deflection softening, **(b)** pseudo deflection hardening (adopted from the [17]).

MPa. In terms of flexural strengths, all series exhibited higher flexural strength than reference, thanks to reinforcement. When triangular patterned 3D reinforcements were used, PA performed 41.38% and 49.48% higher flexural strength than PETG and ABS, respectively. In using honeycomb-patterned 3D reinforcements, the flexural strength of PETG increased from 2.03 MPa to 2.98 MPa (by 46.80%). Similarly, the flexural strength of ABS increased from 1.92 MPa to 2.47 MPa (by 28.65%). A negligible decrease in flexural strength was observed in the case of PA, which is still higher than ABS.

3.3. Deflection Capacities

The average deflection capacities of specimens are given in Figure 6. As mentioned in the previous section, the dashed line indicated the mean deflection capacity of the reference specimens. Therefore, it was found that the deflection capacities were greatly enhanced compared to the reference. This rate was calculated between 107-730%, approximately. In the case of triangular patterned 3D reinforcement, higher deflection capacity was obtained from PETG (0.52 mm) compared to PA (0.39 mm) and ABS (0.27 mm). However, when the pattern type changed to honeycomb, the deflection capacity of PETG was preserved the same, while the deflection capacities of PA increased by 176.92% to 1.08 mm and ABS increased by 251.85% to 0.95 mm.

3.4. Relative Toughness ($T_{1.5}$)

The average relative toughness values of specimens are given in Figure 7. Similar to previous results, toughness values were significantly increased in all series because of 3D-printed reinforcement (from 35 to 70 times greater than reference). Although the toughness depended on the deflection, it also varied depending on the flexural strengths. As seen in the graphs, in the cases where the same patterns were used, PA ensured the best results in terms of $T_{1.5}$ compared to both ABS and PETG. In the series of triangular patterns, toughness values were calculated as 542.41 N.mm, 661.42 N.mm, and 932.51 N.mm for PETG, ABS, and PA, respectively. When the honeycomb-patterned reinforcement was used, toughness values were increased in all series between 13.20%-77.66% and calculated as; 963.62 N.mm for PETG, 852.79 N.mm for ABS, 1055.64 N.mm for PA. According to Foti [24], who cuts waste PET bottles in different shapes and uses them to reinforce concrete, "O"-fiber concrete adds much more toughness when compared to short lamellar fiber concrete, and specific forms to helped bind the concrete on either side of a cracked portion. As a result, concrete buildings reinforced with polymers such as PETG, PA, and ABS have been shown to have better durability and reinforcing qualities.

3.5. Cracked Section Analysis

Detailed crack patterns of honeycomb-patterned PA specimens, which were found to the advantageous series in terms of mechanical performance, were given in Figure 8. In the figure, images taken from the front side, bottom, and back side of the specimens were presented. Crack branching was observed through the tensile zone where the reinforcement was placed in all specimens, which was assumed as the main reason for the pseudo strain hardening behavior. During the formation of each crack, the flexural load is lowered, which can be seen in the flexural load – mid-span deflection curves easily.

Since the flexural load is taken on by the reinforcements in the cracked sections and transferred to other sections of the composite, slipping and ruptures begin to occur between the 3D printed reinforcement and matrix and the layers of the 3D printed reinforcement in the cracked sections (Figure 9). Due to these slipping and ruptures, relatively small load drops were also observed in the flexural load mid– span deflection curves.

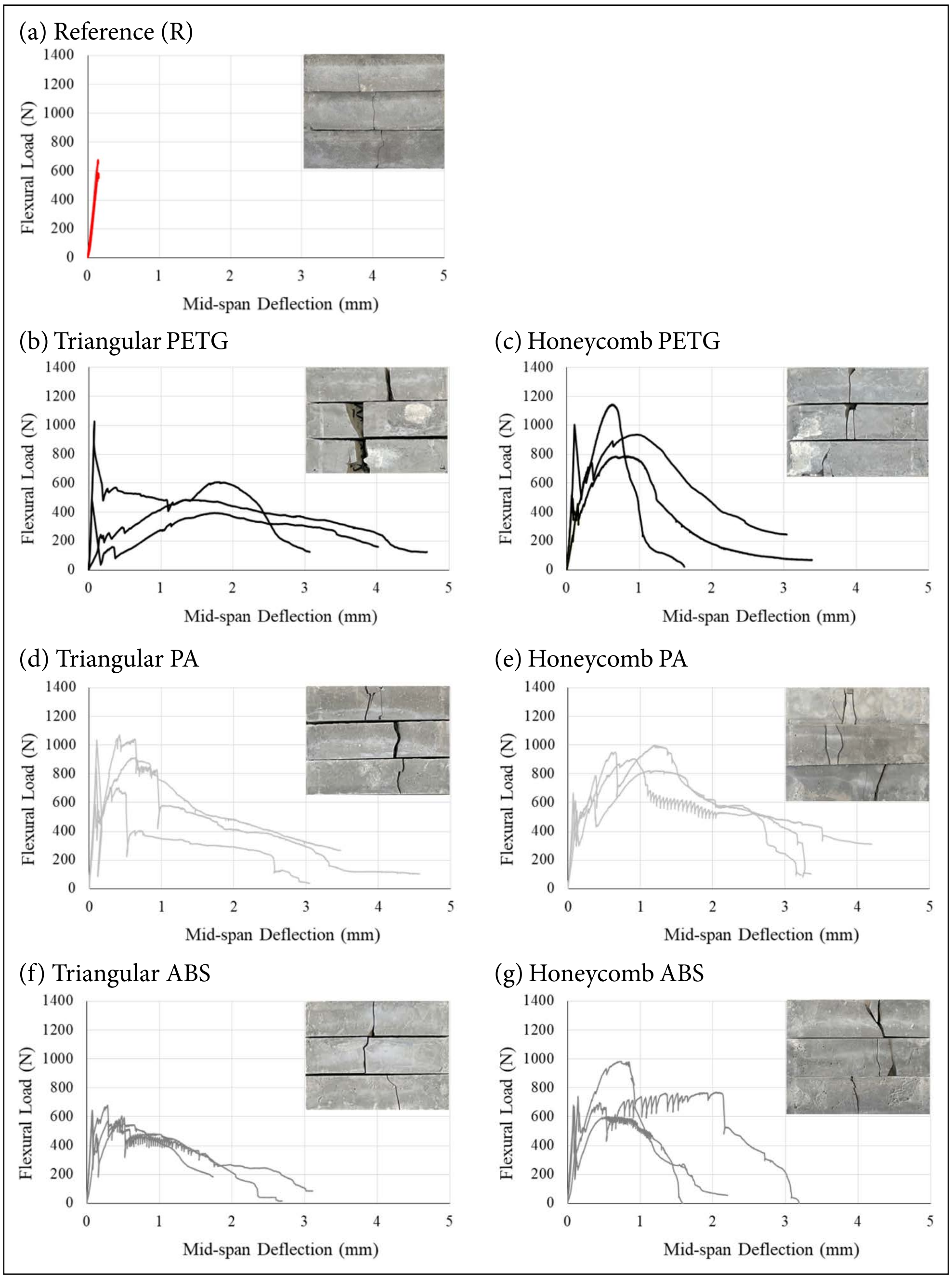

Figure 4. Flexural load – mid-span deflection curves of specimens.

4. CONCLUSIONS

Today, polymer wastes are one of the leading causes of environmental pollution. For this reason, studies on re-evaluating recyclable polymers (thermoplastics) in different areas of use are increasing daily. The concrete 3D printing technique, which has the potential to revolutionize traditional building and construction methods by providing benefits in terms of low cost, high efficiency in automated construction, design freedom, and downsizing [25], can be combined with the 3D printing technique using filaments such as ABS, PA, and PET-G filaments, which are recyclable thermoplastic polymers. This study evaluated the potential use of 3D-printed polymers as an alternative reinforcement in cement-based composites. Within the case, three different 3D-printed polymers (PETG, PA, and ABS) with different geometries (triangular and honeycomb) were prepared, and their mechanical performances under three-point flexural tests were compared.

- The use of the honeycomb pattern further increased flexural strengths compared to the triangular pattern in the case of PETG and ABS. In the PA series, similar val-

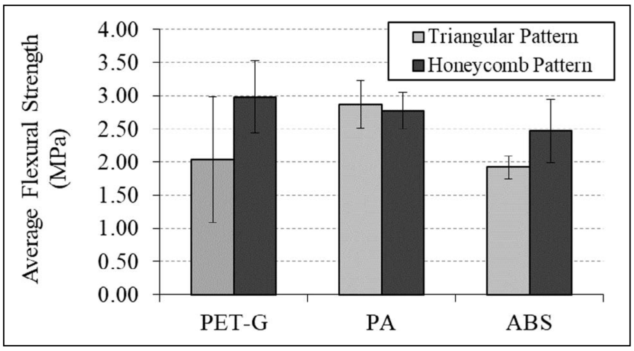

Figure 5. Flexural strengths of composites.

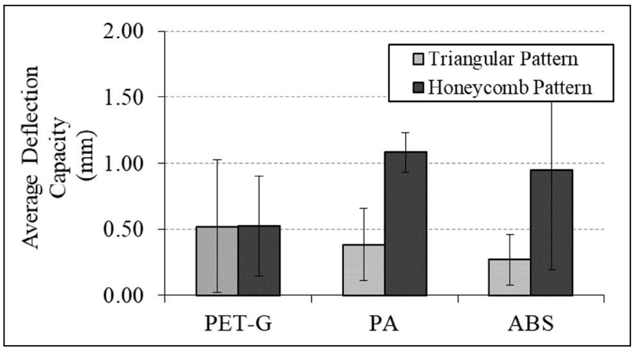

Figure 6. Deflection capacity of composites.

ues were obtained regarding flexural strengths by using either triangular or honeycomb patterns.

- When 3D triangular-patterned reinforcements were applied, PA demonstrated flexural strengths that were 41.38% and 49.48% greater than those of PETG and ABS. The flexural strength of PETG and ABS rose by 46.80% and 28.65%, respectively, with the addition of honeycomb-patterned 3D reinforcements.
- When the reinforcement product was altered from a triangle to a honeycomb pattern, PETG's deflection capacity was preserved. However, PA's deflection capacity grew by 176.92% to 1.08 mm, and ABS's deflection capacity increased by 251.85% to 0.95 mm.
- With the application of the honeycomb-patterned reinforcement, relative toughness values improved in all series by 13.20–77.66% and were found as follows: 963.62 N.mm for PETG, 852.79 N.mm for ABS, and 1055.64 N.mm for PA. The use of the honeycomb pattern also exhibited higher results than the triangular pattern in relative toughness repetitively.

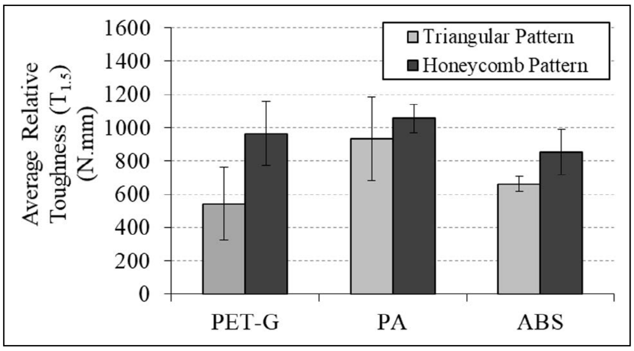

Figure 7. Relative toughness of composites.

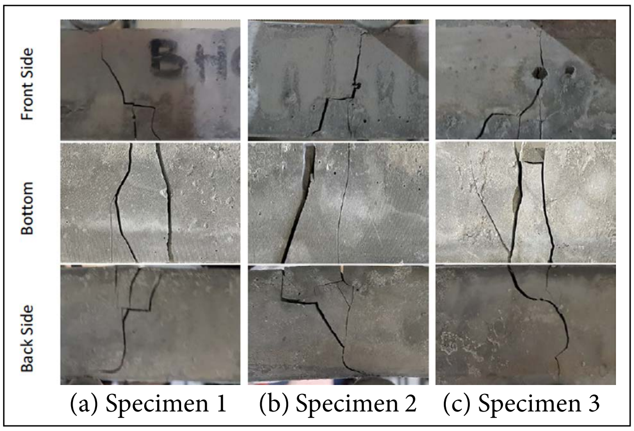

Figure 8. Crack patterns of honeycomb-patterned PA specimens.

- PA gave higher flexural toughness values than PETG and ABS within the same patterns.

In conclusion, this study clearly showed that 3D-printed PA-type filament in a honeycomb pattern is more effective by taking preserved flexural strength, enhanced deflection capacity, and highest flexural toughness into consideration and has the opportunity to be used as reinforcement for ob-

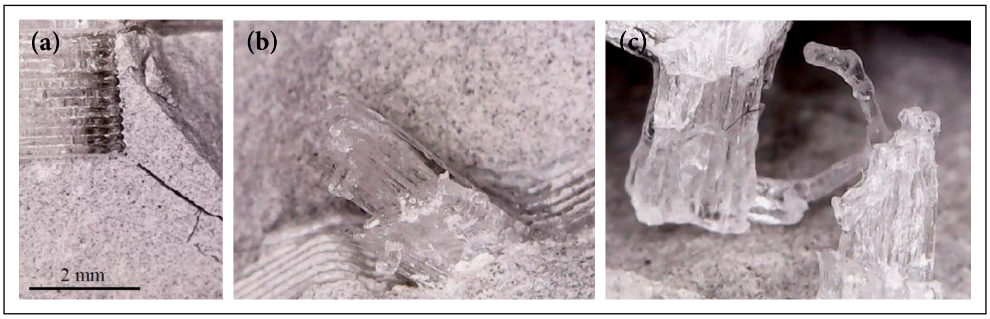

Figure 9. **(a)** Micro-cracking of the matrix, **(b)** Slipping of layers, **(c)** Rupture of the reinforcement.

taining cement-based composites with pseudo deflection hardening behavior. Both novel materials (like those used in this work) and recyclable polymers can be examined for usage in many applications to promote a sustainable future.

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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Research Article

Use of pumice aggregate in cementitious rheoplastic lightweight concrete

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ABSTRACT

Rheoplastic lightweight concrete (RLC) is generally designed for pumping applications as fluid concrete free from segregation. Concrete is produced using polymeric admixtures to enhance concrete workability, strength, drying shrinkage, and durability. This research investigated the suitability of natural porous pumice aggregates in Turkey to obtain rheoplastic lightweight concrete with cement content in normal ranges. To produce and experience rheoplastic concrete mix design data, rheoplastic lightweight concrete mixes were tested with fine pumice aggregate (FPA) and coarse pumice aggregate (CPA) supplied from the Nevşehir region of Turkey. For rheoplastic lightweight concrete with cement contents in the 250 to 400 kg/m^3 range, the percentage of fine pumice aggregates required was in the 73.6-81.0% range with complimentary water/cement ratios of between 0.53 and 0.68. The upper compressive strength limit was circa 30 N/mm^2. The research findings determined that the rheoplastic concrete samples with pumice aggregate met the design requirement of a slump value of 200 mm for fresh concrete predicted for fluid concrete forms. While technical properties of hardened concrete such as oven-dry density (1198-1362 kg/m^3), strength values, static elasticity modulus (9236-10756 MPa), thermal expansion coefficient (5.354 x10^{-6}/°C - 6.929x10^{-6}/°C) and thermal conductivity value (0.405-0.619 W/mK) decrease with increasing aggregate/cement ratios, they increase with increasing cement dosage. In addition, the high amount of fine pumice in concrete composition results in lower drying shrinkage and wetting expansion with decreasing cement dosage. The technical findings showed that RLC might be produced by using a superplasticizer and air-entraining admixtures and mixtures of different sizes of pumice aggregates.

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1. INTRODUCTION

Rheoplastic concrete is a concrete mixture that exhibits high strength, containing selected cement and aggregate, set accelerator, and high plasticizer additives in the correct dosage. It is a concrete form with high workability and a meager water-cement ratio, generally free of segregation and bleeding. The use of different types of artificial and/or semi-artificial lightweight aggregates in this type of concrete production and their compatibility with the application area is a research subject requiring detailed

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investigation. Lightweight aggregate concrete (LWAC) is a widely used construction material that offers technical and economic advantages in the construction industry [1-3]. Unit volume weight values of lightweight aggregate concrete generally vary between 800-1800 kg/m^3 [4], and their compressive strength after setting varies between 30-80 N/mm^2 [1]. LWAC has been used in building projects for load-bearing and/or semi-load-bearing purposes from past to present. However, porous, lightweight aggregates of different origins are also being used to produce (RLC) rheoplastic lightweight concrete, as seen in the literature [2, 3, 5-8].

Lightweight aggregated concrete using pumice (PALWC) could be used in various applications in the construction industry due to its advantages, such as low unit weight, high contribution to heat insulation, and sound insulation. Mixing and placing concrete containing lightweight aggregates is much more complex than conventional concrete practices. Due to their porosity and low specific gravity, lightweight aggregates tend to float with a decreased cohesion value, especially in concrete mixtures with fluid properties [2-9].

RLC is a fluid concrete with a slump of at least 200 mm and can flow easily but does not form segregation. It contains a plasticizer, synthetic fiber if needed, and special additives in its composition. It is a fluid concrete with the same water/cement ratio as additive non-slump concrete (25 mm) [6, 10]. This type of concrete mix is generally designed for pumping applications. Some researchers (including [5, 8, 9, 11, 12]) studied the innovations and use of polymer-modified concrete. Beyond that, there is limited research on using polymers in RLC. Using high range water reducing and air-entraining admixtures in PALWC, rheoplastic mixes (i.e., fluid mixtures that do not segregate but have a low water/cement ratio) can be obtained. This concrete mix approach creates pumice aggregated rheoplastic lightweight concrete, symbolized as "PARLC." It is also possible to obtain PARLC at lower specific gravity without signs of segregation with high range water reducing and air-entraining additives. In addition to overcoming the disadvantages of segregation, PARLC has all the advantages of a meager water/cement ratio. Mainly, RLC can produce materials with better and more continuous thermal insulation; due to its low permeability, the thermal insulation properties are less affected by the humidity conditions of the environment [3, 4].

Several commercially available admixtures, which meet the requirements of ASTM C260 [13] and ASTM C494 [14], have been incorporated in experimental mixes during lightweight structural concrete investigations. All mixes incorporating superplasticizers successively produced high-strength concrete with wet consistencies [7, 15]. In this study, experimental research findings test the provision of PARLC properties and applicability in laboratory conditions by using high water-reducing, air-entraining, and thickening polymeric additives of pumice aggregates with a naturally porous structure are discussed.

2. EXPERIMENTAL STUDY

2.1. Purpose of Assessment

The assessment of this study includes a series of analysis findings to investigate the suitability of pumice aggregates obtained from the Nevşehir region to produce PARLC in coarse and fine-size fractions and to determine suitable mixture design data for this concrete type. In technical evaluation, cement as a primary binder, pumice coarse and fine aggregates with various additives and pump aids would be used. When it is necessary to improve the pumpability and flowability of concrete, using very fine-grained natural sand or an inorganic filler material could be considered a last resort.

2.2. Materials

Ordinary Portland cement (PC) (ASTM Type I, 42.5 N/mm^2) was used to prepare concrete test samples. Blaine's number of cement was 3245 cm2/g, and initial and final setting properties were 250 min and 306 min according to ASTM C191 [16] standard. The specific gravity of Portland cement was 3.1 g/cm^3. The chemical analysis of PC is given in Table 1.

Pumice is widely used as lightweight concrete aggregate in sectoral and industrial applications. It is highly resistant to other chemical materials except for HF acid interaction. It generally exhibits chemically inert material characteristics. As a lightweight aggregate, pumice aggregate (PA) of volcanic origin was obtained from a quarry in Nevşehir, Turkey (Figure 1). Pumice aggregate samples were brought to the laboratory with their natural moisture as they were taken from the quarry and firstly dried in an oven. Afterward, it was subjected to a crushing process and classified as coarse and fine aggregates in two different sizes. The coarse pumice aggregate size range is 4-12 mm, and the fine pumice aggregate is 0-4 mm. Some physical and mechanical properties, such as water absorption, dry bulk density,

Table 1. Chemical composition of the materials

Major element	PC (%)	PA (%)
SiO_2	20.61	74.10
Al_2O_3	5.64	13.45
Fe_2O_3	4.10	1.40
CaO	61.90	1.17
Na_2O	0.11	3.70
K_2O	0.86	4.10
MgO	2.64	0.35
LOI	1.35	1.66

Figure 1. Symbolic view of pumice aggregate before processing.

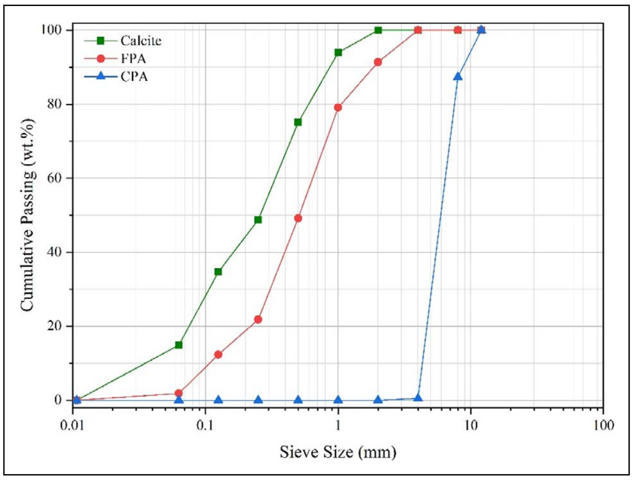

Figure 2. Sieve analysis of calcite, FPA, and CPA.

elastic modulus, and compressive strength, are determined according to TS EN 1097-6 [17], TS EN 1097-3 [18], TS 699 [19], and determined as 23±4%, 870±55 kg/m³, 10.1±1.2 GPa, and 24.2±1.5 N/mm², respectively. The chemical properties of cement and pumice aggregate used are given in Table 1.

0-2 mm calcite powder was also used as an inorganic filling material to prepare PARLC samples. Calcite powder was procured from the Aksaray region as ready-sized material under normal market conditions. Its average bulk density and specific gravity were 1290 kg/m³ and 2.72, respectively.

Sieve analysis of pumice aggregate and calcite filling materials is represented in Figure 2.

A high-range water-reducing admixture commercially available in civil engineering applications could be used in liquid form. A polymeric additive designed as a special additive for rheoplastic concrete was used in the mixtures supplied from market conditions to provide concrete consistency and fluidity. This admixture is in liquid form and is a high-performance superplasticizer for slump retention and high-strength concrete. It is a chloride-free super plasticizing admixture specially designed to produce high-quality rheoplastic concrete. It disperses by electrokinetic action in the concrete mixture, enabling the water phase of the concrete to perform more effectively. This rheoplastic admixture could be used as a dosage of 1.50-2.50 liters/100 kg cementitious material to reach the high concrete strengths. The additive used meets the requirements prescribed for additives in ASTM C 494 [14] for Type A and B. Furthermore, it improves the pumpability of the mixture [10, 20, 21].

An air-entraining admixture, commercially available in civil engineering applications, was also used in liquid form. This admixture also meets the requirements prescribed in ASTM C260 [13] standard. It does not contain air additives, reinforcement embedded in concrete, or any chemical component that will corrode prestressed steels. This additive does not contain any calcium chloride or other chloride-based ingredients [22]. Tap water was used as mixing water.

2.3. Mix Design

More than one mixture was designed for the analysis of PARLC samples. Mixing ratios and concrete density values are given in Table 2. Each mixture series prepared in the study was coded M1 to M6 according to the varying mix-

Table 2. Mixing ratios and concrete density values

Mix	A/C	Cement (kg/m³)	FPA (kg/m³)	CPA (kg/m³)	Filler (kg/m³)	Fines (%)	W/C	Fresh density (kg/m³)	Air dry density (kg/m³)
M1	2.22:1	400	556	199	133	73.6	0.55	1580±28	1362±19
M2	2.42:1	375	571	201	136	74.0	0.61	1590±22	1358±34
M3	2.63:1	350	584	199	138	74.6	0.65	1585±19	1347±15
M4	2.83:1	325	589	192	138	75.4	0.68	1564±33	1322±8
M5	3.07:1	300	600	182	138	76.7	0.70	1541±17	1297±27
M6	3.51:1	250	604	142	132	81.0	0.72	1416±21	1198±21

ing ratios. Different aggregate/cement ratios (A/C) of 2.22, 2.42, 2.63, 2.83, 3.07, and 3.51 were used for the concrete mixtures, respectively. Highly water-reducing admixture (aqueous solution of modified polycarboxylates) was used as a constant dosage of 1.8 liters/100 kg of cementitious material, and an air-entraining agent (aqueous solution of organic materials) was also used in a constant dosage of 100 ml/100 kg cement for all the mixtures. These addition rates were determined through trial batch testing for which the target slumps were 150+ mm. For rheoplastic lightweight concrete with pumice aggregate in the 250 to 400 kg/m^3 range of cement contents, the fineness ratio in the total amount of pumice aggregate required was in the 73.6-81.0% range with free water/cement ratio between 0.55 to 0.72 (where the free water does not include water absorbed by the aggregates (ESCSI, 2005). The upper compressive strength limit was circa 30 N/mm^2. Eguchi et al [23], Teo et al [24], Moreover, Evangelista and Brito [25] reported similar concrete mixture proportions using different lightweight aggregates for lightweight structural concrete.

All pumice aggregates were pre-wetted to account for their porous nature. In order to achieve maximum rheoplasticity for PARLC samples, the aggregate must be pre-wetted before mixing since the surfaces of the pumice aggregates are dry, and the surface tension values are high. During the pumping process, pre-wetting is done to minimize or completely prevent water absorption into the pores of the aggregate. In this way, the pumpability performance of concrete would also increase. This application also enabled lower water/cement ratios for the mixtures. This process also helps to minimize the slump of concrete [6]. In the experimental program, materials in the mixture were mixed in the following order: First, half of the water, cement, and pumice fine aggregate was mixed for about 3 minutes. Second, the remaining water and water-reducing mixture were added to the mixer and mixed for about two more minutes. The third air-entraining agent was added to the mixture and mixed for about 2 minutes. Finally, pre-wetted coarse pumice aggregate was added, and mixing continued for about 6 minutes until a homogeneous concrete consistency was obtained.

2.4. Methods

All concrete test samples were cast 150x150x150 mm in steel molds and compacted by mechanical vibration. For each mixture, six samples were prepared and demolded approximately 24 h after casting. The samples were cured in water at 20 °C for 3, 7, 28, and 90 days until the day before testing. For water absorption tests, 150 x 300 mm cylindrical samples were prepared. The samples were cured in water for 28 days. These samples were then dried in a 105 °C fan oven for 24 hours before testing and immersed at 22 °C in a water bath with a thermostat for 30 to 72 hours. The samples were taken from the water after 72 hours, and the saturated surface was weighed in dry condition. For the flexural strength test, six pieces of 100x100x350 mm prismatic samples for each mixture were produced according to TS EN 12390-5 [26], and they cured the same as compressive strength samples. The flexural strength test was carried out under loading speed conditions of 0.05 MPa/s.

3. EXPERIMENTAL RESULTS

3.1. Fresh Concrete Properties

The properties of PARLC test samples prepared at different mixing ratios are presented in Table 3. The initial slump was 200±8 mm for all fresh concrete mixes according to TS EN 12350-2 standard [27]. The workability of fresh concrete was maintained as self-leveling without any signs of water bleeding or aggregate segregation. The appearance of the fresh concrete was excellent and sticky for all mixes.

3.2. Hardened Concrete Density

Density values of PARLC test samples after 28 days of curing were measured for their air-dry condition, and the values varied in the range of 1198 and 1362 kg/m^3 based on cement contents and aggregate/cement ratios. These values are all in the commonly accepted range of lightweight concrete density between 800 – 1800 kg/m^3. As cement dosage increases, the hardened concrete's density also increases. Aggregate/cement ratios also affect concrete density. The observation for this effect was that increasing the aggregate/cement ratio reduces concrete density. The relationship between 28-day density values of the concrete test samples depending on cement dosage is given in Figure 3 according to the different A/C ratios.

Table 3. Some properties of PARLC samples

Properties	M1	M2	M3	M4	M5	M6
A/C ratio	(2.22: 1)	(2.42: 1)	(2.63: 1)	(2.83: 1)	(3.07: 1)	(3.51: 1)
Cement content (kg/m^3)	400	375	350	325	300	250
Fines content (%)	73.6	74.0	74.6	75.4	76.7	81.0
Thermal expansion coefficient (saturated) /°C	6.929x10^{-6}	6.873x10^{-6}	6.681x10^{-6}	6.377x10^{-6}	6.051x10^{-6}	5.354x10^{-6}
Slump (mm)	192	200	202	203	205	208
Drying shrinkage (%)	0.038	0.032	0.030	0.028	0.026	0.026
Total moisture movement (%)	0.069	0.056	0.053	0.05	0.047	0.049
Thermal conductivity (W/mK)	0.619	0.568	0.548	0.524	0.503	0.405

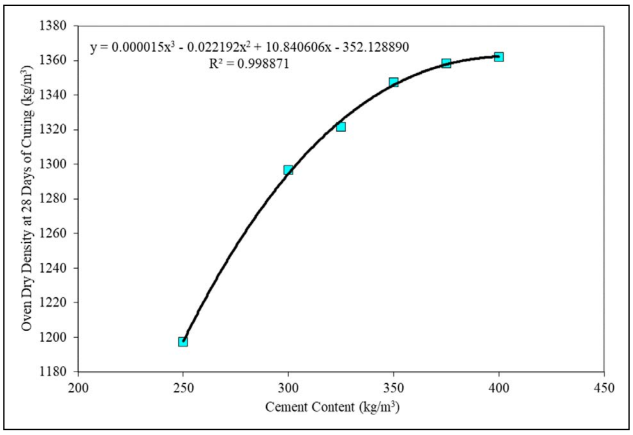

Figure 3. Cement amount versus density of concrete.

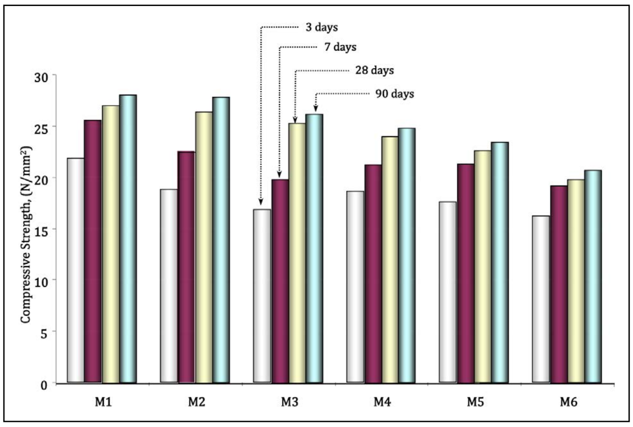

Figure 4. Curing time versus compressive strength of concrete.

3.3. Strength and Elasticity

The strength development of PARLC samples, depending on the curing time, is given in Figure 4. In order to eliminate potential strength changes due to surface moisture, concrete samples were brought to the saturated surface dry condition before testing. It is observed that there is an improvement in the strength values of all concrete samples in each period when considering the curing times. However, as strength-gaining features of PARLC samples were examined, it was observed that the strength improved with a much lower increase in strength until the 60th day period after casting. Predictably, this small amount of strength increases after the 60th day and could be accepted as a constant value for PARLC samples. This improvement showed an even more significant value when the fine grain ratio in the concrete mixture was decreased. Especially over a long period, concrete samples reach a strength value that can be considered constant.

Enhancement in compressive strength is occurring as expected. The strength development due to the change in the A/C ratio of concrete samples in an equivalent curing time (28 days of curing) is also given in Figure 5. Strength values at 28 days and three months are given in Table 4. Air dry densities of PARLC test samples with 250 and 300 kg/m³ cement content were recorded as 1198 and 1297 kg/m³, respectively.

The elastic modulus for PARLC lowers with a decrease in cement content (higher A/C ratios). The static modulus of elasticity varied from 9236 to 10756 N/mm² at 28 days, as shown in Table 4. Generally, the elastic modulus of low-density concrete with lightweight aggregates is lower than conventional concrete because lightweight aggregates undergo greater deformation (more than 50%) than higher-density aggregates [28]. Han and Kim [29] determined the static elasticity modulus of concrete between 25 GPa and 29 GPa at 28 days of curing. The findings obtained in this experimental study showed that the static modulus of elasticity of PARLC mixtures was approximately 37-44% of the static modulus of elasticity for average weight concretes. According to American Concrete Institute (ACI) [30], the compressive strength range of lightweight concrete is 2-14 MPa with 1000-1400 kg/m³ density. Similarly, in this experimental study, PARLC densities change between 1198 and 1362 kg/m³, and the compressive strength of the concrete samples varies between 19.8 to 27 MPa providing ACI moderate strength limitations.

3.4. Flexural Strength

Flexural strength values of concrete samples on the 28th and 90th days are given in Table 4. Their values varied from 4.58 to 5.68 N/mm² at 28 days and from 4.74 to 6.06 N/mm² at three months, depending on the different

Table 4. Some mechanical properties of PARLC samples.

Mix	Compressive strength (N/mm²)		Static elasticity modulus (N/mm²)	Flexural strength (N/mm²)	
	28 days	90 days	28 days	28 days	90 days
M1	27.0	28.0	10756	5.68	6.06
M2	26.4	27.8	10627	5.50	5.84
M3	25.3	26.2	10395	5.32	5.62
M4	24.0	24.8	10119	5.14	5.40
M5	22.6	23.4	9816	4.96	5.18
M6	19.8	20.6	9236	4.58	4.74

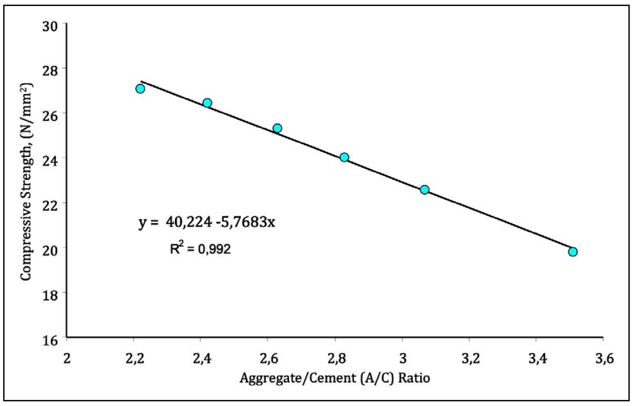

Figure 5. Aggregate/cement ratio versus compressive strength.

A/C ratios of the mixture. PARLC has a lower flexural strength for a specific compressive resistance than conventional normal-weight concrete. Although lightweight concrete has more excellent cement mortar resistance and mortar-aggregate adherence levels than an equal resistance regular weight concrete, the aggregate's low tensile stress resistance noticeably lowers the lightweight conglomerate's tensile stress resistance [28]. Similar results were achieved in this experimental research—flexural strength values of the concrete mixtures given in Table 4. The table shows how this difference varies as a function of the composition and compression resistance of different A/C ratios. This study showed an average difference of 24% after 28 days of curing and 28% after 90 days between the flexural strength of the concrete with the lowest cement dosage and the concrete with the highest cement dosage. The practical reason for this is the change in fine material ratio and the weakening of the cohesion value of the matrix structure.

3.5. Water Absorption of Hardened Concrete

Water absorption values of PARLC samples were measured between 30 minutes and 72 hours in 9 different periods through a series of measurements. As with average weight concretes, water absorption values were higher for lower cement dosage mixtures (higher A/C ratios). The values were between 3.5% and 7% after 30 minutes of immersion according to different A/C ratios, whereas in the range between 13% and 22% after 72 hours of immersion. As expected, the water absorption of PARLC samples was rapid for up to 24 hours; after that, the samples absorbed low water. This effect was based on the toughness of the cement paste surrounding the porous aggregate in the matrix structure and the pressure height above the concrete. The increase in cement content provides a good quality cement paste; therefore, water absorption of the concrete is lower. Another main factor affecting the water absorption was the A/C ratios. Lower A/C ratios have given less water absorption. This relationship was presented in Figure 6 for different PARLC mixtures.

A rapid change in water absorption property for all

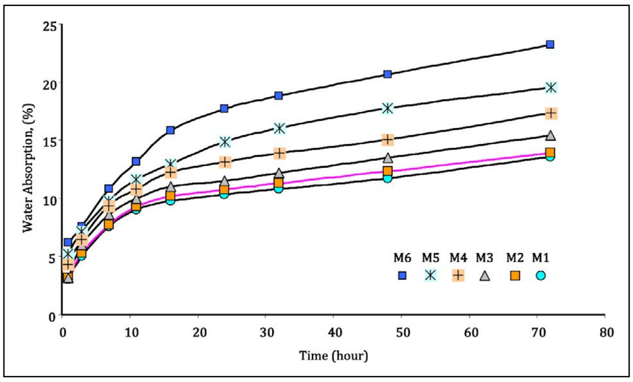

Figure 6. Water absorption versus time for PARLC samples.

six mixtures occurred circa 8 hours after immersion. On the other hand, moisture increase is different currently for PARLC mixtures, increasing with a decrease in cement content, as follows: 400-8.8%, 375-9.2%, 350-9.9%, 325-11.4%, 300-12.3%, and 250-15%, respectively.

3.6. Thermal Conductivity

The thermal conductivity of PARLC samples is given in Table 3 at 3% moisture condition. Coefficients of thermal conductivity varied from 0.405 to 0.619 W/mK based on the increase of A/C ratios. The test results concluded that the thermal insulation properties of PARLC samples depend on their mineralogical composition, residual moisture content, and apparent densities. Increased cement content (higher density) reduced the thermal insulation property of PARLC samples. However, it has been observed that the A/C ratio of the mixture is an important area of interest in the thermal conductivity of pumice aggregated concrete. An increase in porous pumice aggregates in the mixture (higher A/C ratio) decreased the thermal conductivity of concrete samples up to 32-37%. The interaction between densities of test samples conditioned to 3% humidity and thermal conductivity values are analyzed in Figure 7.

In order to determine the thermal conductivity values of PARLC samples, which can be considered partially humid, a series of tests were also performed in this research study. According to the resulting data, an empirical equation was tried to develop as an estimation approach for thermal conductivity values of PARLC with particular reference to Nevşehir pumice aggregate. In the formula created to determine the thermal conductivity coefficients of the samples with different moisture content, the thermal conductivity coefficients of the samples containing different moisture content were determined with the hot-box apparatus and compared with each other. The results showed that the conductivity in PARLC samples increases by 4.7% for each volume percent of moisture content. This relation was formulated for PARLC as given below:

$$\lambda_m = \lambda_0 \times (1 + 4.7 \times M) \quad (1)$$

where;

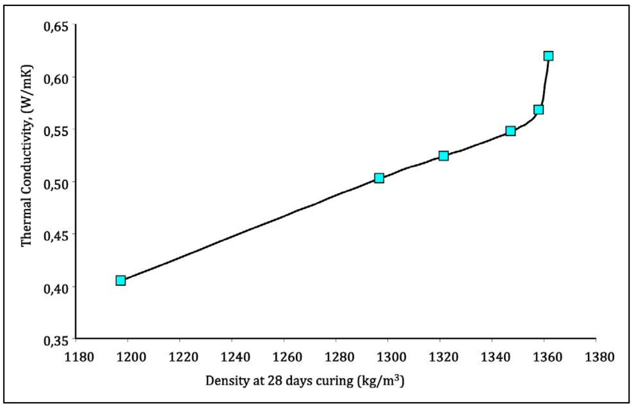

Figure 7. Density versus thermal conductivity of concrete.

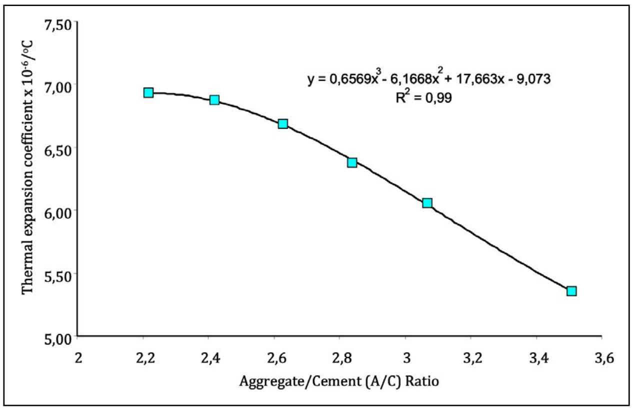

Figure 8. A/C versus thermal expansion coefficients of concrete.

λ_m: thermal conductivity coefficient at moisture condition, W/mK

λ_0: thermal conductivity coefficient at 3% moisture condition, W/mK

M: moisture content of the concrete, %.

3.7. Thermal Expansion

Thermal expansion coefficients of PARLC test samples after 28 days of setting varied between 5.354 x10^{-6}/°C and 6.929x10^{-6}/°C depending on A/C ratio change (Table 3). Thermal expansion coefficients of conventional concrete with average density vary between 12x10^{-6}/°C and 13x10^{-6}/°C [31]. Thermal expansion coefficients of test samples are 45-54% of the values of normal weight concrete, with the effect of porous pumice aggregates in the concrete samples and aggregate particle size distribution.

As a general trend, the thermal expansion property decreases when the mixture's A/C ratio (having low cement content) increases. An interaction is obtained between the A/C ratio in the mixture and thermal expansion in the saturated state, as shown in Figure 8. There is a good polynomial relationship between the thermal expansion property of PARLC and the A/C ratio. It was determined that while the thermal expansion amount was relatively low at low A/C ratio values, the amount of thermal expansion decreased rapidly due to an increase in the A/C ratio.

3.8. Moisture Movement

Moisture movement characteristic of lightweight aggregated concrete depends on the quantity and matrix structure of cement paste, environmental conditions such as the extent of exposure and humidity, as well as type of aggregate, etc. [32, 33]. Table 3 shows drying shrinkage and wetting expansion at 90 days. The results show drying shrinkage from 0.026% to 0.038%, whereas wetting expansion varied from 0.021% to 0.031%. It was observed that the drying shrinkage of standard-weight concrete is more significant than that of PARLC samples by 28-31%. Therefore, the mixture's cement content and fines ratio were experienced as primary interests in drying shrinkage in pumice aggregated concrete. They applied more fine pumice aggregates with reducing cement content rather than coarse ones, reducing concrete samples' shrinkage to 22-27%. Similar effects were also reported on the wetting expansion feature for PARLC mixtures. The augmentation of concrete density and cement content (lower A/C ratio) increased wetting expansion values for PARLC samples. Values of drying shrinkage for the M5 and M6 mixes were the same numerical magnitude. It may be more meaningful to examine the total amount of moisture movement to evaluate the shrinkage of concretes containing porous aggregates in more detail. In concrete samples, total moisture movement can be considered the total value of the drying shrinkage and wetting expansion amounts. Parallel to the drying shrinkage and wetting expansion findings, the total moisture movement amount for PARLC samples also shows a similar trend. As the A/C ratio increases, the total amount of moisture movement decreases, and the total amount of moisture movement is ranged between 0.049% and 0.069 based on A/C ratios. On the other hand, drying shrinkage and wetting expansions of PARLC samples appeared to follow a slightly linear trend.

4. CONCLUSIONS

The findings of this study are briefly summarized below:

1. Rheoplastic concrete with a moderate strength value can be produced using lightweight pumice aggregates ranging from 250 to 300 kg/m^3 for cement contents. Compressive strengths can be obtained between 20 and 23 N/mm^2 using these cement contents.
2. Rheoplastic lightweight concrete can be produced using pumice coarse and fine lightweight aggregate to meet the requirements of ACI classification subject to ceiling in the 25 – 30 N/mm^2 range for concretes for the normal range of cement amount of 350 to 400 kg/m^3.
3. For practical ready-mix supply and pump emplacement, the use of admixtures is predominantly a pumping aid supplemented by a normal water-reducing plasticizer and an air-entraining agent. The pumpability is not

considered sensitive to the generic type, but the correct choice of pumping aid is essential. From the trials undertaken, water-reducing admixture was found to give long workability times, cohesiveness, appearance, and early strengths for pumping.

4. It has been observed that rheoplastic concrete with pumice aggregate with superplasticizer and air-entraining additives in liquid form can produce mixtures with fluid properties with a slump of 210 mm without bleeding and separation.
5. As well as adding admixtures, the percentage of pumice fines is increased for pumpable mixes compared with similar mixes of lesser workability or emplacement requirements.
6. An increase in pumice aggregates in rheoplastic concrete reduces the thermal conductivity value of PARLC and makes the concrete matrix more insulated. The thermal conductivity value of concrete varies depending on the amount of aggregate in the concrete composition, porosity ratio, aggregate fineness ratio, and final concrete density. The thermal conductivity of PARLC was recorded as 2.1-3.5 times lower than normal-weight conventional concretes.

The mixtures' drying shrinkage is higher than those of wetting expansions. Drying shrinkage and wetting expansion values for the mixtures were found to be a function of concrete density and cement content. It was determined that the drying shrinkage and wetting expansion of rheoplastic concrete increased depending on the decrease in the pumice aggregate ratio and the increase in the cement dosage. It has been shown that the ratio of pumice aggregates in the porous structure of the concrete composition is a directly effective parameter on the total moisture movement of the matrix structure.

ETHICS

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

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

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Review Article

Current construction and demolition waste management strategies for Philippine construction sector – A systematic literature review

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ABSTRACT

The construction industry continues to be one of the primary drivers of a country's economic progress. As of 2022, the Philippines' construction sector had an annual growth rate of 9.2% and continues to increase due to the Build! Build! Build! (BBB) program. However, the construction sector is globally known for regularly consuming more raw materials, resulting in natural resource scarcity and environmental implications. Construction activities also generated a massive volume of construction waste from construction, demolition, and renovation. The need to impose construction and demolition waste (CDW) management strategies and policies in all stages of construction is crucial in attaining a more sustainable construction. This study aims to explore the current CDW management practices and policies from existing literature. The findings of this research will present many potential strategies and solutions that the Philippines can adopt to create more sustainable construction while also assisting in combating environmental issues and concerns in attaining sustainable construction. The study will utilize a Systematic Literature Review (SLR) to identify relevant studies in CDW management to gain the best practices and current trends in CDW management. The study's findings show that at least 26 strategies have been implemented in the construction industry. These can be grouped into 6 major groups: information technology, policy, design, operations, knowledge, and procurement based.

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1. INTRODUCTION

The construction industry continues to be one of the primary drivers of a country's economic progress. As of 2022, the Philippines' construction sector had an annual growth rate of 9.2% [1]. The volume of construction activities is expected to increase steadily due to the Build! Build! Build! (BBB) program. The BBB Program aims to increase public infrastructure spending from 2.9% on average to around 7.3% of the Gross Domestic Product (GDP). From 2016 to 2022, this will cost approximately ₱8 trillion to ₱9 trillion to address the country's massive infrastructure backlog [2]. The increase in construction activities, however, signifies an increase also in the waste generated by the industry.

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The construction sector is globally known for regularly consuming more raw materials, resulting in natural resource scarcity and environmental implications [3]. Construction industry resource usage is about 40% of the total materials reserve [4]. On average, more than 85% of mined resources become waste, and in some cases, more than 99% [5]. Furthermore, most materials are frequently wasted by the end of the building's life, resulting in an average of 100 billion tons of garbage, 35% of which ends up in landfills [6]. An estimated 14.66 million tons of solid waste in the Philippines has generated annually [7]. The constant increase in waste volume is attributed to increasing population, rising living standards, and urbanization, all contributing to difficulties related to excessive waste. Thus, immediate action to address waste management challenges is needed.

The excessive solid waste generated by construction and the industry's increasing resource consumption impedes the accomplishment of sustainable construction [8]. The need to impose construction and demolition waste (CDW) management strategies and policies in all stages of construction is crucial in attaining a more sustainable construction.

This study aims to explore the current CDW management practices and policies from existing literature. The findings of this research will present many potential strategies and solutions that the Philippines can adopt to create more sustainable construction while also assisting in combating environmental issues and concerns in attaining a sustainable construction industry in the country.

2. CONCEPTUAL LITERATURE

Construction and demolition waste management (CDWM) is a growing field in the construction industry that aims to reduce the negative environmental impacts of construction activities, which is regarded as one of the essential factors in achieving successful sustainable development [9]. It reduces and minimizes construction waste, such as debris, scraps, and other construction waste, through waste management strategies [10].

2.1. Construction and Demolition Waste

Construction and demolition wastes (CDW) are the most significant wastes generated by the construction sectors, and they are classified into two types. Construction waste is generally defined as relatively clean and heterogeneous wastes generated from various construction activities, while demolition waste is defined similarly to construction waste but with different materials resulting from the demolition action [11]. Construction waste can be generated from six different sources [12], which are as follows: design source, procurement source, handling of materials source, operation source, residual source, and additional sources.

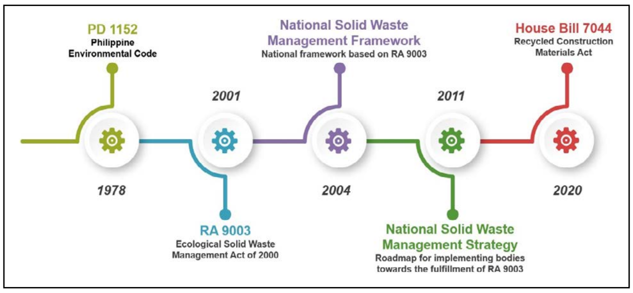

Figure 1. Timeline of CDW related policies in the Philippines.

2.2. Philippines CDWM Initiatives

Several legislations have been created to combat the issues of climate change and pollution. Policies related to CDW and waste management started as early as 1978 and continuously evolved to address the problems on solid waste management better. This study discussed five initiatives by the Philippine government related to CDW management and waste minimization. A timeline is presented in Figure 1, showing the CDW-related policies.

2.2.1. Philippine Environmental Code (PD 1152)

PD 1152 stated the creation of waste management guidelines, including promoting technological and education efforts to prevent environmental damage. The code requires all local government units (LGUs) to prepare and implement waste management programs. It is also stated the methods of proper solid waste disposal. A policy on managing and conserving natural resources includes managing mineral resources [13].

2.2.2. Ecological Solid Waste Management Act of 2000 (RA 9003)

RA 9003 declared the State's policy to implement a systematic, comprehensive, and ecological solid waste management (ESWM) program. The ESWM policy related to CDW includes solid waste avoidance and waste minimization, proper waste segregation, promotion of research and development, private sector participation, and integration of ESWM into academic curricula. The ESWM policy related to CDW includes: (1) solid waste avoidance and reducing waste volume through source reduction and waste minimization techniques, (2) proper segregation, collection, transport, storage, treatment, and disposal of solid waste excluding incineration, (3) promotion of national research and development (R&D) programs to improve solid waste management, and conservation of resources, (4) encouragement for private sector participation, (5) encourage cooperation and self-regulation among waste generators and (6) integration of ESWM and resource conservation in academic curricula to promote environmental awareness. The implementing rules and regulations of RA 9003 relevant to CDW that are mandated include the establishment of an SWM Board, submission of a 10-year SWM plan, the estab-

Table 1. Recent CDWM policies across the world

Country	Year	CDWM policies	Literature
China	2013	Green building plan	[18]
	2014	Comprehensive information platform for CDWM	[19]
	2015	CE promotion plan	[19]
	2016	Environmental protection law	[18]
	2017	Circular development plan	[18]
EU countries	2015	EU Action Plan for CE	[20]
Japan	2014	Construction recycling plan	[18]
	2019	Government funding for CDWM research and recycling businesses	[18]
Spain	2015	Incorporation of CDWM plans in detailed building design	[21]
USA	2016	Resource Conservation and Recovery Act	[22]
	2019	Deconstruction of Building Law	[22]
Australia	2010	New South Wales (NSW) Environmental Protection Agency (EPA) Specifications for Supply of Recycled Materials for Pavement, Earthworks, and Drainage	[23]
	2016	NSW Road & Maritime Services Technical Guide for Management of Road Construction & Maintenance Wastes	[23]
	2018	National Waste Policy	[23]
	2019	NSW EPA CDWM Standards	[23]

CDWM: Construction and demolition waste management; CE: Circular economy; EU: Europe Union; USA: United States of America.

lishment of material recovery facilities (MRFs), closure of open dumpsites and conversion into controlled dumpsites by 2004 and banning of controlled dumpsites by 2006 [14].

2.2.3. National Solid Waste Management Framework (NSWMF)

The NSWMF is a framework built along the three main dimensions: (a) the scope of waste management activities, (b) critical actors and partners in implementing the activities, and the means for achieving the SWM objectives. The scope of the NSWMF is anchored on sections 15 and 16 of RA 9003, which includes: planning and management, waste generation, and waste handling and transport [15].

2.2.4. National Solid Waste Management Strategy (NSWMS)

It is a medium-term plan designed to address critical issues, gaps, and barriers encountered by SWM implementers and demonstrate the path for full implementation of RA 9003. It consists of eight strategic components, which include: (1) bridging policy gaps and harmonizing policies, (2) capacity development, social marketing, and advocacy, (3) sustainable SWM financing mechanisms, (4) creating economic opportunities, (5) supporting for knowledge management on technology, innovation, and research, (6) organizational development and enhancing inter-agency collaboration, (7) compliance monitoring, enforcement and recognition and (8) cross-cutting issues: good SWM governance, caring for vulnerable groups, reducing disaster and climate change risks [16].

2.2.5. Recycle Construction Materials Act (HB No. 7044)

It is a proposed legislation submitted to the House of Representatives on June 30, 2022. The proposed law shall declare a policy of the State to adopt measures in providing economic incentives and assistance for individuals and entities to establish facilities that recycle CDW as components for building or construction materials. It also aims to reduce CDW through granting of the following incentives: import tax exemptions for equipment used in recycling CDW, tax credits in purchasing CDW recycling equipment, tax exemptions on donations to people and entities involved in recycling CDW, directing of government-owned banks in financing businesses related to CDW recycling and giving financial grants to LGUs with approved programs for CDW recycling [17].

2.3. Recent Global CDWM Policies

The issue of CDW is a common problem across the globe. Most developed countries realized the severity of CDW and have advocated for more sustainable construction and waste minimization in the industry. Some of the best policies implemented recently to combat the issue of CDW are presented in Table 1.

3. METHODOLOGY

A Systematic Literature Review (SLR) approach was used to conduct this study. An SLR identifies, selects, and critically evaluates studies to answer a specific question. Compared to many traditional and less systematic approaches to conducting literature reviews, SLR is widely regarded as superior in transparency, as other researchers can more easily verify the study's findings by replicating the research setup [24].

The review will follow Kitchenham and Charters' suggested guide defined as follows: (1) developing the review question, (2) locating relevant studies, (3) selecting and evaluating identified studies, (4) analyzing and synthesizing the results, and (5) reporting the results [25]. The preferred reporting of SLR results is through a PRISMA flow diagram [24].

This study explores emerging CDWM practices and policies from existing literature. The SLR will be guided based on the research question (RQ) formulated to achieve the study's objective.

- RQ – What are the current practices and policies for CDW management?

3.1. SLR Search Strategy

As recommended by Kitchenham and Charters, multiple electronic sources were used to search for relevant primary publications [25]. The search strategy was conducted on reputable journals related to CDWM published by Science Direct, Taylor and Francis, Emerald Insight, and ASCE Library. The keywords used in the preliminary search stage include construction waste, waste management, and demolition waste. There will be no time boundary restraint for the publication dates of related research. The review will focus only on research articles and exclude gray literature such as conference proceedings, thesis, and books.

3.2. SLR Selection Criteria

Following the preliminary search stage, there will be a filtering process to select relevant articles based on their titles and abstracts. Kitchenham and Charters outline the inclusion/exclusion criteria and quality assessment [25]. The filtering process began with the title and abstract of the articles. The quality evaluation included a full-text content and relevance check. The final selection includes only articles on the English language for practical reasons.

3.3. Data Extraction and Synthesis

After the final article sample was completed, the author read each article, and the contents relevant to emerging CDW management strategies were coded to establish a systematic classification. This approach established the main themes of the existing literature relevant to CDW management.

4. RESULTS AND DISCUSSIONS

The initial result of SLR yielded preliminary candidate research articles subject to a series of screenings to come up with highly relevant studies related to current strategies on CDW management. The SLR results summary is presented through a PRISMA flow diagram shown in Figure 2.

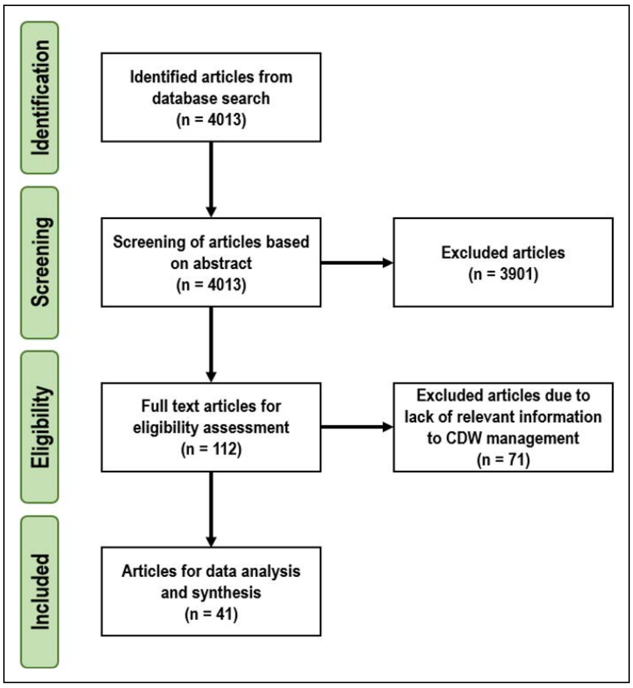

Figure 2. PRISMA flow diagram of the SLR result.

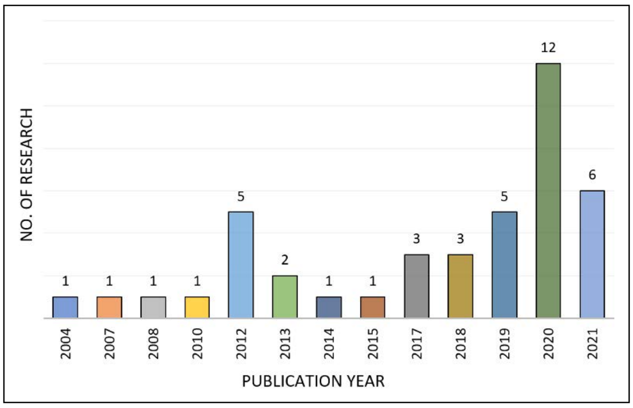

Figure 3. Annual distribution of CDWM articles.

The initial search resulted in 4,013 articles. To further filter relevant articles, a two-stage screening process was used. The first screening involved looking at the titles and abstracts. 3,901 articles were excluded, and the screening yielded 112 articles. Most articles are excluded because the titles do not match the research keywords. The articles were also excluded due to irrelevant content based on the abstract. Next, a quality assessment is performed to further scrutinize the articles by analyzing and reading the whole paper and determining their eligibility. Articles were excluded in this stage due to a lack of reading access and no relevant findings to support the CDW management strategies.

The final list of articles for data synthesis is 41 articles. A distribution of articles published relevant to the research question from SLR in terms of the year of publication is presented in Figure 3.

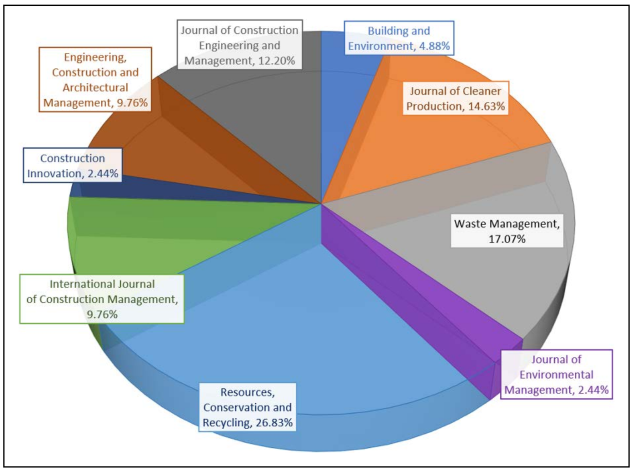

Figure 4. Distribution of CDWM articles across journals.

Figure 3 shows that the year 2020 yielded the most significant number of published research related to CDW management, and the raw data implicitly shows that the field of CDW management is getting more attention in research and development.

The distribution of published articles across various journals is also recorded and presented in Figure 4 to show the journals that published relevant articles in CDW management.

Figure 4 indicates that the top three journals with the highest number of publications related to CDWM are: Resources, Conservation, and Recycling (26.83%), Waste Management (17.07%), and Journal of Cleaner Production (14.63%). Other journals related to engineering, architecture, and construction also listed some articles related to CDWM.

Finally, data were collected and analyzed for the 41 research articles. Each article was examined to identify the strategy used in CDW management and any relevant findings. Each strategy discovered in an article was listed and classified based on its thematic nature. The results of the data synthesis are presented in Table 2.

The data collection and synthesis from the list of research articles yielded numerous strategies relevant to CWD management. By examining each strategy's themes, a systematic classification of strategies led to six main classifications of CWD management strategies: information technology, policy, design, operations, knowledge, and procurement based. Figure 5 presents a conceptual framework showing the current strategies for CDWM.

4.1. Information Technology Based

With the increasing technological advancement, CDWM can benefit from the recent advances, particularly in the digitalization of the construction process. Emerging IT-based processes and methods such as building information modeling (BIM), simulation techniques, and big data (BD) provides evidence in CDW minimization and management.

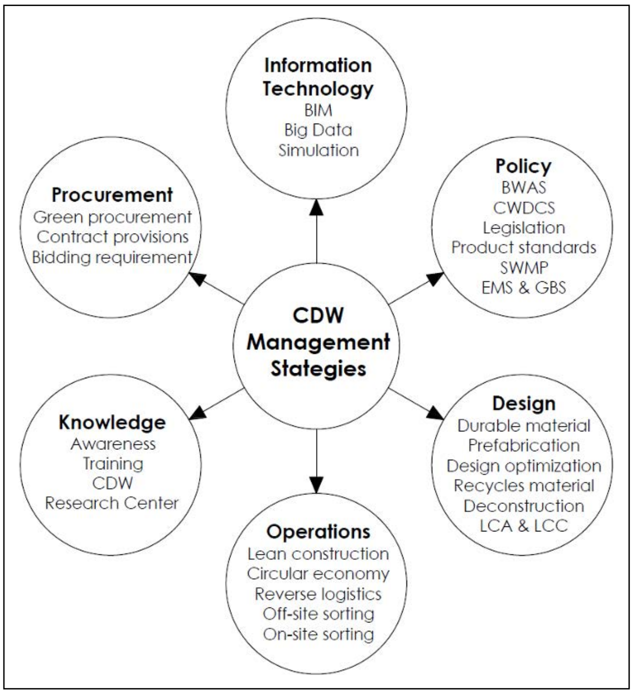

Figure 5. Conceptual framework of CDWM strategies.

Construction waste generation must be accurately quantified before implementing waste management strategies. BIM is a new technology that has sparked widespread interest and has emerged as a critical solution in CDWM [32]. BIM has been considered a front-runner tool in CDW estimation and quantification [29]. CDW estimation capabilities based on BIM guide CDWM, particularly in disposal scheduling, cost estimation, on-site reuse, and waste bin allocation [26]. An information management system on CDW can also be generated using BIM to harmonize CDW data, such as quantification and source identification. Decision-makers can benefit from information on regional waste generation in developing more realistic policies, determining the location of new waste facilities, and allocating labor and tracking resources. Quantification at the project level refers to forecasting the production of construction waste in a specific project. It can assist project managers in adjusting the material purchase schedule, arranging proper on-site stockpiling, and determining the potential waste recycling benefit and disposal cost to the client [29].

Another IT-based strategy uses simulation modeling techniques such as Systems Dynamics to perform what-if scenarios regarding CDW policies to aid decision-making [33, 63]. On-site waste management is difficult and time-consuming. The simulation model was developed using system dynamics, a comprehensive approach. It has been demonstrated that simulation modeling can identify complex scenarios' effects and ultimately indicates that increasing on-site sorting positively impacts public filling [31]. Construction site methods can also be simulated to analyze waste generation and prevent CDW-generating activities [30].

Table 2. Classification of CDWM strategies from SLR data synthesis

Classification	CDW management strategy	Literature
Information technology based	BIM-based CDW information management system, CDW quantification, CDW estimation to streamline decision making, planning of concrete and drywall waste reuse and recycling throughout construction projects, CDW disposal planning & scheduling, disposal cost estimation planning, BIM-enabled building waste analysis (BWA)	[26–30]
	Big data-assisted CDW quantification and source identification	[31], [32]
	Simulation-based methods for prevention/reduction of CDW generation and CDW management policies	[31], [33], [5], [34]
Policy-based	Building Waste Assessment Score (BWAS)	[35], [36]
	Construction Waste Disposal Charging Scheme (CWDCS)	[37], [34], [38]
	Legislation to penalize or incentivize CDW initiatives	[22], [39], [40], [37], [41]
	Establishment of product standards for recycled CDW	[40], [37]
	Site Waste Management Plan (SWMP)	[42], [37]
	Environmental Management Systems (EMS) and Green Building Standards (GBS)	[40], [21]
Design based	Promotion of the usage of durable materials	[43-45]
	Use of modular/prefabrication/off-site/IBS construction	[44-49]
	Design for deconstruction/disassembly	[50], [45], [9]
	Design for the use of recycled CDW	[51], [40]
	Design optimization to minimize material consumption	[30], [45]
	Life Cycle Assessment (LCA), Life Cycle Costing (LCC)	[28], [9], [33]
Operations based	Application of lean construction principles	[52-54]
	Application of Circular Economy (CE) principles	[55], [56], [34], [38]
	Utilization of Reverse Logistics (RL)	[57], [58]
	Off-site CDW sorting	[59]
	On-site CDW sorting	[50], [60]
Knowledge-based	Increase CDW awareness and promotion	[31], [40], [61], [45]
	Establishment of CDW research center for CDW technology initiatives	[61], [40]
	Training of personnel to ensure quality and eliminate reworks and CDW	[44], [62], [45]
Procurement based	Green procurement	[36], [51]
	Contractual provisions for CWD management	[50], [55], [51]
	Construction project bidding agency qualification measures	[22], [51], [21]

CDWM: Construction and demolition waste management; CDW: Construction and demolition waste; BWA: BIM-enabled building waste analysis.

Most research about CDW mentions the problems of the lack of CDW data. Waste forecasting is a complex learning process involving objective and subjective data interpretation. Nonetheless, it is necessary to forecast CDW quantities on-site using an up-to-date method [31]. Big data is a technology used to analyze massive amounts of data generated by CDW to resolve management issues. It can be used to establish a CDW database to aid CDW initiatives such as CDW quantification and CDW source identification. These data can then be used in performing advanced analysis such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) in the design stage to optimize the design and help in minimizing the generated CDW [32].

4.2. Policy Based

Several countries have initiated government-led policies regarding CDW including China and the USA. These policies involve legislation and standards related to CDW. Legislations are further divided into penalty-based and incentive-based policies.

Many countries have widely adopted the Polluter-Pays-Principle (PPP) enacted under environmental law, which holds polluters accountable for adverse environmental impacts. In the construction industry, the PPP puts economic restraints on contractors to implement waste-reduction measures such as recycling and waste segregation as part of the construction processes [38]. One policy is the Construction Waste Disposal Charging Scheme (CWDCS) implemented in Hong Kong. CWDCS encourages waste generators to optimize the 3Rs practices over disposal. Upon implementation, the amount of CDW disposed of in landfills decreased by approximately 40% from 6600 tpd in 2005 to around 4000 tpd in 2006 [38]. However, strict implementation should be used and safeguarded due to the risk of illegal CDW dumping to avoid paying discharge fees [34].

The implementation of mandatory policies related to construction, such as EMS [40], strict implementation of SWMP [42], and a building requirement for BWAS [35], helped to implement agencies monitoring construction activities in regulating CDW generation and compliance. Among the ISO 14001 EMS requirements is the monitoring and control of consequential impacts of the construction process and the fulfillment of lawful accountability concerning environmental aspects of such activities [27]. SWMP encourages contractors to effectively manage construction waste on construction sites through adequate waste planning, monitoring, and reporting and reduce illegal construction waste transportation and disposal. This instrument is used in several countries/regions, including the UK, Hong Kong, Australia, the USA, Japan, and Singapore [37]. Green building standards (GBS) frequently include CDWM provisions, promoting CDW reduction and recovery. Criteria points can be obtained by achieving the prescribed CDW parameters and targets using recycled CDW. Cities in China have started implementing GBS to regulate the capacity of landfills by mandating the use of recycled CDW and promoting CDW segregation [40].

Establishing approved product standards in the use of recycled CDW fostered the increased marketability of CDW as alternative building materials, and some countries increased the tax on raw materials to promote the use of recycled CDW. The recycling product certification label can boost consumer confidence, increase recycled product sales, and ensure the recycling industry chain runs smoothly. Contractors are also more willing to use certified recycled products. The European Commission has created a technical specification called EN 12620:20 02 + A1:2008 to encourage using secondary recycled materials as aggregates. Japan devised a set of standards for using recovered and recycled aggregate as filler construction material, which led to an increase in the recycling rate of more than 97% [40].

4.3. Design Based

Many researchers have argued that much construction waste is generated due to poor design considerations [35]. CDW reduction during the pre-construction phase reduces CDW generation during the construction phase by optimizing the design through innovative technologies and sustainable construction materials, resulting in decreased resource consumption and more empowered environmental protection.

The construction industry continues to rely heavily on traditional building technologies such as cast-in-situ, timber formwork, plastering, and painting. As a result, the construction process is highly labor intensive. This, combined with poor quality and the overuse of multi-layered subcontractors, impedes management control and results in excessive waste from construction activities. Specifying innovative technologies and methodologies in the design will aid in reducing CDW generation. Modern Methods of Construction (MMC), such as prefabrication and IBS, are some innovative methods the designer can specify. Plastering waste can be reduced by up to 100% using prefabrication methods. Timber formwork has the potential to reduce waste by 73.91% to 86.87%. Concrete waste can be reduced by approximately 51.47% to 60%. Steel bar waste can be reduced from 35% to 55.52% [49]. An Industrial Building System (IBS) can reduce the waste generation rate (WGR) from 4.8 tons/100sq.m to 1.55 tons/sqm compared to the conventional cast in-situ methodologies [47].

Deconstruction is the process of fully or partially separating the building parts to facilitate the reuse and recycling of materials. The design for the deconstruction method anticipates producing the least waste at the end of each building's lifespan [55]. Designing for flexibility and adaptability reduces the risk of CDW generation. Buildings should be designed to optimize the geographical location and design flexibility to accommodate interior space reconstruction and disassembly. This further suggests that proper documentation's role in the design stage should include provisions for deconstruction plans [45]. The consideration during design for deconstruction/disassembly using offsite methods yielded favorable results to minimize demolition wastes [50].

Material optimization during design to reduce resource consumption. This includes optimizing design sections and rebar usage in terms of length, weight, quantity, and cutting using BIM-based methods [30]. Substandard materials can easily break away during construction, necessitating replacement, which may often necessitate the destruction of other parts of the structure. The use of approved materials can reduce wastage due to cutting. Similarly, choosing resistant materials will eliminate repairs and replacement [45].

4.4. Operations Based

The construction stage includes construction execution, material deliveries, site management, and logistics management. CDW is generated due to errors in these processes and poor communication and execution.

Many process improvement techniques are available for construction implementation. Lean construction is a technique for reducing waste and increasing productivity in the construction industry. Researchers believe adopting lean-based methodologies and tools will reduce all forms of CDW because lean entails refocusing on the construction process and creating value through process improvement [54].

The lean concept of Just-In-Time (JIT) in material handling and delivery reduces the risk of material wastage during operations [52]. In the modular construction industry, value stream mapping is used to identify waste. To improve the identified waste-generating processes, lean principles in the form of the 5S (sort, straighten, shine, standardize, and sustain) were applied [53].

The establishment of sorting facilities for CDW improved the flow of waste management. Launching off-site CDW facilities in Hong Kong for separating and sorting construction waste before final disposal significantly reduces the depreciation of existing landfills for receiving and processing construction waste [59]. CDW segregation is a crucial part of project site management practice for reducing CDW. Recycling, as a waste-management strategy, necessitates the separation of recyclable and non-recyclable waste during the construction stage [60]. Site sorting has received much attention in the UK because it simplifies recycling operations and accurately separates inert and non-inert materials. There is a chance that the materials will be reused on-site in waste skips or for other projects if these practices are followed [50]. On-site CDW sorting could boost reuse and recycling rates while significantly lowering construction waste transportation and disposal costs. Construction waste sorting can potentially extend the life of landfills designed for or receiving non-inert CDW [60].

The concept of circular economy (CE) involves resource consumption. Infrastructure and construction projects are the primary end-users of this consumption [56]. CE aims to reduce resource consumption, pollution emissions, CDW generation, and environmental impacts and provide social benefits [55]. Most mineral resources are consumed during construction activities, and most are discarded as CDW during end-of-life. The transition to a more circular economy, where output flows can be reintegrated as secondary resources, appears to be a promising solution for the construction industry [34]. CE concepts such as disassembly, reuse, and flexibility are critical components of circular construction. Suppliers manufacture these parts precisely to order specifications, minimizing material and waste on the construction site. This involves promoting secondary materials from recycled and recovered CDW as materials for new construction by increasing its competitive value and quality to compete with raw materials [56].

Reverse Logistics (RL) is the method of organising, integrating, and monitoring the continuous flow of generated waste from the point of generation to final disposal to recapture value (RL). As a result, selecting an RL method is an essential part of an action strategy for effective CDWM [57]. RL can drive sustainable performance in the construction industries (CI) by guaranteeing the adequate supply of raw materials, warehouse processing, finished inventory, and related information needed for recapturing or creating value, as well as proper waste disposal [58]. RL can help with waste management, selective demolition, and using recovered materials in construction, reinforcing responsible and sustainable behavior [57].

4.5. Knowledge-Based

The lack of proper knowledge and awareness of the effects of CDW remains a significant concern in the industry. The Chinese government in Shenzhen realized that raising awareness about CWM is one of the keys to waste reduction. Since 2007, the government has launched a set of promotional activities for the general public and stakeholders, training for construction professionals and the workforce to raise awareness and establishing awards to encourage active participation from both the public and private sectors [61]. The lack of public awareness in the recycling industry is also a challenge. Increasing public perception towards CDWM and recycling can be enhanced through demonstrations and publicity measures. Using recycled aggregate in three road projects in Belgium helped boost consumer confidence in recycled products. Shenzhen conducted 14 project expositions in China that extensively utilized recycled CDW products as the primary material in pavement constructions and drainage applications [40].

CDW can be generated due to a lack of proper training for construction workers regarding waste generation and resource consumption resulting in collective massive waste generation, particularly in concrete, masonry, and steel works. Introducing proper training and awareness programs will help develop a zero CDW attitude throughout the construction cycle [54, 40]. Another effective way to reduce waste generation is through education and training. The effectiveness of CDWM strategies can be increased by educating construction professionals about CDW minimization strategies, emphasizing the benefits of profit maximization, and instilling in all employees that CDWM is as important as time, cost, quality, and safety issues in construction projects [54]. A CDWM and recycling information platform can help to reduce misinformation and knowledge gaps between the recycling industry and construction stakeholders. To promote CDW reuse as renewable materials, Japan launched an information platform that has provided information about CDW and building aggregates [40]. According to a study, lacking training is a significant barrier to effective waste minimization. In professional development, waste minimization strategies should be included to improve the knowledge base, particularly in CDW innovation and technology [45].

Establishing a research center focused on CDW management, including developing recycled CDW as construction materials, segregation and sorting methods, and CDW quantifications and source identifications will initiate collective efforts in combating CDW generation and improving CDW minimization [61]. Since 2007, there has been a significant increase in CDWM research funding in China. The study covers various subject matters, including using recycled materials from CDW, Shenzhen CDWM guidelines, and Shenzhen clay waste landfill strategic planning [61].

4.6. Procurement Based

CDW generation can occur during the construction project procurement (bidding process) and material procurement. Implementing a more innovative procurement process is a step toward a circular economy. China began implementing innovative procurement through a relational contract that included mechanisms to protect both parties' interests and a transparent information-sharing platform. Including CDW management contractual provisions as a requirement for prospective bidders can aid in strict compliance and implementing CDW minimization policies [55]. Adding compliance to EMS for contractors will provide a positive view on implementing CDW management policies during execution [22]. Contract revisions which include a compulsory site waste management plan (SWMP), incentives for effective implementation of SWMP, penalties for violations, mandatory application of Green Building Index (GBI), and scrutiny of sub-contractors in managing waste effectively, can be adopted to promote CDW management during procurement process [36]. The Netherlands started to apply green procurement, also known as sustainable procurement, by acknowledging the utilization of secondary materials as a point of evaluation during the procurement process's initial planning stages. During the award of the construction project, the core sustainable public procurement criteria require the contractor to apply appropriate waste reduction and recovery initiatives [51, 64].

5. CONCLUSION

Through a systematic literature review, this study identified, categorized, and analyzed the various CDW management strategies implemented in the construction industry and their benefits in the sustainability agenda. The following conclusions are drawn from the findings of the SLR. From 41 final samples of articles, the construction industry has implemented at least 26 different CDW management strategies. Second, the identified CDW management strategies can be divided into six major groups based on their themes: information technology, policy, design, operations, knowledge, and procurement based.

The findings of this review are very instructive in that they show that the construction industry is making progress in improving its sustainability efforts through the implementation of the CDW management strategies based on the growing volume of literature on lean construction. Some strategies have already been practiced in the Philippines, particularly policy-based ones involving legislative actions. However, the evidence provided by the review can guide policymakers and construction stakeholders in the Philippines to put more concrete efforts towards CDW minimization and, ultimately, a sustainable construction industry in the country. The increasing use of BIM globally presents an opportunity to utilize BIM tools and methodologies in CDWM application and waste minimization. Additionally, it is recommended that further research is needed in terms of studies targeting the possible adoption of any of these current CDW management strategies in the Philippine context to identify the compatibility, facilitators, and barriers that will affect the adoption of the said strategies.

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 authors declare that they have no conflict of interest.

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