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Research Article

Performance of superabsorbent polymer as admixture in hollow concrete blocks

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ABSTRACT

This study investigates the efficacy of superabsorbent polymer (SAP) waste as an admixture in producing hollow concrete blocks. Using the central composite design (CCD) of the response surface methodology (RSM), the concrete blocks were created by adjusting the SAP percentage from 0.05% to 0.25%, with a constant amount of cement and sand ratios ranging from 2.00 to 4.00. After 28 days of curing, the blocks were evaluated for their compressive strength, density, and water absorption capacity. Analysis of Variance (ANOVA) was used to analyze the data. The results showed that the created hollow concrete blocks at optimum condition exceeded the Philippine National Standard and ASTM Standard of 4.14 MPa for compressive strength on non-loadbearing concrete masonry, with theoretical properties of compressive strength of 8.20 MPa, density of 1900 kg/cm^3 and 5.28% water absorption at the optimized conditions after numerical optimization using the CCD. This innovation could reduce solid waste output and help the environment by using by-products from companies. This research provides valuable insights into sustainable construction materials and highlights the potential of using superabsorbent polymers in producing hollow concrete blocks.

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1. INTRODUCTION

In recent years, the world has faced various environmental challenges, including climate change and global warming, primarily caused by human activities. One environmental issue that has emerged is the disposal of Superabsorbent Polymers (SAP) generated by industries, which have detrimental effects on soil quality. Superabsorbent polymers are widely used materials known for their exceptional water absorption and desorption capacities [1]. However, a significant drawback of SAP is its non-biodegradability, leading to environmental pollution [2].

Typically found in products like diapers, adult incontinence items, and feminine hygiene products, superabsorbent polymers have been extensively used for their water-absorbing properties [3]. Several factors have driven ongoing research and development in advanced superabsorbent polymers. Superabsorbent polymer hydrogels can influence soil permeability, density, structure, texture, evaporation, and infiltration rates [4]. These polymers can

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be classified as either natural or synthetic, with synthetic variants gaining prominence due to their high absorption capacity, wider availability of raw materials, and extended durability. Their hydrophilic, non-toxic, biodegradable, and biocompatible properties make synthetic superabsorbent polymers highly suitable for various applications, including drug delivery, agriculture, bioremediation, firefighting, biosensors, food industries, thermal energy storage, and tissue engineering [5].

Incorporating superabsorbent polymers (SAP) as a novel component in the production of concrete materials offers promising opportunities for water regulation and control over the rheological properties of fresh concrete [6]. Hollow concrete blocks (HCB) remain widely used in the construction industry globally [7]. These blocks have gained popularity as substitutes for burnt clay brick masonry walls in developed and developing countries, playing a crucial role in modern construction practices [8]. Adding Superabsorbent Polymers (SAPs) to cementitious mixtures enhances the material's self-healing capabilities. When cracks occur, SAPs within the cracks expand upon contact with water, releasing the water to facilitate the hydration of unhydrated cement particles and the formation of calcium carbonate crystals [9]. However, excessive water absorption and the subsequent creation of excessive pores by SAP can adversely affect the strength of the cementitious material. Precise measurement of additional water absorption is vital to effectively minimize autogenous shrinkage, a critical consideration for structures prone to shrinkage and cracking [9].

By incorporating superabsorbent polymers in concrete production, autogenous shrinkage can be effectively reduced, and the hydration of cementitious materials can be facilitated, leading to enhanced concrete strength [10]. Considering the widespread reliance on water across various sectors, including construction, it becomes imperative to manage water availability and usage efficiently. Water plays a crucial role in the concrete mixing process and is also utilized for concrete curing in the construction industry. Curing, performed for specified durations such as 7, 14, or 28 days, significantly influences the strength and durability of structures. Exploiting SAP's reversible expansion and contraction properties when exposed to water and dry conditions can prove advantageous in concrete applications [11].

This study aims to utilize superabsorbent polymers to produce hollow concrete blocks (HCB). The effects of SAP admixture on various properties of HCB, including water absorption, density, and compressive strength, will be investigated. By exploring the potential of SAP in concrete manufacturing, this research contributes to sustainable construction practices. It provides insights into using waste materials to pursue environmentally friendly construction solutions.

2. MATERIALS AND METHODS

2.1. Collection and preparation of raw materials

The Superabsorbent Polymers (SAP) were collected at Mega Soft Hygienic Incorporated in Zone 3, Sinaloc, El Salvador City, Misamis Oriental, Philippines.

The raw ingredients utilized to make hollow concrete blocks are cement (CEM 1) with a fineness of 225 m²/kg, natural sand as fine aggregate with fineness that passes through 2.36 mm (Sieve No. 8), and superabsorbent polymers as an admixture. The researchers looked at the possibilities of increasing the characteristics of hollow concrete blocks by combining these materials.

After receiving the sample from its firm, the rejected by-product superabsorbent polymer (SAP) was examined immediately. The moisture content of the SAP was used to classify it initially. The SAP was employed as an admixture in producing hollow concrete blocks and was classified by particle size and moisture content. The moisture content of SAP was evaluated using the ASTM D 2974 process (Standard Test Method for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils). The particle size of the SAP admixture was determined by drying it uncovered for at least 16 hours at 105 °C or until there was no change in mass of the sample following repeated drying periods of more than 1 hour. The sample pieces were removed from the oven, covered tightly, and cooled in a desiccator before weighing.

$$\text{Moisture Content (\%)} = \frac{(\text{wet mass} - \text{dry mass}) \times 100}{\text{wet mass}} \quad (1)$$

The SAP utilized in the experiment was a superabsorbent polymer as a white granular dry powder with particle sizes ranging from 0.8 to 1.0 mm. Cement and sand were purchased from Nailes Sand and Gravel Merchandise at Poblacion, Claveria, Misamis Oriental, Philippines. Sand and cement, which acted as binding ingredients for producing hollow concrete blocks, were also valuable in mixing. The cement used in the mixing was Ordinary Portland cement. Table 1 presents the technical information of the raw materials used in this study. Furthermore, Figure 1 shows the macrograph and micrograph of SAP adopted from the study of Cheng et al. [12].

Table 1. Technical Information of the Raw Materials Used

Material	Technical Information
Superabsorbent polymer (SAP)	Size: 0.8 to 1.0 mm
Sand	Fineness: 2.36 mm (Sieve No. 8)
Cement	Cement Designation: CEM 1
	Fineness: 225 m²/kg

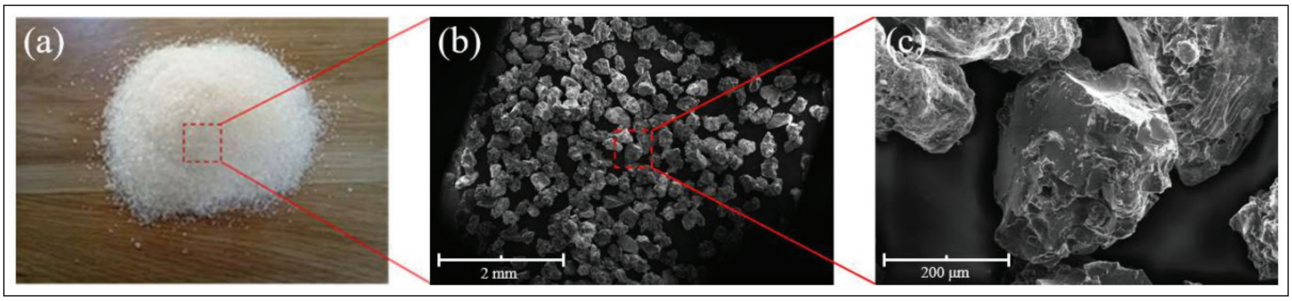

Figure 1. Image of the macrograph and micrograph of SAP as reported in the study of Cheng et al. [12].

2.2. Experimental Design

The researchers used the Central Composite Design (CCD) of the Response Surface Methodology (RSM) to establish the experimental mixtures. In addition to the essential components of the hollow concrete block mixture, superabsorbent polymer (SAP) was added as an admixture. Table 2 below depicts the low and high component ranges.

Using the values of the independent variables in Table 2, thirteen mixtures were generated, represented in different ratios in Table 3.

The proportion of 1.00 cement was kept consistent across all samples.

2.3. Procedure for Making the Hollow Concrete Blocks

Using the mixtures suggested by the central composite design (CCD), hollow concrete blocks were made through the respective proportions of the raw materials needed. The superabsorbent polymer (SAP) was mixed with cement, sand, and water to form a cementitious material until the mixture thickened and became homogeneous. Begin by adding water to the container that contains your cement and mixture. Use a rod to stir the mixture continuously. Keep adding water and stirring until the concrete mix reaches an easy consistency to pour into the hollow

Table 2. Experimental Range and Levels of Variables in Making Hollow Concrete Blocks

Variables	Coded Levels				
	-2	-1	0	1	2
Cement to Sand Ratio (CSR)	1:2	1:2.5	1:3	1:3.5	1:4
SAP (%)	0.05	0.10	0.15	0.2	0.25

Table 3. Experimental Mixtures with Values of Independent Variables in Hollow Concrete Blocks with Superabsorbent Polymers

Mixture	Ratio		
	Cement	Sand	SAP
1	1.00	4.00	0.15
2	1.00	3.00	0.15
3	1.00	3.00	0.15
4	1.00	2.50	0.10
5	1.00	3.00	0.25
6	1.00	3.00	0.15
7	1.00	2.00	0.15
8	1.00	2.50	0.20
9	1.00	3.50	0.10
10	1.00	3.00	0.15
11	1.00	3.50	0.20
12	1.00	3.00	0.05
13	1.00	3.00	0.15

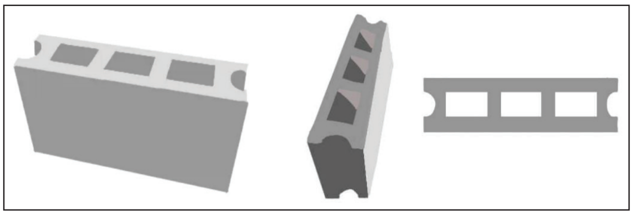

Figure 2. Hollow concrete block.

concrete block mold. It should be pliable and hold its shape when molded but still wet enough to spread quickly. This is a crucial step in making hollow concrete blocks, as the right consistency ensures that the blocks will be sturdy and hold their shape after they are removed from the mold. The mixture was then poured into the molder [40 cm (length) x 20 cm (width) x 4 in (thickness)] to produce the hollow concrete blocks as graphically shown in Figure 2, and compacted using pressure and jolting. The weight of the hollow concrete block ranged from 5,350 g to 6,850 g.

2.4. Product Testing

2.4.1. Water Absorption Analysis

At the USTP-Claveria Environmental laboratory, a water absorption test was performed. The following steps were used to determine the water absorption analysis procedure according to Kishore and ASTM C 140. ASTM C covers the physical properties of concrete masonry units. These properties include the absorption of the unit, density, moisture content, and as well as the compressive strength of the unit.

$$wt\% = \frac{w_m - d_m}{d_m} x100 \quad (2)$$

Where w_m equals the wet mass of the unit in kg, and dm equals the dry mass of the unit in kg. For 24 hours, three full-size blocks must be thoroughly immersed in clean water at room temperature. After removing the blocks from the water and allowing them to drain for one minute on a 10 mm or coarser wire mesh, visible surface water should be wiped with a damp towel, and the saturated and surface dry blocks should be weighed immediately. All blocks must be dried in a vented oven from 100 °C to 115 °C for at least 24 hours until two successive weighing at 2 hours demonstrate an increment of loss of not more than 0.2 percent of the specimen's last previously calculated mass.

2.4.2. Density Test

The density test was performed in the USTP-Claveria Environmental Laboratory. The mass and volume of the sample were determined to compute it. The density was calculated according to Equation 3.

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

Where m is the mass of the hollow block after drying to a constant mass in an oven, V is the volume of the hollow blocks after chilling the sample to ambient temperature, and the overall volume is estimated in cubic centimeters and translated to a cubic meter.

2.4.3. Compressive Strength

The compression test of the samples was conducted at the University of Science and Technology of Southern Philippines - Cagayan De Oro City. The compression sample was examined utilizing the Universal Testing Machine using ASTM C140/C140M or the Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. Figure 3 shows an image of the compressive testing of the hollow concrete blocks through the UTM.

Figure 3. Compressive Testing of the Hollow Concrete Blocks through the UTM .

Table 4. Properties of Superabsorbent Polymers

Material	Moisture Content	Particle Size
Superabsorbent Polymers (SAP)	3.1%	0.8 - 1.00 mm

3. RESULTS AND DISCUSSION

3.1. Properties of the Superabsorbent Polymer

The characteristics of Superabsorbent Polymers were determined using standard methods and are shown in Table 4.

The moisture content was calculated using the method indicated in Equation 1 by using an oven and setting it to 100-105 °C for 24 hours. The particle size of 0.8-1.0 mm was determined by sieving.

Due to osmotic pressure, SAPs can absorb up to 500 times their mass in aqueous solutions, forming a bloated hydrogel. SAPs are lengthy chains of linear polymers that are linked at multiple locations. They are employed as care articles or smart pills in the hygiene and medical industries, and they can even be used for firefighting or food packaging. It was just a matter of time before this polymer was used as a cement ingredient. SAPs can be utilized in cementitious materials to reduce autogenous shrinkage, alter the rheology of the fresh material to improve freeze/thaw resistance, self-sealing, and even promote autogenous healing [13]. Several studies have looked into the impact of SAP on mixing. Concrete and mortar, the hydrophilic feature of SAP piques curiosity since all the water absorbed will be chemically accessible to react with the cement. It can improve the hydration degree of cementitious matrices, reduce contraction, reduce micro-cracked development, and improve the durability of cement matrices [14].

3.2. Properties of the Hollow Concrete Blocks with SAP

The percentage proportion provided by Central Composite Design software was used to calculate the mixtures required to make a hollow concrete block with a volume of 2,601.77 cm^3.

Table 5 displays the physical and mechanical parameters, which include compressive strength, density, and water absorption of hollow concrete blocks created using the various proportions defined by the central composite design software.

Table 5 shows that mixture 7 had the highest compressive strength of 6.617 MPa, while mixture 9 had the lowest compressive strength of 3.327 MPa. However, aside from autogenous shrinkage, adding SAP to concrete can affect various concrete properties. SAP can boost hydration and increase strength [15]. As a result, regardless of the SAP dosage or the mixing sequence, all SAP-containing combinations have improved strength. This is because the basic liquid-binder ratio decreases when SAP is present, resulting in a denser interstitial structure that improves compressive strength. As a result, the impact of SAP dosage on strength is not always positive [16].

With a water absorption rate of 26.23%, mixture 13 was the most absorbent, and mixture 12 got the least water absorption capacity as a result of the small ratio of the SAP mixture. Due to osmotic pressure, SAPs can absorb up to 500 times their mass in aqueous solutions, forming a

Table 5. Physical and Mechanical Properties of HCB with SAP

Mixture	Test Results		
	Compressive Strength (MPa)	Density (kg/m^3)	Water Absorption (%)
1	5.840	2180	6.06
2	3.585	2630	25.17
3	3.927	2570	21.17
4	5.661	2230	11.48
5	5.960	2020	20.58
6	4.497	2570	21.68
7	6.617	2195	10.79
8	4.986	2470	18.96
9	3.327	2510	7.93
10	3.519	2590	23.10
11	5.765	2210	16.96
12	5.916	2100	3.70
13	3.658	2612	26.23

Table 6. Analysis of Variance of Response Surface Quadratic Model for Compressive Strength

Source	Sum of Squares	df	Mean Square	F Value	p-value
Model	14.83	5	2.97	16.81	0.0009[a]
A-Sand	0.8	1	0.8	4.56	0.0701[b]
B-SAP	0.29	1	0.29	1.62	0.2438[b]
AB	2.42	1	2.42	13.72	0.0076[a]
A^2	8.18	1	8.18	46.31	0.0003[a]
B^2	6.31	1	6.31	35.76	0.0006[a]
Residual	1.24	7	0.18		
Lack of Fit	0.59	3	0.2	1.24	0.4061[b]
Pure Error	0.64	4	0.16		
Cor Total	16.07	12			

$R^2 = 0.9231$

Adj $R^2 = 0.8682$

a=*significant;* b=*not significant*

bloated hydrogel. It was a matter of time until this polymer was also used as a cementitious material additive [17].

Meanwhile, mixture 2 had the highest density at 2630 kg/m^3, whereas mixture 5 had the lowest density at 2020 kg/m^3. A reduced density of lightweight concrete blocks, according to [18], results in cost reductions in terms of design flexibility, transportation, and handling.

3.3. Models in Predicting Hollow Concrete Block Properties

3.3.1. Compressive Strength

According to the fit summary analysis of the three attributes, the best-fit model in forecasting its values was quadratic. Equations 4-6 show the model equations where SAP is represented.

The analysis of variance (ANOVA) of the quadratic model for compressive strength of the hollow concrete block interpreted in Table 6 shows the model F-value of 16.81 implies the model is significant. There was only a 0.09% chance that a model "F-value" this large could occur due to the variability of the data. This indicated that the model's output values were correct. It can also be noted that the ANOVA showed that the variables A (Sand) and B (SAP) were not significant at 0.05 level of significance as their respective p-values were greater than 0.05. However, it can be noted that the interactive effect of these variables (A, B) significantly affected the compressive strength of the hollow concrete blocks, as evidenced by their significant p-values. This finding is consistent with the observations in previously published research, which states that the interactive effect of variables significantly impacts the compressive strength of concrete blocks [19].

The "Lack of Fit F-value" of 1.24 implied the Lack of Fit was insignificant relative to the pure error. There was a 40.61% chance that a "Lack of Fit F-value" this large could occur due to noise. A non-significant lack of fit is good because the model needs to fit.

It is also worth noting that the coefficient of determination value, R^2, was recorded as high at 0.9231, which determined that the regression model was 92.31% accurate based on the observed data. In other words, it can be interpreted that the generated model can support and explain the relationship between the experiment's actual and predicted values. To support this, the model-generated equation is presented in Eq. 4.

$$Y = 45.15282 - 19.52183A - 153.25844B + 31.12090AB + 2.38928A^2 + 209.94117B^2 \quad (4)$$

Y is the predicted compressive strength, *A* is sand, and *B* is the SAP. The model equation above is significant because it can determine an expected response based on the desired values of the independent variables of the experiment. The negative coefficients suggest that the factor tends to decrease the result of the predicted compressive strength, while the positive coefficients indicate otherwise. As observed in the equation, this interpretation is consistent with the results of the ANOVA of the quadratic model of the compressive strength, as shown above. Table 7 shows the actual and the predicted compressive strength values based on the generated model equation.

3.3.2. Effects of the Operating Variables to the Compressive Strength

As can be seen in Figure 5, it can be noted that the 3D surface plots showed a sagging graph. This means that a high compressive strength can be achieved at the combinations of low sand and SAP ratio and the high sand and SAP ratio. This could mean that the interaction of these two variables is significant in the compressive strength of the hollow concrete block, which is also proven by the important results of the interaction of the variables based on the

Table 7. Actual vs. Predicted Compressive Strength of the Hollow Concrete Blocks with SAP

Mixture	Mixture Components Ratio (wt. %)			Result	
	A Cement	B Sand	C SAP	Actual	Predicted
1	1	4.0	0.15	5.840	5.701
2	1	3.0	0.15	3.585	3.830
3	1	3.0	0.15	3.927	3.830
4	1	2.5	0.10	5.661	5.835
5	1	3.0	0.25	5.960	6.238
6	1	3.0	0.15	4.497	3.830
7	1	2.0	0.15	6.617	6.737
8	1	2.5	0.20	4.986	4.588
9	1	3.5	0.10	3.327	3.761
10	1	3.0	0.15	3.519	3.830
11	1	3.5	0.20	5.765	5.626
12	1	3.0	0.05	5.916	5.621
13	1	3	0.15	3.658	3.830

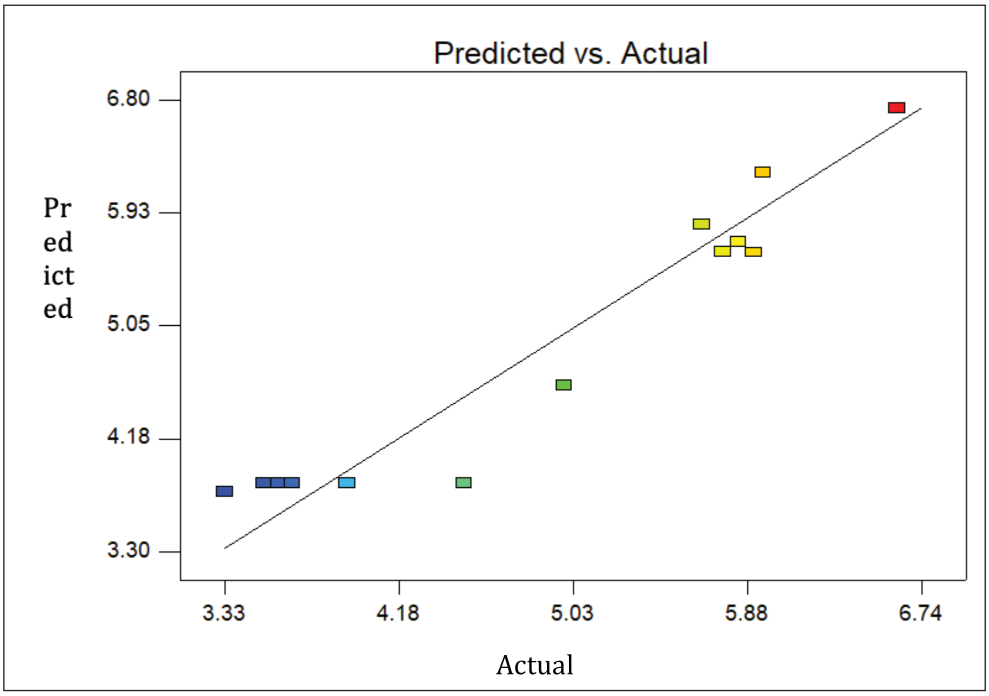

Figure 4. Diagnostic Graph on the Actual versus Predicted Compressive Strength of HCB with SAP.

ANOVA analysis. It can also be interpreted that the right ratio of sand and SAP is necessary so that each independent variable will not overpower the other.

3.3.3. Density

The best-fit model in forecasting its value was quadratic according to the fit summary analysis of the three attributes.

Table 8 shows that the model F-value of 265.19 implies the model is significant. There is only a 0.01% chance that a "Model F-value" this large could occur due to the variability of the actual results of the experiment. The "Lack of Fit F-value" of 0.15 implied the Lack of Fit is insignificant relative to the pure error. The lack of fit p-value suggests a 92.35% chance that a "Lack of Fit F-value" this large could occur due to noise. A non-significant lack of fit is good because it wants the model to fit. The "Pred R-squared" of 0.9879 is in reasonable agreement with the "Adj R-squared" of 0.9910.

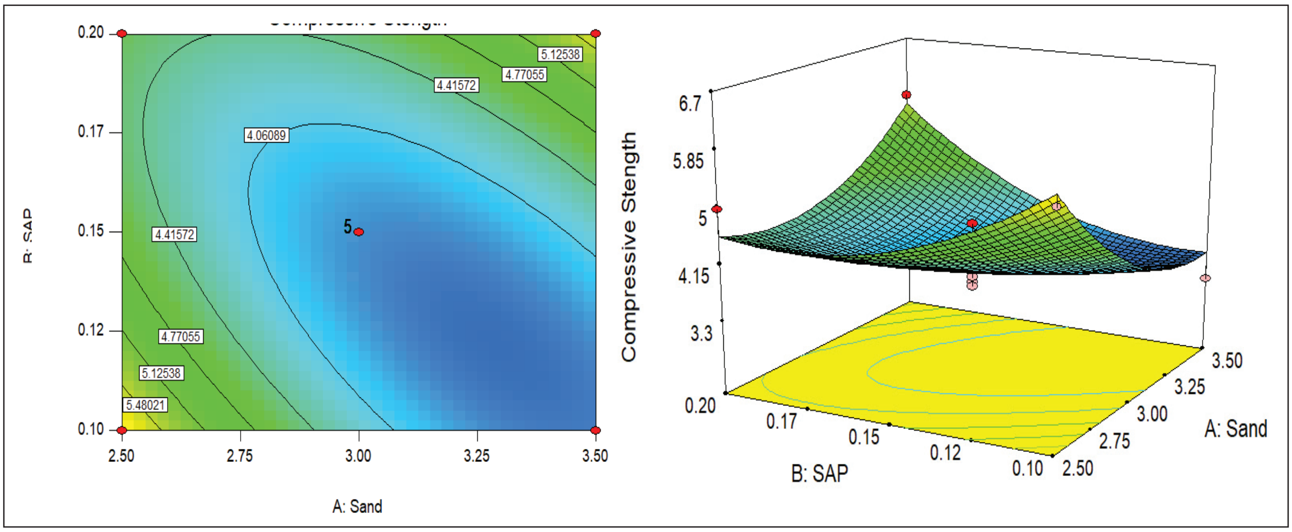

Figure 5. Contour and 3D Surface Plots of the Effects of Sand and SAP on Compressive Strength.

$$Y = -4644.578 + 3251.41954A + 31873.76437B - 5400AB - 407.18103A^2 - 53468.10345B^2 \quad (5)$$

Y is the expected density, A denotes the sand, and B represents the SAP. The model equation above is critical because it can anticipate a response based on the desired values of the experiment's independent variables. The negative coefficients indicate that the component has a propensity to reduce the expected density result, while the positive coefficients indicate the opposite. This interpretation is compatible with the results of the ANOVA of the quadratic density model, as shown in the equation. Based on the developed model equation, Table 9 illustrates the actual and predicted density values, which are graphically shown in Figure 6.

3.3.4. Effects of the Operating Variables on the Density

As can be seen in Figure 7, it can be noted that the contour and 3D surface plots show that with low amounts of sand, if the amount of SAP is increased, there is also a notable increase in the density of the hollow concrete blocks. Meanwhile, when SAP is low, and the amount of sand is increased, an increasing trend in the density of the HCB is also noted. Furthermore, it can be observed that the interaction of both variables, sand and SAP, have a significant effect on the trend of the density of the concrete. Looking back at equation 5, the coefficient of AB as the interaction of the variables is negative, which means that the interactive effect of SAP and sand on the hollow concrete block is the reduction of the density. This idea is consistent with the

Table 8. Analysis of Variance of Response Surface Quadratic Model for Density

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	587929.08	5	117585.82	265.1877	< 0.0001 [a]
A-Sand	8.3333333	1	8.3333333	0.018794	0.8948 [b]
B-SAP	4033.3333	1	4033.3333	9.096254	0.0195 [a]
AB	72900	1	72900	164.4091	< 0.0001 [a]
A^2	237436.81	1	237436.81	535.484	< 0.0001 [a]
B^2	409413.85	1	409413.85	923.3386	< 0.0001 [a]
Residual	3103.842	7	443.40599		
Lack of Fit	316.64195	3	105.54732	0.151474	0.9235 [b]
Pure Error	2787.2	4	696.8		
Cor Total	591032.92	12			
$R^2 = 0.9947$					
Adj $R^2 = 0.9910$					

a=*significant*; b=*not significant*

Table 9. Actual vs. Predicted Density of the Hollow Concrete Blocks

Mixture	Mixture Components Ratio (%)			Results	
	A. Cement	B. Sand	C. SAP	Actual	Predicted
1	1	4.0	0.15	2230	2241.98
2	1	3.0	0.15	2510	2510.31
3	1	3.0	0.15	2470	2475.31
4	1	2.5	0.10	2210	2203.64
5	1	3.0	0.25	2195	2187.76
6	1	3.0	0.15	2180	2184.43
7	1	2.0	0.15	2100	2095.26
8	1	2.50	0.20	2020	2021.93
9	1	3.50	0.10	2630	2593.28
10	1	3.0	0.15	2590	2593.28
11	1	3.5	0.20	2612	2593.28
12	1	3.0	0.05	2570	2593.28
13	1	3.0	0.15	2570	2593.28

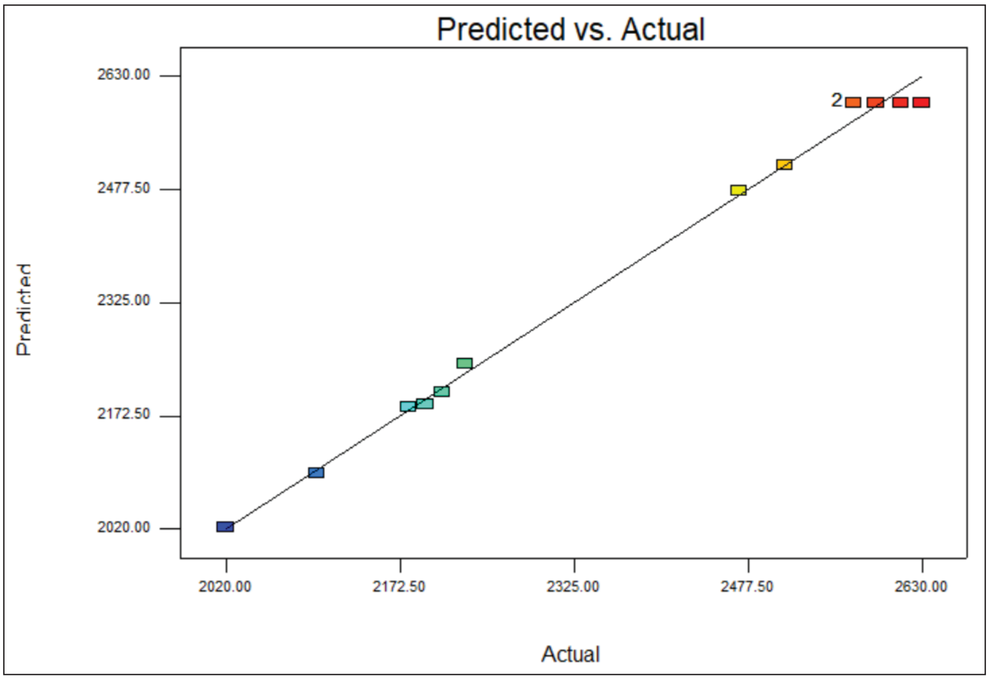

Figure 6. Diagnostic Graph on Actual versus Predicted Density.

findings of a previous study, which observed that adding SAP to the concrete mixture reduces the density, considering that SAP is less dense [14]. This observation can also be explained by the results of the analysis of variance for the density, as presented in Table 8 above.

3.3.5. Water Absorption

According to the fit summary analysis of the three qualities, quadratic was the best-fit model for forecasting its values. Table 10 shows the analysis of variance (ANOVA) of the Response quadratic model for water absorption.

The Model F-value of 20.12 implies the model is significant. There is only a 0.05% chance that a "Model F-value" this large could occur due to noise. In this case, B, A^2, B^2 are significant model terms. This means that factor B (SAP) significantly affects the water absorption quality of the hollow concrete blocks, which is not surprising because of the absorbent property of the superabsorbent polymer. The "Lack of Fit F-value" of 1.79 implies the Lack of Fit is insignificant relative to the pure error. The p-value also suggests a 28.83% chance that a "Lack of Fit F-value" could occur due to noise. The "Pred R-Squared" of 0.7046 is in

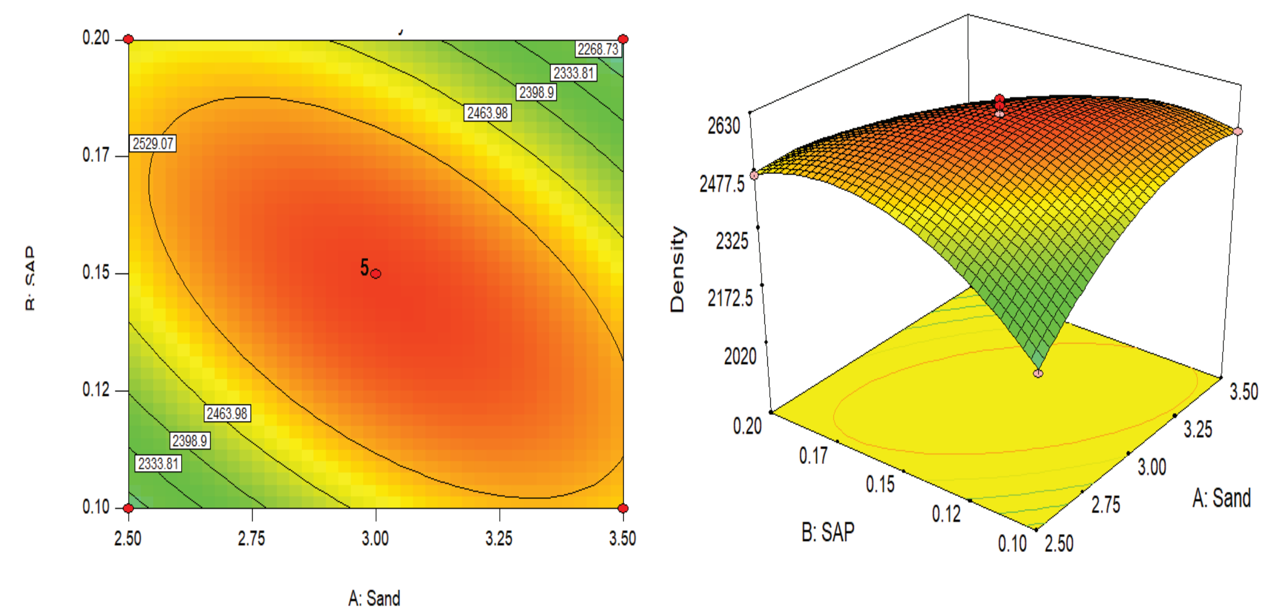

Figure 7. Contour and 3D Surface Plots of the Effects of Sand and SAP on Density.

Table 10. Analysis of Variance of Response Surface Quadratic Model for Water Absorption

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	644.1686	5	128.8337	20.11658	0.0005[a]
A-Sand	18.77501	1	18.77501	2.9316	0.1306[b]
B-SAP	210.5894	1	210.5894	32.88222	0.0007[a]
AB	0.600625	1	0.600625	0.093784	0.7683[b]
A^2	333.2671	1	333.2671	52.03758	0.0002[a]
B^2	190.712	1	190.712	29.77849	0.0009[a]
Residual	44.83049	7	6.404355		
Lack of Fit	25.69189	3	8.563963	1.789883	0.2883[b]
Pure Error	19.1386	4	4.78465		
Cor Total	688.9991	12			
R^2 = 0.9349					
Adj R^2 = 0.8885					

a=*significant;* b=*not significant*

reasonable agreement with the “Adj R-Squared” of 0.8885. The equation below describes the quadratic model equation of water absorption.

$$Y = -138.71619 + 86.70282A + 383.48075B + 15.50000AB - 15.25491A^2 - 1153.99138B^2 \quad (6)$$

Y represents the expected water absorption, A represents the sand, and B represents the SAP. The above model equation is crucial because it can anticipate a response based on the desired values of the experiment’s independent variables. The negative coefficients indicate the opposite. This interpretation is compatible with the results of the ANOVA of the quadratic model of water absorption, as shown in the equation. Based on the developed model equation, Table 11 illustrates the actual and predicted water absorption values, which are graphically shown in Figure 8.

3.3.6. Effects of the Operating Variables on the Water Absorption

As can be seen in Figure 9, it can be observed that a change in the amount of sand only had a little effect on the water absorption quality of the hollow concrete block. At the same time, the increase in the same property was evident, while there was an increase in the amount of SAP. This

Table 11. Actual vs. Predicted Water Absorption of the Hollow Concrete Blocks

Mixture	Mixture Components Ratio			Results (%)	
	A. Cement	B. Sand	C. SAP	Actual	Predicted
1	1	4.0	0.15	11.48	13.38
2	1	3.0	0.15	7.93	10.10
3	1	3.0	0.15	18.96	20.98
4	1	2.5	0.10	16.96	19.26
5	1	3.0	0.25	10.79	9.88
6	1	3.0	0.15	6.06	4.87
7	1	2.0	0.15	3.70	2.71
8	1	2.5	0.20	20.58	19.47
9	1	3.5	0.10	25.17	22.63
10	1	3.0	0.15	23.1	22.63
11	1	3.5	0.20	26.23	22.63
12	1	3.0	0.05	21.68	22.63
13	1	3.0	0.15	21.17	22.63

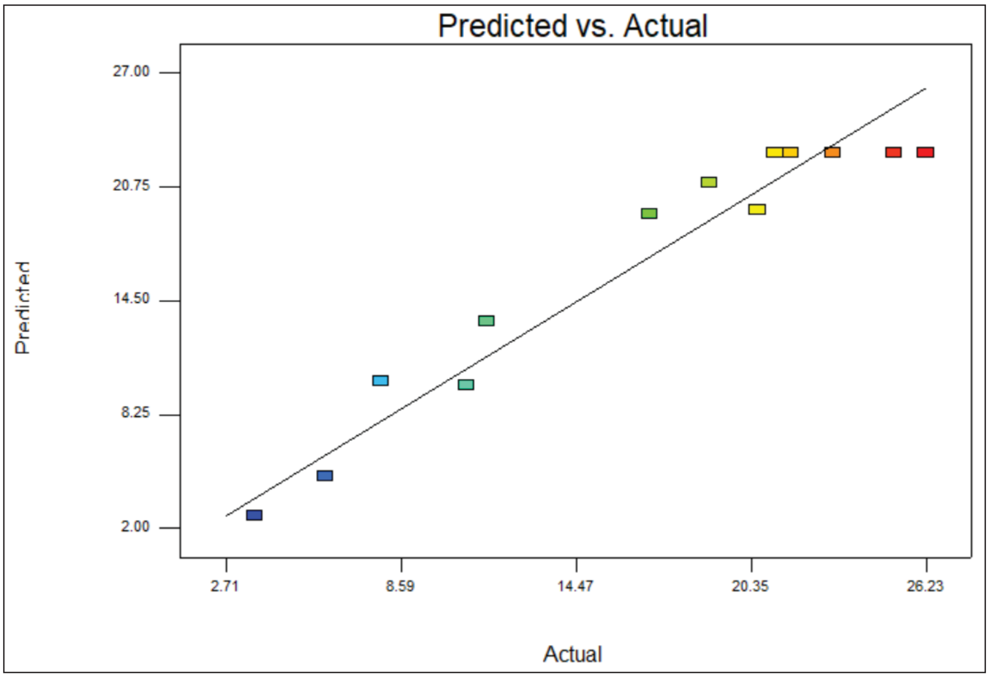

Figure 8. Diagnostic Graph on the Actual versus Predicted Water Absorption.

can be explained by the absorbent property of the superabsorbent polymer, as discussed previously in this paper. The same observation can be noted in a previous study where the addition of SAP increases the water absorption of the concrete [14]. The same observation can also be justified by the results of the analysis of variance (ANOVA) of the mixture quadratic model of the water absorption property of the HCB, as presented in Table 10, where the sand was not significant, and the SAP was substantial in affecting the water absorption quality of the hollow concrete blocks.

3.4. Theoretical Optimized Conditions for Compressive Strength, Density, and Water Absorption

Through the central composite design of the Design Expert 7.0 software, numerical optimization was done following the goals indicated in Table 12.

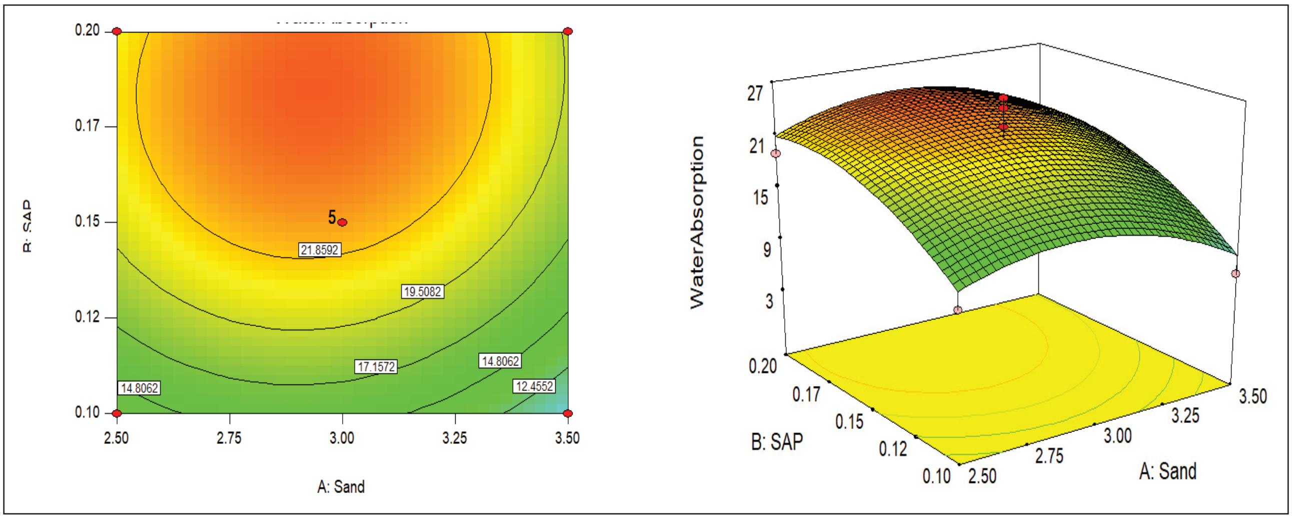

Figure 9. Contour and 3D Surface Plots of the Effects of Sand and SAP on Water Absorption.

Table 12. Numerical optimization criteria in the theoretical optimization of the production of hollow concrete blocks

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
SCR	is in range	2.0	2.5	1	1	3
SAP	is in range	0.1	0.15	1	1	5
Compressive Strength	maximize	5	20	1	1	5
Density	is in range	1900	2400	1	1	3
Water Absorption	minimize	3.7	15.0	1	1	3

Table 13. Theoretical Compressive Strength, Density, and Water Absorption of the hollow concrete blocks after numerical optimization

Solution	Operating Variables		Compressive Strength (MPa)	Density (kg/cm^3)	Water Absorption (%)	Desirability
	SCR	SAP				
1	2.00	0.110	8.20	1900	5.28	0.360
2	2.01	0.109	8.18	1900	5.38	0.357
3	2.04	0.105	8.13	1900	5.65	0.350

The sand-to-cement ratio (SCR) ranged from 2.0 to 2.5, considering that the experiment results showed that a desirable value of the properties identified was achieved at a lower SCR. The same consideration was considered in the SAP loading, which ranged from 0.1 to 0.15. The compressive strength was maximized because this study aims to have a good-quality hollow concrete block. The density was held from 1900 to 2400 concerning the ASTM standards. Finally, water absorption was minimized since it is not ideal for a hollow concrete block to have a high water absorption capacity. It may lead to decreased durability, increased risk of cracking, and reduced insulation properties.

Table 13 presents the theoretical results of an experiment investigating the effect of two operating variables, sand-to-cement ratio (SCR) and superabsorbent polymer (SAP) content, on concrete blocks' compressive strength, density, and water absorption. The table shows the values of these three output variables for three experiments with different values of the two input variables. The desirability values are calculated based on the target values for each output variable. A desirability value of 1.0 indicates that the experiment met all the target values, while a value of 0.0 indicates that the experiment did not meet any of the target values. A higher desirability value suggests that the suggestsiment is closer to meeting the target values. The

Table 14. The Philippine National Standard and the American Standard for Testing Materials for Hollow Concrete Blocks as Compared to This Study

Standards	Compressive Strength (MPa)	Water Absorption (%)	Density (kg/m^3)	Reference
Philippine National Standard				
Load-bearing	11.7 – 13.1	Not more than 10% by mass	< 1680 (LW) 1680 to < 2000 (MW) > 2000 (NW)	[20,21]
Non-Load-bearing	4.14	Not more than 10% by mass	< 1680 (LW) 1680 to < 2000 (MW) > 2000 (NW)	[20,21]
American Standard for Testing Materials				
Load-bearing	11.7 – 13.1	max of 24.01%	< 1680 (LW) 1680 to < 2000 (MW) > 2000 (NW)	[22,23]
Non-Load-bearing	4.14	max of 24.01%	< 1680 (LW) 1680 to < 2000 (MW) > 2000 (NW	[23,24]
This Study	8.20	5.28%	1900	

Legend: LW-lightweight, MW-medium weight, NW-normal weight

table shows that increasing the sand-to-cement ratio (SCR) and decreasing the superabsorbent polymer (SAP) content generally leads to a decrease in compressive strength and density but an increase in water absorption. The desirability values for each experiment indicate that Solution 1 is the most desirable among the three, as it has the highest desirability value of 0.360. This suggests that the SCR of 2.00 and the SAP content of 0.110 used in Solution 1 produced concrete blocks closest to the target values for compressive strength, density, and water absorption as set in the criteria.

Theoretically, solution 1 will produce a compressive strength of 8.20 MPa, density of 1900 kg/cm^{3,} and 5.28% water absorption, which all pass the Philippine National Standard (PNS) and the American Standard for Testing Materials (ASTM) for non-load-bearing hollow concrete blocks. Table 14 compares the theoretical properties of this study's hollow concrete blocks against the PNS and ASTM.

The qualities of the hydraulic cement paste, which is the active element of Portland cement concrete (PCC), are significantly responsible for the concrete's attributes and performance. Superabsorbent polymer admixtures are the components that interact in the hydrated cementitious system by physical, chemical, and physical-chemical action, modifying one or more properties and conferring specific beneficial effects to concrete, such as enhanced durability, improved workability and increased strengths, when added in small amounts (usually less than 3% wt.) to the concrete batch, immediately before or during mixing [25]. The SAPs occupy space during the manufacture of a concrete mixture. Internal cure water generated during cement hydration due to self-desiccation was utilized for further hydration and autogenous shrinkage reduction. Due to the decline in relative humidity, the water in the SAP was released into the cementitious matrix [13]. Adding various water-soluble organic polymers to new concrete batches significantly increases workability while providing strengths comparable to non-admixture concrete and several advantages over casting concrete [25].

4. CONCLUSION

This study has successfully demonstrated the potential of superabsorbent polymer (SAP) as an admixture in producing hollow concrete blocks. By adjusting the SAP percentage from 0.05% to 0.25% and maintaining constant cement and sand ratios ranging from 2.00 to 4.00, various blocks were produced and subjected to rigorous testing. The results were promising, with the blocks exceeding the compressive strength requirement set by the Philippine National Standard, thereby confirming their structural integrity and potential for load-bearing applications. Specifically, the blocks achieved a compressive strength of 8.20 MPa, significantly higher than the standard of 4.14 MPa for non-loadbearing concrete masonry. In addition to their impressive strength, the blocks exhibited a density of 1900 kg/cm^3 and a water absorption capacity of 5.28% at the optimized conditions after numerical optimization using the central composite design (CCD). These properties further attest to their durability and suitability for various construction applications. Beyond its technical contributions, this research also underscores the importance of sustainability in construction practices. Utilizing SAP as an admixture offers a practical solution to reducing solid waste and repurposing industrial by-products. This aligns with the industry's growing emphasis on sustainable construction materials and environmentally friendly practices.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest concerning this article's research, authorship, and/or publication.

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

AUTHOR'S CONTRIBUTIONS

Phoebe Love Candano: Drafted and wrote the manuscript and performed the experiment and result analysis. Assisted in analytical analysis. **Kate Rose Elorde:** Assisted in drafting and writing the manuscript and performed the experiment and result analysis. Assisted in analytical analysis. **Irl Rica Ann Mejos:** Assisted in drafting and writing the manuscript and performed the experiment and result analysis. Assisted in analytical analysis. **Rhoe James Cabada:** Assisted in the drafting and writing the manuscript and performed the experiment and result analysis. Assisted in analytical analysis. **Val Irvin Mabayo:** Supervised the experiment's progress and helped in the results analysis and manuscript preparation.

ETHICS

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

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Research Article

An analysis of the effectiveness of new generation self-leveling lightweight composite screed for underfloor heating systems

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ABSTRACT

Energy saving has become a significant concern in recent years due to increasing carbon emissions and environmental pollution. When examined from a global perspective, it is known that the energy consumed for heating and cooling of buildings is relatively high. In this regard, researchers attach great importance to energy efficiency issues. In recent years, an issue that has been given priority in heating buildings more efficiently is underfloor heating systems. Underfloor heating systems are composite structures of slab concrete, insulation material, hot water pipes, and screed. Here, the thermal performance of the screed is vital as the hot water pipes remain embedded in the screed. This study has produced a new composite and self-leveling screed type that can transfer heat easily. For this purpose, nine screed mixtures were prepared, including a reference (nearly conventional) screed mortar. The screed mortars' flowability, density, and compressive strength were determined regarding physical properties. Thermal properties, thermal conductivity, specific heat, thermal diffusivity, and heat storage analyses were carried out. In the second stage of the study, a basic underfloor heating system was installed, and the temperatures of the water circulating in the system, the outer surface of the pipe carrying the water, and the outer surface of the screed were measured at specific periods. According to the study results, it has been observed that depending on the thermal properties of the screeds produced within the scope of this study, when used in underfloor heating systems, it can transfer heat from the hot water pipes to the surface with minimum losses.

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1. INTRODUCTION

Self-leveling leveling screed is a cement-based polymer-modified, self-leveling mortar with high fluidity to obtain generally a smooth floor surface. The first pumpable self-leveling flooring material was developed in the mid-1970s. This product uses Portland cement as a binder with a casein-based flowing agent to provide an easy and quick way to level concrete floors before applying a topcoat [1].

Self-leveling screed has a composite structure consisting of binders, fillers, polymers, and additives. Screed mortar

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can be named under separate definitions according to the type of binder material. These nomenclatures are grouped into five different categories in the TS EN 13813 standard [2]: cementitious screeds (CT), calcium sulfate screeds (CA), magnesite screeds (MA), mastic asphalt screeds (AS) and synthetic resin screeds (SR). It is seen that finely ground mineral materials such as sand and limestone are mainly used as filling materials. Alternative mineral and chemical polymer-based additives of different origins can be used as additives, for example, to control setting time, curing time, flow properties, air entrainment, etc. [3–5].

Self-leveling screed mortar generally has three primary uses. The first is underlays, which smooth any surface and remove irregularities that the concrete may have [6]. This application is done before the installation of all kinds of floors. For example, it can be used to level the floor under materials such as Polyvinyl Chloride (PVC), tiles, ceramics, granite ceramics, marble, natural granite, parquet, carpet, laminated flooring, laminate flooring, rubber flooring. The second place of use is to apply self-leveling mortar as a finishing coat from the beginning of the project to act as an actual finished floor without the need for a floor covering. A third use of self-leveling mortar is a repair material for damaged concrete in applications such as bridges or roads. In addition, self-leveling mortars can provide a smooth and durable new surface for decorative treatments in areas with heavy traffic, residential, commercial, industrial buildings, hospitals, supermarkets, educational buildings, hotels, and shopping malls. It is also used in [7]. In addition, their use can be seen in applications under epoxy. Self-leveling mortar is a ready-to-use mortar that must be mixed with water before being used directly. It is also used to create a flat and smooth surface with a compressive strength similar to or higher than conventional cement mortar. It is mainly used as a backing or filling material.

It can be seen that there are several types of flooring in actual applications (Figure 1). Among these, underfloor heating systems have become popular in recent years. Today, the need for self-leveling mortar applications has increased due to the flatness and smoothness of floor coverings, especially in underfloor heating systems. These systems have been widely used as an alternative to conventional heating systems in recent years [8]. The main logic of the underfloor heating system is heating the area by giving heat to the pipes (water system) or cables (electric system) placed under the floor from the floor surface to the indoor environment. An underfloor heating system, which expands the surface area, consumes less energy by reducing the temperature difference and provides more comfortable heat distribution. Since most of the energy consumption in buildings originates from the heating and cooling [9], floor heating systems have become an essential application in recent years in terms of energy efficiency used for heating in buildings, especially to comply with strict rules such as European Union Energy Efficient Directive [10]. Underfloor heating systems provide uniform temperature distribution, reduce distribution losses, and increase thermal comfort compared to conventional systems by minimizing the vertical temperature gradient [11–13]. In reinforced concrete structures, underfloor heating systems are applied as slab on the lowest layer, insulation material on a slab, hot water pipes on insulation material, screed on insulation material and pipes, and coating material on the last layer. A more detailed view of underfloor heating systems is given in Figure 2. The underfloor heating system's effectiveness depends on these layers' performance. The most important of these layers can be considered as the screed material since it remains embedded in the hot water pipes. The thermal conductivity of the screed material plays a vital role in the system's efficiency. It should be expected that the screed material used in underfloor heating systems can self-level in a way that minimizes workmanship errors and has an identity that conducts heat as much as possible. An underfloor system with a high thermally conductive self-leveling screed provides improvements over conventional screed or slab construction systems. Increased thermal conductivity reduces reaction time, and the flowing nature of the self-leveling screed results in an improved pipe coating, enhancing the pipe/screed interface, which, combined with homogeneity, can further improve thermal energy transfer. The inherent strength, durability, and low shrink characteristics of screeds enable depths to be reduced without compromising performance.

Wu et al. [14] examined the thermal conductivity of concrete with the addition of graphite. They used graphite with the replacement of fine aggregate in different mass ratios. They found that the thermal conductivity of concrete specimens can increase from 20% to 50%. However, compressive strength was reduced to 90% at a replacement level of 15%. Liu et al. [15] studied the thermal conductivity of carbon fiber-reinforced concrete. They used 0.5, 1, and 1.5% of volume carbon fiber in concrete production. According to

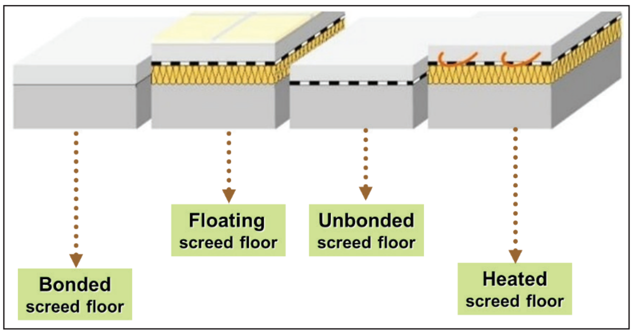

Figure 1. Different Types Of Flooring Applications.

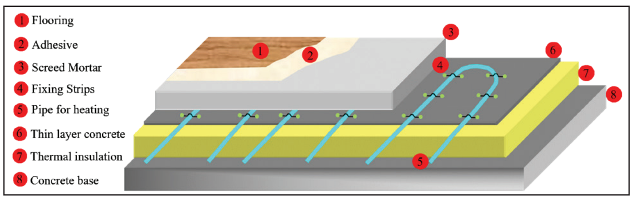

Figure 2. Detailed view of underfloor heating systems.

their test results, they stated that when the water: cement (w/c) ratio is 0.5, the thermal conductivity of carbon fiber reinforced concretes maximum. Besides, they found that increased carbon fiber content increases the thermal conductivity. Although there are few results in the literature that blast furnace slag and silica fume reduce thermal conductivity in concrete Fields[16,17], it has also been determined that these admixtures can increase the thermal conductivity coefficient by reducing the voids by improving hydration [18]. Khan [19] found that higher thermal conductivity in concrete may be obtained using quartz sand compared with basalt, limestone, and siltstone. Although mica is an insulating and high-temperature resistant material with a similar structure to graphite [20], Zhang and Zhang [21] found that the thermal conductivity of plasticized polyvinyl chloride (P-PVC)/mica composites increased with a linear trend with the increase in the mica content. The thermal conductivity of mica in any direction parallel to the cleavage plane was found to be relatively high in previous research (from 3.7 to 4.0 W/mK) and perpendicular to the plane relatively low (from 0.44 to 0.46 W/mK) [22].

When the literature is examined, more research must be done on using self-leveling lightweight composite screed (SLCS) products. In this context, it is necessary to study the applicability of this type of cement-based screed mortars in today's trending and advantageous new underfloor heating systems.

This paper aims to contribute to a better knowledge of the performance of a unique mix design of superplasticizer, mineral admixtures, carbon fiber, quartz sand, mica, and graphite with cement binder for SLCS. An experimental study was conducted to develop cement-based screed mortars with nine different mix designs tested in the laboratory are discussed. In the experimental analysis, especially the effects of an increase in graphite content on the density, compressive strength, thermal conductivity, specific heat, thermal diffusivity, and heat storage capacity of the SLCS mortar were analyzed in detail, and the findings were briefly discussed in this study.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Cement

CEM I 42.5R ordinary Portland cement (PC), similar to ASTM Type I cement, was utilized in the design of nine screed mixes. The specific gravity of the cement is 3.15. It is used as the primary binder material.

2.1.2. Blast Furnace Slag

The blast furnace slag (BFS) used in this study was supplied from commercial establishments in the Izmir-Foça region of Türkiye. The unit weight of the BFS is 1550 ± 50 kg/m^3. The average particle size of BFS is classified as 125 µm. It is used as a mineral admixture in the screed design.

2.1.3. Silica Fume

The maximum particle size of silica fume (SF) is 90 µm. Silica fume was supplied from the Antalya region of Türkiye. The unit weight of the SF is 680 ± 50 kg/m^3. It is used as a mineral admixture in the screed design.

2.1.4. Mica

Mica in powder form is classified as 300 µm in average particle size. Mica powder (MP) was supplied from KALTUN Madencilik A.Ş in the Aydın-Çine region of Türkiye. The unit weight of the MP is 760 ± 30 kg/m^3. It is used as the main filler in the screed design.

2.1.5. Quartz Sand

Quartz sand (QS) is classified in size of 0/1 mm. It was supplied from commercial establishments in the Manisa – Salihli region of Türkiye. The unit weight of the QS is 1450 ± 50 kg/m^3. It is used as the primary aggregate in the screed design.

2.1.6. Graphite

The graphite powder (GP) used in this study was supplied from commercial establishments in the Izmir region of Türkiye. GP is classified as 45 µm in average particle size. The unit weight of the GP is 650 ± 50 kg/m^3. It was used as a conductive material.

2.1.7. Carbon Fiber

Carbon fibers (CF) with 6 mm length were supplied from commercial establishments under market conditions in the Izmir region of Türkiye. The unit weight of the CF is 460 ± 70 kg/m^3. It was used as a conductive material.

2.1.8. Superplasticizer

Polycarboxylate ether (PCE) type superplasticizer (SP) was used to provide self-leveling property to the screed mortars. The SP used in this study was supplied by commercial establishments in the Izmir region of Türkiye.

A general view of all ingredients of SLCSs is shown in Figure 3. Sieve analysis of BFS, QS, and MP is represented in Figure 4.

2.2. Methods

2.2.1. SLCS Production

In this experimental study, different screed mortar mixing ratios were designed to investigate the effect of especially carbon fiber and graphite on self-leveling lightweight composite screeds. In addition, a separate mixture without using CF and GP was designed as a reference screed mixture to accurately examine the effects that may arise from using CF and GP. The design of the composite combinations is given in Table 1.

A mortar was produced close to the conventional cement mortars in terms of mixture ingredients as a reference mortar. In the reference mortar (S0), cement, silica fume, quartz sand, and superplasticizer are used as mixture materials. Mixtures between S1 and S8 are the test mixtures designed

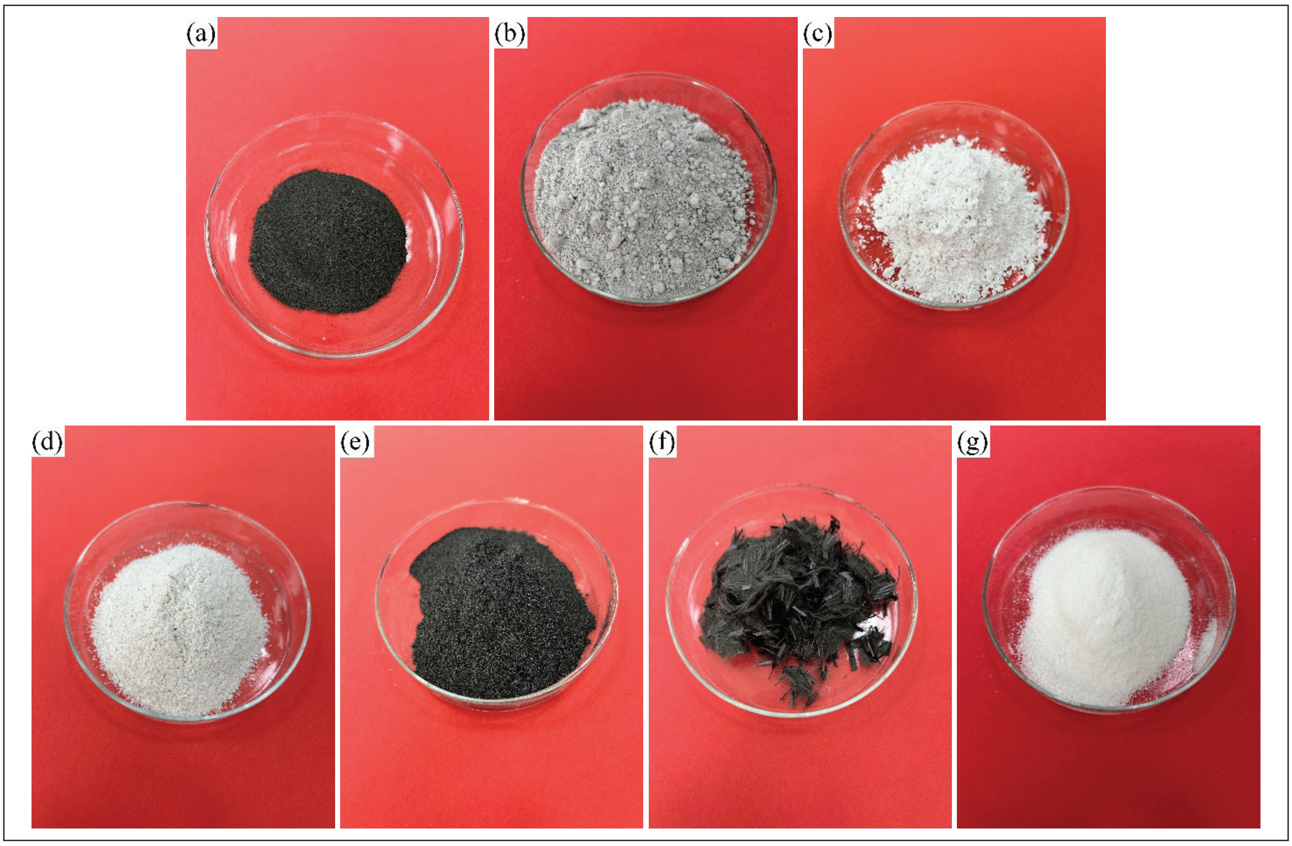

Figure 3. (a) BFS; (b) SF; (c) MP; (d) QS; (e) GP; (f) CF; (g) SP.

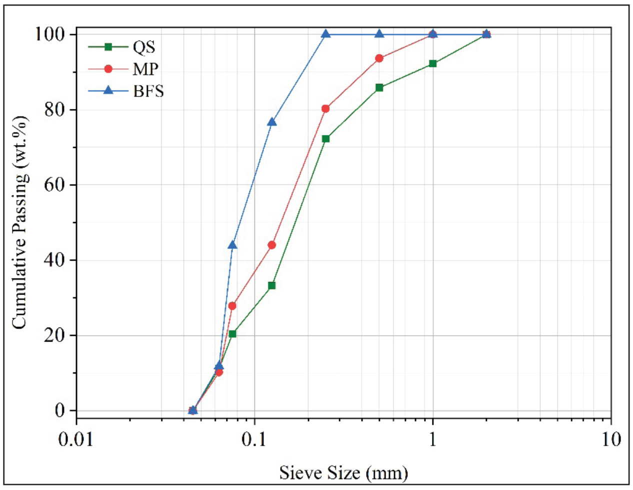

Figure 4. Sieve analysis of BFS, MP, and QS.

to increase the thermal conductivity. In test mixtures, PC (34%), BFS (18%), SF (2.8%), QS (4.9%), CF (0.56%,) and SP (3.22 wt.% of PC) were used in fixed rates. Test mixtures are designed to replace GP and MP with increasing proportions as 0.69, 1.38, 2.07, 2.76, 3.45, 4.14, 4.60 and 5.75 %. In the mixing phase, all solid ingredients were first put in the mixer and mixed for 2 min to achieve a homogeneous dry mixture. Water was added to the mixer to produce fresh cement-based lightweight composite screed mixtures, and the mixture was mixed for another 2 min. The water was regular tap water, and it was at 20 ± 2 °C. The w/c ratio is adjusted according to the constant fresh mortar flow values on the flow table apparatus. Fresh screed mortar samples' flow diameters were determined using the flow table apparatus by ASTM C1437-15 [23]. Flow table test views of S0, S1, S4, and S8 samples are shown in Figure 5. The flow diameters of all samples were produced to be 185 ± 10 mm, w/c ratios were detected, and samples were produced with this principle.

2.2.2. Physical and Mechanical Tests

Fresh and hardened unit weights of mortars were carried out on the fresh and hardened composite specimens concerning TS EN 1015-6 [24] and TS EN 1015-10 [25]. Compressive strength tests were conducted on the hardened composite samples concerning ASTM C109-21 standard [26]. Three pieces of 5×5×5 cm^3 cubic specimens were produced for each series for the compressive strength test. A compressive strength test was carried out on 28 days of the curing period. All test specimens were kept in molds for 24 h at room temperature and removed from molds. After the samples were removed from the molds, plastic sheets were covered on them and cured at room temperature. All tests were completed after the moisture-cured materials were dried in the oven until their weight remained unchanged.

Table 1. Proportions of trial mixtures (% by weight)

Mixture	PC	BFS	SF	MP	QS	GP	CF	SP (wt.% of PC)	w/c
S0	34.0	0.0	2.8	0.00	46.5	0.00	0.00	3.22	0.46
S1	34.0	18.0	2.8	22.31	4.9	0.69	0.56	3.22	0.48
S2	34.0	18.0	2.8	21.62	4.9	1.38	0.56	3.22	0.50
S3	34.0	18.0	2.8	20.93	4.9	2.07	0.56	3.22	0.51
S4	34.0	18.0	2.8	20.24	4.9	2.76	0.56	3.22	0.52
S5	34.0	18.0	2.8	19.55	4.9	3.45	0.56	3.22	0.53
S6	34.0	18.0	2.8	18.86	4.9	4.14	0.56	3.22	0.55
S7	34.0	18.0	2.8	18.40	4.9	4.60	0.56	3.22	0.56
S8	34.0	18.0	2.8	17.25	4.9	5.75	0.56	3.22	0.59

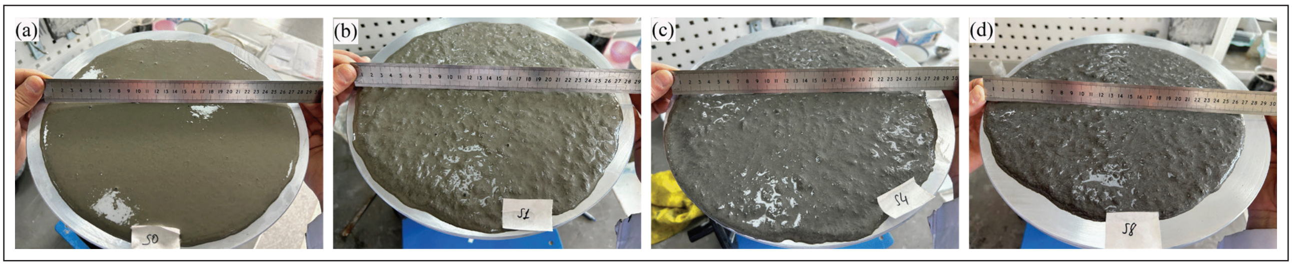

Figure 5. Similar flow diameters of (a) S0; (b) S1; (c) S4; and (d) S8 specimens.

2.2.3. Thermal Properties Tests of SLCSs

For each mixture, three pieces of 20×40×3 cm^3 rectangular specimens were produced to determine the thermal properties of the specimens. Another three 5×5×5 cm^3 cubic samples were produced and used for the test specimens to be cut into pieces to be used in the specific heat value measurements. Again, all thermal property tests were carried out after the moisture-cured materials were dried in the oven until their weight remained unchanged. Thermal conductivity values of test specimens were carried out by hot box apparatus. This laboratory scale hot box device is a device that measures in a steady state via conduction. The Hot Box method allows for measuring thermal conductivity in the test sample, with the option to vary temperature environments between 0 °C and +55 °C. The temperature of each sample surface was measured at a minimum of 9 points, forming a grid on the surface. The thermal conductivity device consists of three components: an electrical heater known as the hot room, the section where the sample is placed, and the cold room. The temperature sensors in the cold and hot chambers were in complete contact with the sample surface, ensuring accurate measurement of the sample surface temperature with a precision of 0.1 °C. The supplied heat could be controlled using a continuously variable current ranging from 20 to 400 watts.

The test device is designed to minimize errors by considering the three-dimensional nature of heat transfer. Before recording temperature data, the sample was allowed to stabilize, and data recording commenced once a steady state was reached. The desired temperature difference between both surfaces of the test sample, positioned within the apparatus, was achieved by applying electrical power (QT, Watt) to the heater. The temperature difference (ΔT, °C) between the surfaces was determined as the average value derived from the measured values. The thermal conductivity value (λ, W/mK) of the test sample was then calculated using the following equation (Eq. 1):

$$\lambda = (Q_T{*}d) / (A{*}\Delta T) \quad (1)$$

Where; λ is the thermal conductivity value of the test sample (W/mK), Q_T is electrical power applied to the heater (Watts), D is sample thickness (m), and A is the heated area in the heating section (m^2). ΔT is the temperature difference between surfaces (°C).

To determine the specific heat value of the hardened SLCS specimens, a calorimeter device and associated formulations with defined technical characteristics in the literature were used throughout the experimental studies [27]. The thermal diffusivity coefficient of the specimens was calculated with Eq. 2.

$$\alpha = \lambda / (\rho{*}C_p) \quad (2)$$

Where; α is thermal diffusivity (m^2/s), λ is thermal conductivity (W/mK), ρ is oven-dry apparent density (kg/m^3), and C_p is specific heat (J/kgK).

The amount of heat stored depends on the specific heat of the medium, the temperature change, and the amount of storage material, which is expressed by Eq. 3 [28].

$$\Delta Q = m \times \int_{T_i}^{T_f} C_p(T).dT \quad (3)$$

Where ΔQ is the heat stored (J), m is the mass of specimen (kg), C_p is specific heat (J/kgK), and dT is the temperature difference.

2.2.4. Basic underfloor heating system production

Screed specimens were produced to be used in underfloor heating systems. Also, a basic underfloor heating experiment setup was prepared to analyze the screed specimens' performance within the study's scope. The symbolic view of the basic underfloor heating system installed is shown in Figure 6. This underfloor heating system installed has an insulation layer at the bottom. Hot water pipes are fixed on this layer. 40 mm thick SLCSs produced in this study were applied to the structure where the hot water pipes were fixed. The temperatures were then measured at three different system points at other times. These are the temperature of the water (T_w), the outside temperature of the pipe carrying the water (T_1), and the temperature of the screed surface (T_2). The experiment was continued for 8 hours. The water was heated in the pipe for the first 4 hours. At the end of this period, the water temperature reaches 45 °C. Afterward, the water heating was stopped, and the water was left to circulate with its temperature and started to cool. During this process, T_w, T_1, and T_2 temperatures were recorded at different times (after 0, 0.2, 0.3, 0.5, 0.6, 0.7, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5 and 8 hours).

3. RESULTS AND DISCUSSION

3.1. Physical and Mechanical Tests

The physical and mechanical properties of the screed specimens produced in this study are given in Table 2. Since the fiber and graphite ratios in the mixture change, it is impossible to use a fixed amount of water, so the mixtures are designed with constant consistency. The consistency of the mortars was measured using the flow table, and the water ratio was adjusted so that the flow diameter of the screed mortars was a constant 185 ± 10 mm. It was determined that the fresh and hardened densities of the mortars decreased as the mica ratio decreased and the graphite ratio increased in the mixtures. However, this change is relatively minimal, as shown in Table 2.

On the other hand, the density values of the reference mortar produced with a formula close to the conventional screed mortar are considerably higher than the density

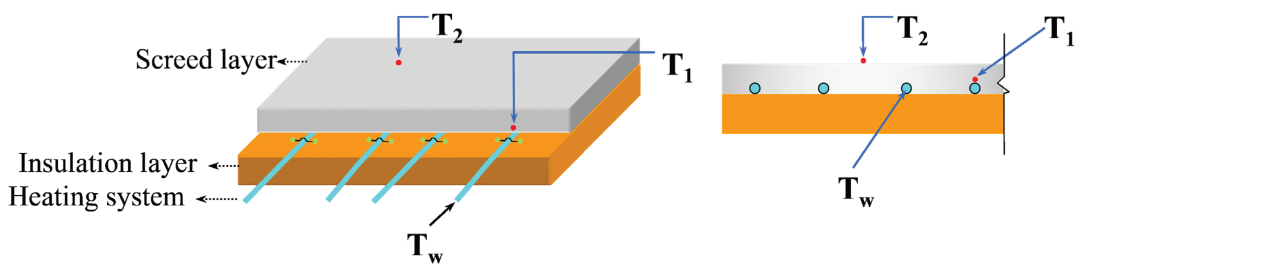

Figure 6. Symbolic view of the measurement locations of the application and temperature values of the screed mortar specimens in the heating system.

Table 2. Physical properties of tested specimens

Mixture	Density in Powder Form (kg/m³)	Fresh Density (kg/m³)	Hardened Density (kg/m³)	Consistency (mm)	Compressive Strength at 28 days (N/mm²)
S0	1198	1773	1585	185±10	18.75
S1	1011	1473	1319	185±10	18.37
S2	1009	1470	1317	185±10	17.63
S3	1008	1468	1315	185±10	17.42
S4	1006	1466	1312	185±10	17.20
S5	1004	1463	1310	185±10	16.66
S6	1003	1461	1308	185±10	16.34
S7	1002	1459	1307	185±10	15.30
S8	999	1455	1303	185±10	14.51

values of the SLCS mortars produced within the scope of this study. Although the hardened densities of the SLCS mortars were almost similar, the increase in the amount of graphite in the mortars caused significant losses in the compressive strength of the mortars (see Figure 7). The significant decrease in compressive strength is due to the lubricating effect of graphite and the weakening of the bond strength in the matrix structure [14]. In this study, the compressive strength of the reference mortar (S0) produced similar to the conventional screed mortar was 18.75 MPa, while the compressive strength of the S8 mortar, which had the highest use of graphite, decreased by 22.61% and was found to be 14.51 MPa. However, higher compressive strength values were obtained than 5 MPa, the lowest screed compressive strength value mentioned in the TS EN 13813 standard [2].

3.2. Thermal Properties Tests of SLCSs

The thermal properties of all specimens are given in Table 3. According to the test results, the thermal conductivity of the reference mixture was 0.597 W/mK, and the thermal conductivity of hardened SLCS specimens using GP was changed between 0.735 and 0.985 W/mK. Generally, thermal conductivity in cement-based materials is associated with the porosity and density of the material [29–31]. Although the density values of the SLCS mortars produced in this study are almost the same, the thermal conductivity values increase depending on the carbon fibers and significantly the increase in graphite in the mortar mixtures (see Figure 8). Compared to the reference screed mortar, the thermal conductivity values of the test specimens increased by 23.12, 26.13, 34.84, 35.68, 42.38, 45.23, 54.77 and 64.99% by MP with GP replacement ratio with 0.69 (S1), 1.38 (S2), 2.07 (S3), 2.76 (S4), 3.45 (S5), 4.14 (S6), 4.6 (S7) and 5.75 % (S8). In other words, the hardened screed mortars get a more conducive form with increased graphite content.

The experimental analysis findings of the specific heat value (Cp) of the SLCS specimens under constant pressure

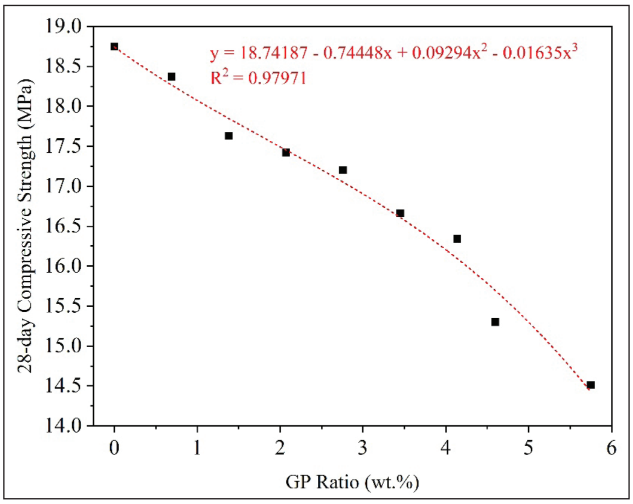

Figure 7. Relation between the GP ratio in SLCS mixtures and compressive strength of SLCSs.

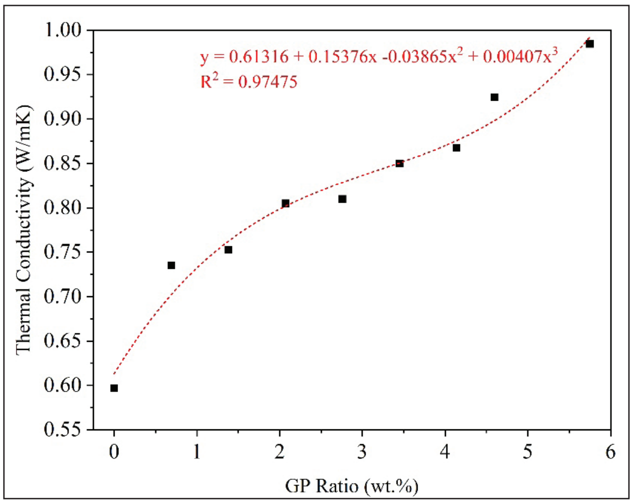

Figure 8. Relation between the GP ratio in SLCS mixtures and thermal conductivity of SLCSs.

Table 3. Thermal properties of tested specimens

Mixture	GP/MP Ratio	Thermal Conductivity (W/mK)	Cp (J/kgK)	Thermal Diffusivity x10^{-6} (m^2/s)	Heat Stored* ΔQ (calories)
S0	0	0.597	1070	0.352	4050
S1	0.03	0.735	1018	0.547	3207
S2	0.06	0.753	974	0.587	3063
S3	0.10	0.805	966	0.634	3033
S4	0.14	0.810	947	0.652	2968
S5	0.18	0.850	918	0.707	2873
S6	0.22	0.867	891	0.744	2784
S7	0.25	0.924	853	0.829	2662
S8	0.33	0.985	815	0.927	2537

*Heat Stored, ΔQ is related to 1 cm thickness and 1 m^2 surface application area for a one °C temperature increase in the surface of the screed layer.

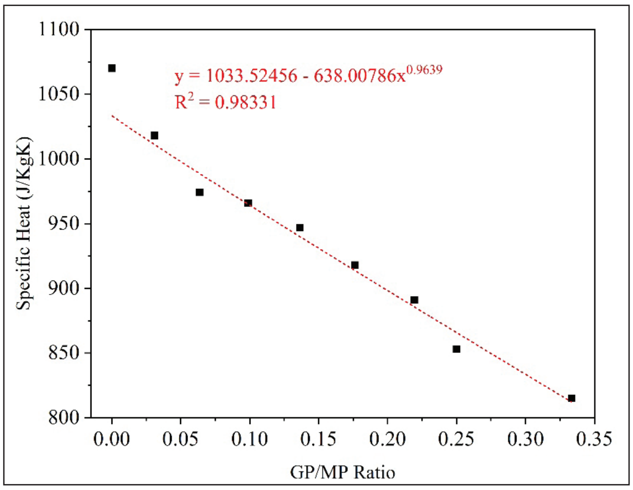

Figure 9. Relation between the GP/MP ratio in SLCS mixtures and specific heat of SLCSs.

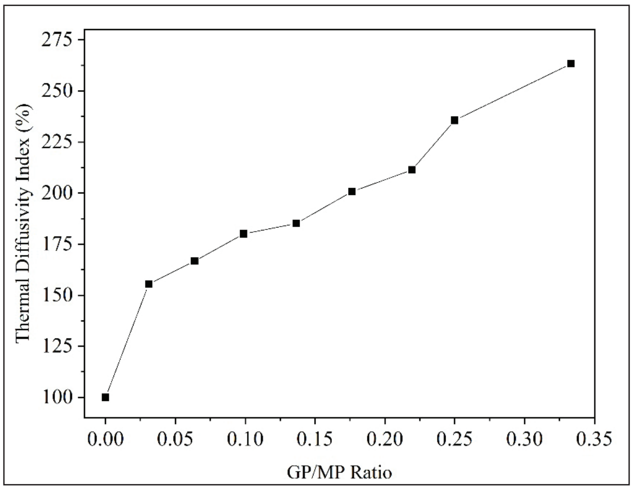

Figure 10. Thermal diffusivity indices of SLCSs as a percentage of reference screed.

are given in Table 3. The test findings pointed out that the specific heat of the reference mixture, which may be considered conventional screed mortar without any CF and GP, was 1070 J/kgK. Besides, the heat of hardened SLCS specimens using significant GP decreased from 1018 to 815 J/kgK. It is aimed to increase the specific heat value in cement-based materials, which are required to provide thermal insulation properties [29]. These types of materials can gain the ability to absorb heat from the environment where it is used. The opposite effect is desired in screeds with increased thermal conductivity rather than thermal insulation. It aims to produce products with lower specific heat values in thermal conductive materials. It was observed that the specific heat values of the screed mortars produced for underfloor heating systems decreased with the increase in the GP/MP ratio (see Figure 9). The specific heat value of a hardened mortar is the amount of heat necessary to increase the temperature of the unit mass by one degree in a given temperature environment. The lower the specific heat, the less energy is used to heat that mortar. In this regard, it can be concluded that the SLCSs produced in this study are efficient in this context.

The findings of the thermal diffusivity (α) of the SLCS specimens are given in Table 3. The test results indicate that the thermal diffusivity of the reference mixture, which may be considered a conditional screed mortar without any CF and GP, was 0.352 x10^{-6} m^2/s. On the other hand, the thermal diffusivity of hardened SLCS specimens using, especially GP, was eased from 0.547 to 0.927 x10^{-6} m^2/s. The typical values of ordinary concrete rearrange between 0.55 and 1.55 x10^{-6} m^2/s, depending on the aggregate type used in the concrete [32]. In their study, Howlader et al. [33] determined the thermal diffusivity in concrete with a density range of 1922-2339 kg/m^3 to be between 0.568 and 1.006 x10^{-6} m^2/s. They also concluded that thermal diffusivity increases with increasing density. A material with high thermal diffusivity allows for rapid heat transfer due to its ability to conduct heat efficiently compared to its volumetric heat capacity or "thermal bulk" [33]. When the analysis results are evaluated, it can be observed that increasing the GP using rate increases the heat diffusion through the screed mortar structure. This phenomenon can be assessed as heat is transferred much faster through the material in the application case, and the material will exhibit a more conductive structure for heat passages. Thus, the more heat diffused, the lower the insulation property for heating purposes in a material structure. In Figure 10, the thermal diffusivity indices of the screed mortars are given as the percentage of the thermal diffusivity index value of the reference screed. The thermal diffusivity of the reference screed was 0.352 m^2/s (i.e., 100%). The thermal diffusivity indices of SLCSs were increased with increasing MP replacement levels of GP, in other words, the GP/MP ratio. Although the thermal diffusivity indices of SLCSs were all higher than that of the reference mixture, the most noticeable jump was seen in the S1 screed by adding GP to the screed mortar design. Then, it is observed that the increase in thermal diffusivity is close to linear as the GP/MP ratio increases. Thus, in the test specimens, the heat spreads more rapidly in the screed layer, causing the surface temperature to rise even more. This study found that despite the decrease in density with the increase of graphite and carbon fiber, the thermal diffusivity has increased due to the superior conductivity characteristics of these materials.

Also, it could be concluded from Table 3 that specimens' heat storage capacity is decreasing from 4050 to 2537 calories (see Figure 11). According to Figure 11, a lower amount of heat is required to increase the temperature on the surface of the screed mortar layer by 1 °C in the context of the increased thermal conductivity value depending on the graphite additive amount of the screed mortar. This means that the heat value of the screed surface can be increased with lower heat energy consumption in the screed mortar with a high thermal conductivity value.

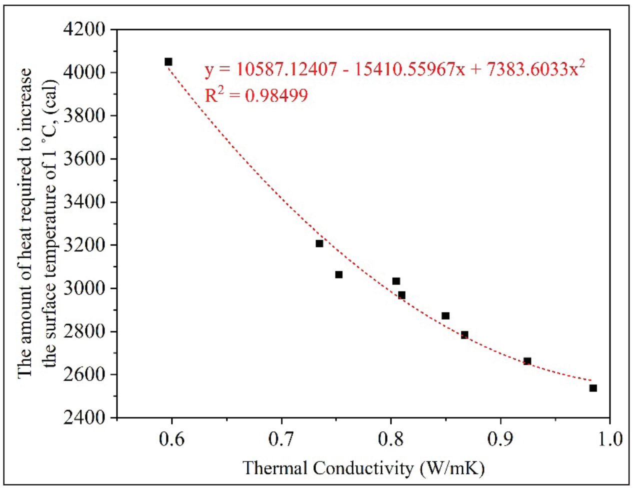

Figure 11. Relation between the amount of heat required to increase the surface temperature of 1 ˚C and the thermal conductivity of SLCSs.

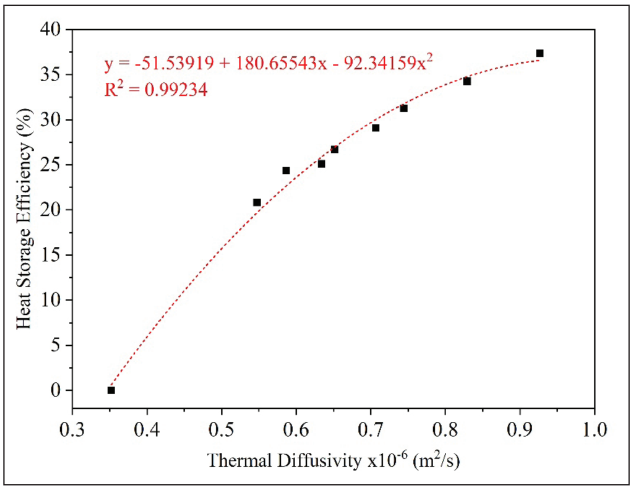

Figure 12. Relation between heat storage efficiency and thermal diffusivity of SLCSs.

Therefore a more energy-efficient heating environment can be provided. When a heat source emits heat through a material, some heat reflects from the surface, and some heat transfers through the material to the other side; moreover, some heat is absorbed in the material and stored. This stored heat should be as low as possible to make an efficient screed mortar. The heat storage capacity varies depending on the specific heat and density of the material. Because the specific heat values of the specimens produced in this study were relatively low, their heat storage characteristics were also low because of their low density and specific heat. In the experiments, the produced specimens (S1–S8) were stored at a heat of 1.26 to 1.60 times lower than the reference/nearly conventional screed mortar specimen (S0). This means that less heat energy is consumed by SLCSs (from S1 to S8). Applying this type of screed mortar to underfloor heating systems may create less heat storage capacity and contributes to energy saving by preventing the heat consumption by the screed material when energy is used to heat the indoors. Figure 12 shows the heat storage efficiency of the SLCSs with thermal diffusivity values. This graphical relationship shows that with the increase in the heat diffusion performance of the screed mortar due to the increasing amount of graphite additive, the screed surface temperature can increase rapidly by storing less heat in the screed layer. The general phenomenon expected in materials with high thermal diffusivity is that allowing heat flow in the application section layer without storing heat in their body enables the heat to pass through the section thickness quickly and increase the surface temperature in a short period. In the context of the findings obtained within the scope of this study, as the graphite ratio in the screed mortar composition increases, the heat flow performance of the screed material increases, and a lower amount of heat is stored in the body, allowing the heat to be transported to the surface quickly. This naturally causes an increase in the screed surface temperature value.

3.3. Performance of the Basic Underfloor Heating System

An experimental underfloor heating system setup was built, as shown in Figure 6. As the time elapsed from the start of heating, the water was heated for the first 4 hours, and when the maximum water temperature of 45 °C was reached, the heating of the water was cut off, and the existing hot water was circulated in the pipe. In Figure 13, T_2 temperature change analysis of S0, S1, S4, and S8 screed mortars against T_1 temperature change over 8 hours. The temperature profiles highlighted that temperature rises quickly for all screed specimens in the first 20 to 30 minutes. This indicates a significant energy transfer to the screeds in this period. After that time, the temperature continued to increase at a slower rate. However, in this second phase, the SLCS test specimens' temperature increasing rate is also higher than the S0 reference screed mortar. When the figure is analyzed, it can be easily observed that the surface temperature of the S0 (reference/conventional) screed is lower than that of the hot water pipe. In SLCS test specimens, the situation is reversed, and the difference between the temperature of the outer surface of the hot water pipe (T_1) and the temperature of the screed surface (T_2) decreases considerably. This means the SLCS specimens perform pretty well compared to the reference specimen in conducting heat and reducing heat losses. In addition, although the heating of the circulating water in the pipe is stopped after the 4th hour, it is observed that the cooling rate of the SLCS test specimens after this moment is relatively slow. The surface temperature of the S4 and S8 specimens was higher than the pipe surface temperature at the 7.5th and 8th hours. This shows how late the screed mortars cool down and retain heat.

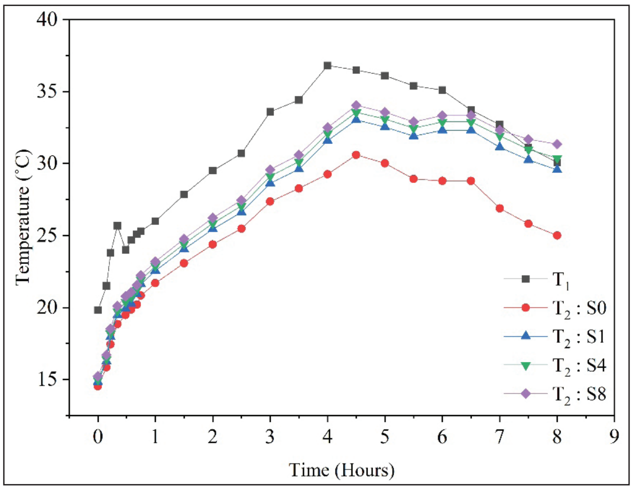

Figure 13. T_2 temperature change of S0, S1, S4 and S8 screeds versus T_1 temperature change over time.

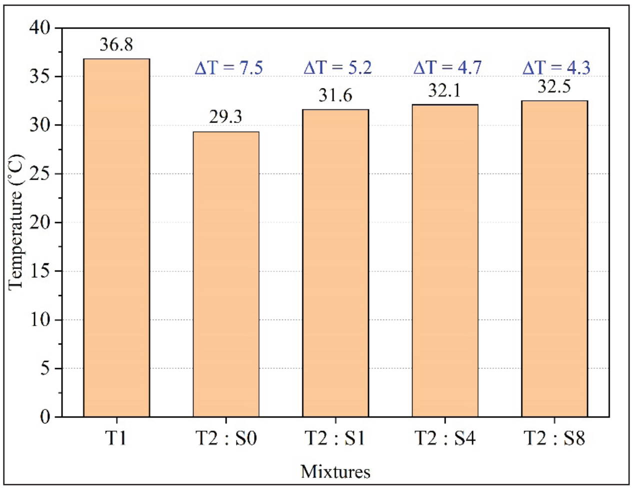

Figure 14. T_2 temperature change of S0, S1, S4 and S8 screeds versus T_1 temperature change at T_w is maximum.

A comparison of the T2 temperatures of SLCS mortars and T1 temperature is given in Figure 14. In this analysis, the results when T_w reaches 45 °C are shared. As it can be easily noticed from the figure, when the circulating water is 45 °C, the outer surface temperature of the hot water pipe is measured as 36.8 °C. The outer surface of the reference screed (S0) was measured at 29.3 C, while the temperature loss between T_1 and T_2 was determined as 7.5 °C. In SLCS specimens, the temperature loss between T_1 and T_2 temperatures decreased and was defined as 5.2, 4.7, and 4.3 °C in S1, S4, and S8 specimens, respectively. Farid & Kong [34] used phase change materials in concrete and modeled an underfloor heating system by using this concrete above hot water pipes. According to their study, the concrete slab varied in its surface temperature between 22.5 and 36.5 °C for three days (a 24 h cycle of 8 h heating followed by 16 h heat discharge). Thermal properties of screed mortars, which are high thermal conductivity, thermal diffusivity, and low specific heat and heat stored, are critical factors in the efficiency of the underfloor heating systems.

4. CONCLUSIONS

This study presented the results of an experimental work on developing a new type of screed mortar. It analyzed the result of applying screed mortars on a basic underfloor heating system as a floor slab finishing material.

The experimental test showed self-leveling lightweight composite screeds obtained 1303-1319 kg/m^3 densities. Besides, although the compressive strength of the mortars decreases as the graphite ratio in SLCS mixes increases, the compressive strength of the 14.51-18.37 MPa range was obtained, which is well above the minimum lower limit of 5 MPa compressive strength specified in the relevant standard.

In the first stage of the study, the thermal properties of the screed mortars were analyzed and compared with a reference (nearly conventional) screed mortar. According to the results, in SLCS test specimens, adding carbon fiber and significantly increasing the graphite ratio increased the thermal conductivity by up to 65 %, and the highest thermal conductivity value was determined as 0.985 W/mK. Similarly, it was observed that thermal diffusivity increased by 163% compared to the reference screed mortar. It has been observed that the specific heat values of SLCS specimens can decrease up to 23.83% compared to the reference mortar. Thus, less energy would be used to heat those screed mortars. Similarly, the amount of heat required to increase the surface temperature of 1 °C and thermal conductivity of SLCSs were decreased as the graphite ratio increased in the test screed mortars.

In the second stage of the study, an experimental underfloor heating system setup was built. The temperatures of the water circulating in this system, the outside of the pipe carrying the water, and the surface of the screed were measured at specific intervals. It can be accepted that the closer the temperature of the outer wall of the pipe carrying the hot water and the temperature of the screed surface is, the better the system's efficiency. According to the results of time-dependent temperature values taken from different system parts, SLCS test specimens can heat up faster and retain their heat for longer than the reference screed. Moreover, while there was a loss of 7.5 °C between the pipe outside temperature and the screed surface temperature in the reference sample when the water temperature was maximum, this value was measured as only 4.3 °C in the S8 test screed mortar.

In this experimental study, it has been determined that self-compacting screeds in composite structures produced with different pozzolanic, chemical, reinforcement, and filling materials can be used effectively in underfloor heating systems.

Based on the findings of this study, the combined use of graphite and carbon fibers can be recommended for screeds to be used in underfloor heating systems. However, since an increase in the graphite content leads to decreased compressive strength, the content should be controlled (with a minimum compressive strength of 4 MPa according to the standard). Similarly, the carbon fiber content should be increased in a controlled manner as it directly affects the self-leveling property. According to the results of this study, even though the addition of carbon fiber and increased graphite content reduces the density of the mortar, the conductivity values have improved. Moreover, the high incorporation of carbon fiber and graphite can be recommended due to meeting the desired limit values for mechanical properties.

ETHICS

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

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Author #1 Şevket Onur Kalkan: Drafted and wrote the manuscript and performed the experiment and result analysis. The planned methodology concludes.

Author #2 Lütfullah Gündüz: Supplied the materials and designed the experimental setup. Supervised the experiment's progress and helped in manuscript preparation.

PEER-REVIEW

Externally peer-reviewed.

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Research Article

Achieving sustainability in Nigerian households: Investigating factors impacting energy efficiency practices

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ABSTRACT

The looming global energy crisis of the 21st century is predicted to worsen as building energy consumption is expected to rise by 50% by 2060. Investing in energy-efficient technologies and reducing carbon emissions is essential to combat this crisis. To this end, this paper delves into the complex issue of energy-efficient building practices in Nigerian households and how they can help curb carbon emissions. Using a statistical method known as the Relative Importance Index (RII), we analyzed nine key factors that influence a building's energy efficiency. The research revealed that government oversight, support, and financial and technical assistance are crucial for achieving household energy efficiency. It also highlights the significance of addressing the energy crisis in Nigeria through the development, implementation, and adaptation of energy-efficient building practices.

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1. INTRODUCTION

Energy is essential in promoting different countries' economic expansion, development, and financial feasibility [1]. However, the energy sector has been dramatically affected by the COVID-19 pandemic, resulting in a 5% decline in worldwide energy consumption and a 7% reduction in carbon dioxide emissions related to energy in 2020 [2]. Nevertheless, energy demand is predicted to recover to its pre-pandemic level by the beginning of 2023[2]. With the planet's population projected to reach 9.7 billion by 2050, the energy demand is anticipated to rise, further exacerbating climate and environmental change [46,48]. To address these issues, its essential for stakeholders to explore older explore alternative solutions to mitigate the impact on their economies and promote energy efficiency across all sectors, particularly the buildings sector, which accounts for about 19% of global GHG emissions and 40% of overall global energy usage through lighting and air conditioning [5]. Building energy consumption is expected to rise by 50% by 2060, contributing to increasing global carbon emissions [6]. This increase is

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mainly due to rapid urbanization and social demand [8,18], which contributes to the sector's consumption of about 30% of the total energy usage worldwide [9,10]. Consequently, there is an urgent need to improve the overall energy efficiency of both commercial, residential, and industrial development through the implementation of distributed energy systems (DESs), as they are the most feasible and least contentious method to address the energy crisis and environmental issues [3], although their development, performance, and operational strategies are not yet fully utilized [4, 12].

Many countries are currently focusing on buildings that consume less energy, industries that require less energy, and transportation systems that use less energy to address the various issues related to their energy crisis. However, in Nigeria today, energy efficiency practices are less considered, resulting in energy waste, increased demand, and energy expenses [47]. As such, it is essential to look into the factors influencing the implementation of energy-efficient building practices in Nigerian households and the adaptation of those practices by users and various public stakeholders. Applying these remedies will significantly reduce energy waste, modifying the country's energy demand and saving unnecessary expenses [13].

A. Energy Crises in Nigeria

Nigeria is a major oil producer in West Africa; however, the nation is facing a significant energy crisis resulting from the inability of its fuel-generated energy to meet the needs of its densely populated citizens [30]. Nigeria's energy resources are mainly non-conventional, depending mainly on the nation's oil, primarily depending on natural gas, tar, and coal while putting less emphasis on the country's numerous renewable energy resources [29]. The main grid power systems are thermal and central electric power plants with an installed capacity of 8,18MW. Unfortunately, 25.1% of this capacity is lost due to technical issues in transmission, distribution, and residential inefficiencies [26]. The problem is further compounded by issues such as poor maintenance of power plants, outdated equipment, and widespread gas pipeline vandalism [35]. The heavy reliance on fossil fuels contributes to climate pollution and can be costly and hard for certain parts of the country [31, 32].

Furthermore, the energy crisis in Nigeria has been linked to inefficient construction and usage of buildings [35,36]. Many buildings in Nigeria are not energy-efficient and lack insulation, leading to high energy consumption for cooling and heating [36]. As a result, most residents are ten unfamiliar with energy efficiency and unaware of the differences between conventional and more energy-efficient materials. Thus, to have a deeper understanding of the implications of energy conservation, it is necessary to investigate the behavior of residents in their daily energy consumption [26]. Therefore, improving power generation in the country should focus on reducing transmission and distribution losses and understanding residents' perceptions of energy conservation by considering key essential policy formulations and execution strategies [27].

Despite all these challenges, a glimmer of hope is on the horizon. Renewable energy sources, such as biomass, solar, wind, and hydroelectricity, offer a sustainable, locally-produced solution to Nigeria's energy crisis [33]. These technologies can create jobs, reduce dependence on fossil fuels, and improve the environment [34]. But to fully harness their potential, Nigeria must invest in the necessary infrastructure and technology and educate the public on the significance of energy saving and the effect of their actions on the environment. The government could also explore other options, such as implementing energy-efficient building policies, incentivizing companies to use renewable energy, and promoting sustainable materials [36].

B. Nigerian Building Energy Efficiency Code

Nigeria's code for energy efficiency in buildings was agreed upon and formally introduced in 2017 by the "federal minister of power, works, and housing" [24, 50]. The code was created in partnership between the "Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)" and Solid Green sustainability experts, who acted as primary consultants, and the code covers various essential rules and guidelines for the country's energy efficiency practices [49]. The "Nigerian Energy Support Program (NESP)" and the "Federal Ministry of Power, Works, and Housing" are tasked with putting the code into effect in conjunction with related professional organizations like the "Green Building Council of Nigeria (GBCN)" and the "Architect's Registration Council of Nigeria (ARCON)" [17,19]. The developed efficiency guidelines for a building include measures for energy efficiency and breaking them into passive and active elements of an energy-efficient structure. The principles aid Nigerian experts in planning, constructing, and operating energy-efficient buildings. It also teaches the general public about energy efficiency methods and tells clients about a better alternative to constructing energy-efficient buildings [19].

The existing building code and guidelines, set by the federal government, elaborate on system structure, fire safety, and general safety procedures but lack detailed information on renewable energy or energy efficiency practices [17]. As such, there is a need for the code to be available legally to all the member states across the country to formulate an operational rule for practice and enforcement at the local and state level. Building license regulations and standards are vital requirements in metropolitan settings, except in minor construction specified by project size or in rural regions where such activities are rarely regulated. Nevertheless, one of the significant obstacles to effectively enforcing regulations in the country's building sector has been the lack of a strong enforcement mechanism for absentee landlords [17,19].

C. Challenges in the Adaptation of Energy Efficient Building Practices in Nigeria.

The energy crisis in Nigeria is a pressing issue that has been plaguing the nation for decades. Despite the several efforts made by non-governmental organizations, the private sector, and the government, the challenges of inadequate energy generation and inefficient energy usage continue to plague the country [1]. The barriers to the mainstreaming of building energy efficiency practices in the country are multifaceted and include financial challenges, corruption in the administration, lack of sufficient information, and a host of legal and regulatory policy, technical, and development barriers [47]. Residents of Nigeria are not known for their energy-saving habits, often leaving appliances on when not in use and neglecting to use natural ventilation to achieve thermal comfort. This lack of consideration for energy efficiency in household practices significantly contributes to the country's energy crisis [19]. To address this, the government and other stakeholders must take a proactive approach by implementing energy efficiency policies, providing regular information and education, and raising awareness about the importance of energy efficiency.

The rapid population growth in Nigeria has also led to an increase in energy demand and consumption across all sectors of the economy, exacerbating the already dire energy situation. This increase in energy demand, coupled with inefficient consumption patterns and environmental problems in energy transmission and distribution, has emerged as a significant source of worry for the country [19]. The construction industry is among the country's most energy-intensive and consuming sectors. Therefore, implementing energy-efficient design principles and practices in this sector is crucial for achieving energy efficiency and sustainability. This includes using materials with low embodied energy, designing for natural ventilation, and incorporating energy storage systems [18]. Additionally, it is equally vital to note that although building energy efficiency may have a higher initial cost, it ultimately counterbalances unnecessary costs associated with its provision [45].

D. Factors Influencing Energy-Efficient Building Practice Implementation

The primary factors influencing energy efficiency practices in buildings are the building itself (its shape, ideal insulation depth, building wall insulation, orientation, window glazing, insulation materials, as well as window-to-wall ratio), the technology and equipment used in the building (thermal energy storage, variable air volume, heating retrieval, control upgrade, and evaporative cooling), and the behavior of its occupants (smart grid, smart meter, control upgrade, and plug load). The building attributes alone cannot be used to determine the optimal design approach, as the other two factors could influence it. For example, some energy-efficient design solutions do not consider economic and environmental benefits under certain conditions. On the other hand, building designers have access to many technological advancements, but cost-effectiveness remains challenging [15].

Occupant behavior intervention can provide a cost-effective and easy-to-implement avenue for increasing energy efficiency for the residents. Ultimately, building service systems, technical improvements, and resident behavior engagement in energy efficiency monitoring is essential as a channeling basis to help the country conserve its energy from the sector [15]. Moreover, occupant responsiveness to energy-saving behaviors may influence innovation, while responsiveness may increase the need for creation and subsequent implementation [16].

In general, lack of suitable technological access, resource limitations, and knowledge of energy efficiency techniques are significant obstacles to adopting energy-saving measures in most emerging economies. As a result, urgent measures and increased awareness are required to motivate human behavior toward energy-efficient practices [14]. Many factors influence the adoption of building energy efficiency practices. However, this paper considered nine factors based on the relative importance index (RII) to determine the factors that impact building energy efficiency and suggest better ways to implement these practices in Nigerian households. Figure 1. summarizes some factors affecting the adoption of energy-efficient building practices.

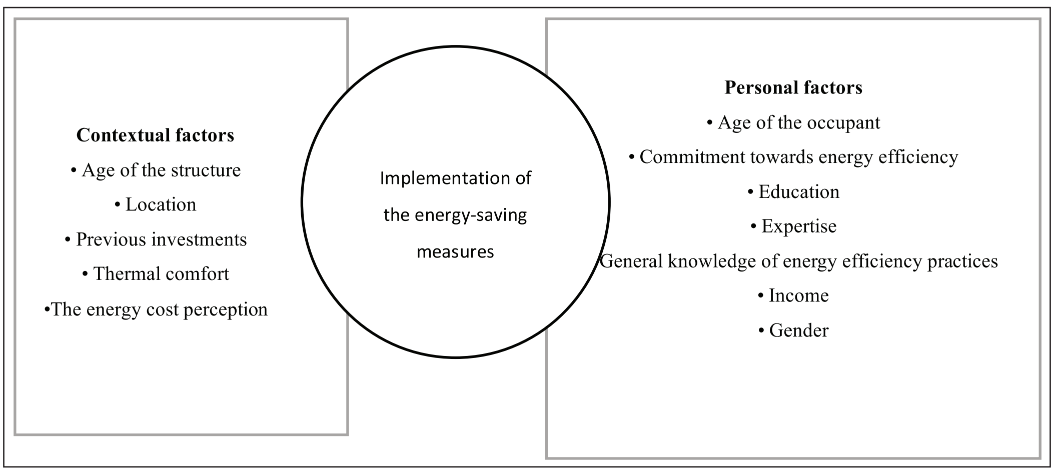

Figure 1. Factors influencing the implementation of building energy-efficient practices.

E. Contribution to Knowledge

This study adds to the current body of knowledge on energy efficiency in Nigeria's building industry by providing insight into the factors that influence the application of energy-efficient practices in the country. Previous studies in this field have also examined the implementation of building energy-efficient practices in the country, but this study provides a much more detailed examination of the specific factors influencing adaptation. For example, some of the previous researchers have looked at the role of government policy in promoting energy efficiency. Still, this study delves deeper by explicitly examining the importance of government supervision and support in encouraging households to adopt energy-efficient practices.

The study also fills a gap in the literature by focusing on the specific case of Kano state, the second-largest industrialized state in Nigeria and a commercial and economic center. By analyzing the situation in this region, the study provides valuable insights into the opportunities and challenges for energy efficiency in a significant urban area. Moreover, the study provides a more comprehensive examination of the energy consumption patterns in Nigerian households, including the use of multiple sources of energy, generator usage, and dependence on the national grid. The study also provides insight into the respondents' behavior toward energy efficiency, which is not covered in most previous studies.

2. APPROACH AND METHODS

The research presented in this paper is both applied and exploratory, as it aims to address practical difficulties and discover new insights. The research questions were designed to survey the country's current level of energy efficiency in buildings and shed light on the critical drivers of adoption [43, 44].

A. Research Population and Sampling

Sampling is a powerful tool that allows researchers to make sense of complex data sets by selecting a smaller, more manageable population subset. This is particularly useful when resources or time are limited, as it allows researchers to focus on the most important aspects of their study [37]. For this research, we looked at Nigeria's rapidly growing energy needs, a developing nation with a rapidly expanding population, and the booming construction sector, particularly in major cities like Kano [45]. Kano state was selected as a case study as it is the second-largest industrialized state in Nigeria. This economic and commercial center faces tremendous issues due to energy inefficiency and scarcity [26]. The state is sitted in the northwest part of Nigeria, covering about 20760 sq. km of area and with a demography of approximately 9,384,682 people, according to the 2006 census [20,21].

B. Data Collection

The research presented in this paper relies on a combination of data sources to comprehensively understand the topic. These sources include archival documents and residential household owners' responses [38]. We used self-structured questionnaires that included open and closed-ended questions to gather data from household owners. Archival records, such as articles, published papers, and journals, were also consulted to provide additional context and support for the research objectives and questions [38,39]. The data collected was analyzed using various methods, including explanatory and descriptive statistics for sections one, two, and three of the questionnaires and the Relative Importance Index (RII) for section four. For data cleaning and analysis, both SPSS and Microsoft Excel were used [40,41]. At the same time, a Likert Scale was also employed to gather information about the respondents' feelings and perceptions about buildings' energy efficiency. The participants were asked to assess how much they agreed or disagreed with various topics and questions on a scale of one to five [42]. This simple scale was chosen for its ease of use and ability to provide clear and easy-to-analyze data.

C. Data Analysis

To analyze the collected data a "relative importance index (RII)" method was employed using the "statistical package for social sciences (SPSS)". Each response was analyzed and ranked based on the selected factors influencing the implementation of energy-efficient building practices in the country using the RII formula below [23].

$$RII \ \frac{\Sigma w}{AN} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + 1n_1}{5N} \quad (1)$$

Were,

W = Weight as allocated to "Likert's scale" by each participant on a scale of 1 to 5 (very low to very high).

A = is the heaviest weight (5)

N = Total number of people that responded

Note: 1 indicates Very Low, 2 indicates Low, 3 indicates Moderate, 4 indicates High, and 5 shows Very High.

3. RESULTS

A. Demographic Information

According to the findings from 190 households, most respondents are 92.6% male, 5.3% female, and 2.1% missing, as shown in Table 1. Most surveyed respondents are between 20 and 30, with 9.5% between 30 and 40 and 0.5% between 40 and 50. The majority of participants (around 50.5%) are postgraduates, followed by 'graduate' (40.5%), 'other' (5.8%), 'diploma graduate' (2.1%), and missing value (1.1%). Furthermore, the results identify the number of people in households, which reveals that 19.5% of houses have 1–5 people, 37.9% have 6–10 people, 21.6% have 11–15 people, and 21.1% have more than 15 people. It also reveals that 6.1% of households have a single apartment in the buildings, 8.4% have a room and parlor, 1.1% have a mini flat, 11.1% have a 2-bed room flat, 16.8% have a 3-bed room flat, 33.7% have a 3-bed room flat, and 22.1% have other, with 0.5% missing value.

B. Nigerian Household Energy Consumption Pattern.

This section gathers data to evaluate the different types of energy usage in Nigerian houses, determine the standard supply and services, and evaluate the methods of energy usage.

i. Source of energy in the buildings

The presented data below was collected to help determine the various household energy sources.

The above figure describes the energy sources (both renewable and non-renewable) of the various household from the survey conducted. The results show that 66.5% of the respondent gets their energy from PHCN, personal fuel-powered generators generate 10.2%, 3.6% from solar panels/other renewable sources, and 4.1% from other sources. Furthermore, 12.7% of the households obtain energy from PHCN (NEPA) and Generator sources. 1.5% from PHCN (NEPA) and solar panels; 0.5% from solar panels and other renewable sources; 0.5% from PHCN (NEPA), Generator, and solar panels; and 0.5% from Generator and Other sources.

ii. Average Daily Supply/Usage

The daily average energy supply to individual residents is presented in table 2. The survey results indicate that a significant % of households, 13.2%, receive no energy supply at all. Most respondents, 45.5%, reported receiving 1-5 hours of energy supply daily, while 24.1% reported receiving 6-10 hours. A smaller percentage, 15%, reported receiving 11-15 hours of collection, with 1.1% receiving 16-20 hours and 1.1% receiving 21-24 hours. These findings suggest that the primary energy source for most households is PHCN (NEPA) at 45.5%. However, the survey also revealed that a considerable number of respondents, 44.4%, do not use generators as a source of energy, while 42.7% use generators for 1-5 hours, 11.7% use generators for 6-10 hours, and 1.2% use generators for 11-15 hours.

Table 1. Personal information

Demographic variable	Description	Frequency	Percentage (%)
Gender	Male	176	92.60
	Female	10	5.30
	Missing value	4	2.10
Age range	20-30	171	90.00
	30-40	18	9.50
	40-50	0	0.00
	Above 50	0	0.00
	Missing value	1	0.50
Level of education	Diploma graduate	4	2.10
	Graduate	77	40.50
	postgraduate	96	50.50
	Other	11	5.80
	Missing value	2	1.10
Number of residents in the building	1-5	37	19.50
	6-10	72	37.90
	11-15	41	21.60
	more than 15	40	21.10
Apartments in the buildings	single	12	6.30
	Parlor & rooms	16	8.40
	Mini apartment	2	1.10
	Two bedroom apartment	21	11.10
	Three bedroom apartment	32	16.80
	Four bedroom, terrace, or duplex	64	33.70
	Others	42	22.10
	Missing value	1	0.50

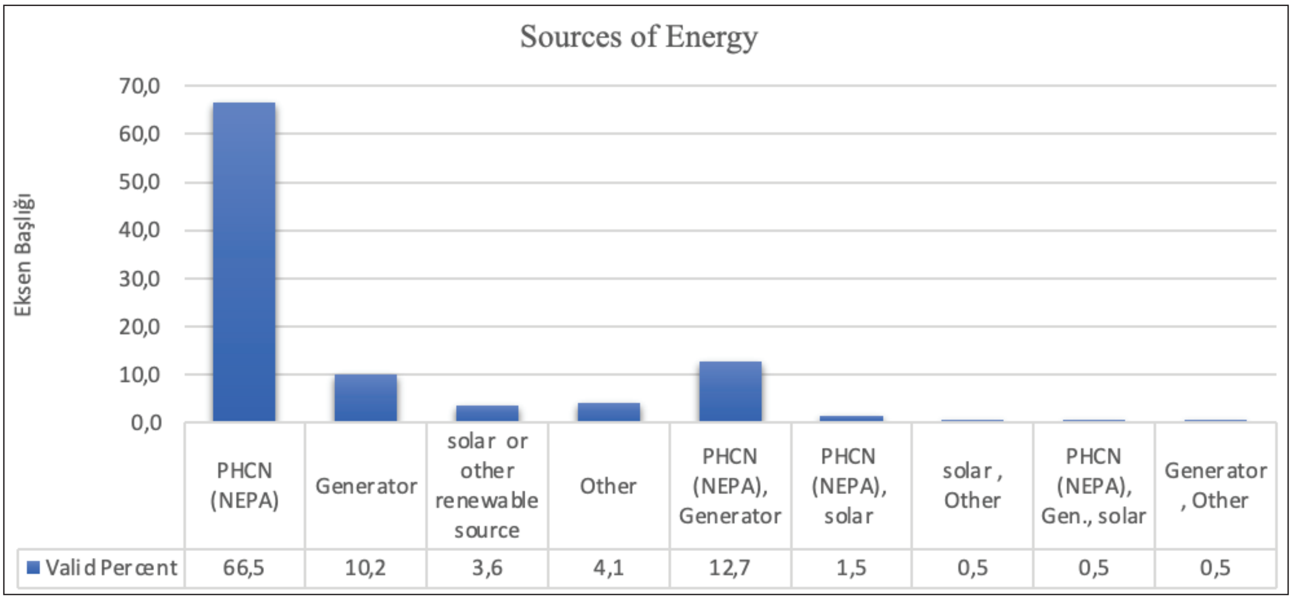

Figure 2. Sources of energy.
Note: PHCN refers to the Power Holding Company of Nigeria

C. Implementation of Energy Efficiency Practices

The section collects information to evaluate Nigeria's household energy consumption concerning building energy efficiency practices.

i. Number of appliances, fittings, and fixtures in the survey buildings

To study the energy consumption of these households, we collected data concerning the number of fittings, fixtures, and appliances used in the buildings, as presented in the table below;

The table above presents the prevalence of various household appliances, fixtures, and fittings. The data reveals that many households utilize LED bulbs, with 34.1% having more than 4 in their buildings. Fluorescent bulbs are also commonly used, with 31.9% of households having more than 4. However, most families do not use halogen and incandescent bulbs, at 57.6% and 59.8%, respectively. Additionally, many households have one electric pressing iron and electric water heater, at 60.8% and 45.0%, respectively. Most households do not have air conditioners, at 60.0%, and a significant number have one refrigerator, at 38.9%. Furthermore, 36.7% of households have one TV, 27.4% have more than four fans, 55.0% don't have a pumping machine, 53.3% do not use electric cookers, and 27.4% do not use any other appliances

Table 2. Daily average energy supply

Sources/ Hours	0 (%)	1 – 5 (%)	6 – 10 (%)	11 – 15 (%)	16 – 20 (%)	21 – 24 (%)
PHCN	13.40	45.50	24.10	15.00	1.10	1.10
Generator	44.40	42.70	11.70	1.20	0.00	0.00

Table 3. Nigerian Households Energy Efficiency Practices

Questions	Yes (%)	No (%)	Remarks
Do you turn off the lights and appliances when not in use?	86.8	13.2	Most survey participants turn off their appliances while they are not in service.
Energy consumption measurement	20.8	79.2	They don't measure their energy consumption.
Implementation of energy efficiency practices and guidelines in the building	43.8	56.2	Most of the respondents do not consider any energy efficiency guidelines.
Do you have the proper ventilation in your building?	79.4	20.6	The majority have proper ventilation in their buildings.
Does your building envelope have a focus on insulation?	50.8	49.2	Some buildings focus on insulations while some do not have.

ii. Daily average energy consumption duration of the fittings, fixtures, and appliances.

To have more understanding of the household consumption pattern, we collected information on the daily average duration of energy consumption in the buildings from fittings/appliances/fixtures, which is summarized in the table below;

The above table describes the average daily usage time of the building's utilities, fixtures, and fittings. The results indicate that most homes (45.60%) use LED lights for 1.0 - 5.0 hours per day, and fluorescent bulbs for 1.0 - 5.0 hours per day, while halogen bulbs aren't used. Furthermore, 61.10% do not use incandescent bulbs, 71.70% use electric pressing iron for 1.0–5.0 hours daily, 55.20% use electric water heaters for 1.0–5.0 hours, 62.60% do not use air conditioners, 31.90% use refrigerators for 1.0 – 5.0 hours, 37.90% spend 1.0 –5 .0 hours on TVs, 33.10 use fans for 11.0–15.0 hours, 52.90% do not use pumping machines, 50.00% do not use electric cookers, and 34.50% spend 1.0 – 5.0 hours on other appliances.

D. Assessment of factors influencing the adaptation of energy-efficient building practices.

In this part, we collect data to assess the factors influencing adoption of energy-efficient practices in Nigerian homes [49]. The data is based on respondents' perceptions of the variables that impact the adoption of building energy efficiency practices[51]. The detailed data is shown in the table below;

Table 6 highlights the factors that significantly influence efficient construction techniques in Nigerian households. The survey results illustrate that government supervision has a strong impact, with an RII value of 0.376. On the other hand, government support has an RII value of 0.394, and economic and technical support has 0.437. Legal,

Table 4. Building's Fittings, Appliances, and Fixtures

Fittings/Appliances/Fixtures (%)	Not in use	1.0	2.0	3.0	4.0	More than 4.0
Air Conditioner	60.00	14.00	14.00	4.70	4.00	3.30
Electric Cooker	53.30	32.00	6.70	6.70	0.70	0.70
Electric Pressing Iron	11.40	60.80	16.50	6.30	1.90	3.20
Electric Water Heater	20.60	45.00	18.10	10.00	3.80	2.50
Fan	5.10	18.90	22.30	13.70	12.60	27.40
Fluorescent Bulbs	25.90	10.20	17.50	7.80	6.60	31.90
Halogen Bulbs	57.60	18.40	8.80	5.60	2.40	7.20
Incandescent Bulbs	59.80	14.80	10.70	4.10	7.40	3.30
LED Bulbs	13.40	10.60	25.70	8.40	7.80	34.10
Other Appliances	27.40	20.50	21.90	10.30	11.00	8.90
Pumping Machine	55.00	28.20	9.40	5.40	1.30	0.70
Refrigerator	29.90	38.90	19.70	5.70	5.20	0.60
Tv	11.80	36.70	29.00	10.70	5.90	5.90

Table 5. Daily average energy consumption

Fittings/Appliances/Fixtures (%)	Not in use	1 to 5 hrs	6 to 10 hrs	11 to 15 hrs	16 to 20 hrs	21 to 24 hrs
Air Conditioner	62.60	21.10	12.20	2.70	0.70	0.70
Electric Cooker	50.00	34.20	11.00	3.40	1.00	0.00
Electric Pressing Iron	16.40	71.70	8.80	1.90	1.30	0.00
Electric Water Heater	27.30	55.20	14.90	0.00	2.60	0.00
Fan	5.20	27.90	33.10	16.90	10.50	6.40
Fluorescent Bulbs	25.00	34.40	26.30	13.10	0.60	0.60
Halogen Bulbs	63.00	17.80	14.80	3.70	0.70	0.00
Incandescent Bulbs	61.10	18.30	16.80	3.80	0.00	0.00
LED Bulbs	15.80	45.60	23.40	12.30	2.30	0.60
Other Appliances	32.40	34.50	14.80	12.00	4.20	2.10
Pumping Machine	52.90	32.10	10.00	4.30	0.70	0.00
Refrigerator	25.80	31.90	20.90	14.70	3.70	3.10
Tv	7.10	37.90	30.80	13.60	7.10	3.60

Table 6. Factors influencing the adaptation of energy-efficient building practices

Identified factors	Very high 5.0	High 4.0	Moderate 3.0	Low 2.0	Very low 1.0	Total	Total number (N)	(A×N)	(RII)	Rank
Government Supervision	0	20	132	128	77	357	190	950	0.376	1
Governments Support	5	24	126	154	63	372	189	945	0.394	2
Economic & Technical Support	5	36	174	150	44	409	187	935	0.437	3
Legal Environment Code & Enforcement	10	52	153	156	43	414	187	935	0.443	4
Occupant's Behavior	0	64	195	130	44	433	190	950	0.456	5
Knowledge & Information	10	56	213	124	39	442	179	895	0.494	6
Awareness	45	32	255	108	33	473	189	945	0.501	7
Equipment & Technologies	40	56	306	90	16	508	185	925	0.549	8
Construction Quality	25	100	288	88	40	541	190	950	0.569	9

environmental code, and enforcement have 0.443; occupancy behavior scores 0.456; knowledge and information scores 0.494; awareness scores 0.501; equipment and technology have 0.459. And construction quality score of 0.569. The lower the value, the more significant the impact of the respective factor on energy efficiency practices. Therefore, it is clear that government supervision, support, technical and economic support, and enforcement of a solid legal, environmental code are critical elements in ensuring building energy efficiency.

4. DISCUSSION

The study's findings have uncovered a significant shortfall in adopting building energy conservation practices in Nigeria. Most respondents acknowledged a poor understanding and prior knowledge of energy-efficient design principles and a failure to implement energy-efficiency measures [48]. The lack of awareness and understanding of energy-efficient practices is a significant barrier to sustainable development in the building sector. Previous studies, such as those conducted by Painuly (2001) [52], Thorne (2008) [53], and Bagaini (2020) [54], have uncovered a significant barrier to sustainable development in the sector: a lack of awareness and understanding of energy-efficient practices. However, this new study takes a closer look at the Nigerian scenario and adds to the existing knowledge. It becomes apparent that industry-wide and government awareness initiatives to educate the public on the numerous benefits of energy efficiency are urgently needed. In terms of household consumption patterns, the study found that many households do not rely on one energy source but instead use multiple sources. Most households reported receiving energy from the national grid (PHCN) for only 1–5 hours per day, which is insufficient to meet their energy needs [36]. This explains why many households must look for alternative energy sources [35]. Additionally, many households do not use generators, which is positive for the environment but indicates low living standards as they cannot afford to purchase or maintain them.

It was also revealed that about 13.4% of the respondents do not have any supply from the national grid, and in such instances, they have to look for other alternatives to cater to their energy demands. Such alternatives are mostly small-scale generators, as they are cheap, but at the same time, they are carbon-intensive, contributing to the country's total carbon footprint. Therefore, there is a need for the authority to foresee energy efficiency and supply improvements in the country [35]. Also, considering the vast availability of sunlight in the country, it is an excellent opportunity for the government to diversify energy sources by shifting towards renewable and sustainable energy programs. In addition, the research further evaluated the implementation of energy-efficient practices in Nigerian households [19]. Most households cannot afford to install energy-efficient appliances, fittings, and fixtures. However, a positive finding was that many respondents reported turning off their appliances, fittings, and fixtures when not in use. But this might be more a result of saving on fuel costs rather than a proper understanding and adoption of energy-efficient practices. The study also revealed that many households do not measure their energy consumption or consider any energy efficiency guidelines, indicating a poor implementation of energy-saving practices [36].

Finally, the study analyzed the factors influencing implementation of energy-efficient building practices in Nigeria. The findings suggest that government regulation and supervision, support, financial and technical aid, etc., are the most crucial household considerations concerning the country's adoption of energy-efficient practices. Previous studies conducted by esteemed researchers such as Painuly (2001) [52], Doukas et al. (2009) [55], Thorne (2008) [53], Ravindranath and Balanchandra (2009) [58], Karakosta et al. (2010) [56], Jagadeesh (2000) [57], and Bagaini (2020) [54] identified these barriers as part of their research findings. This study has proven to be a valuable insight into their results, as it has revealed that none of the barriers identified by these researchers are insignificant, indicating their impacts on the implementation of building energy efficiency practices.

5. CONCLUSION

As the world faces a pressing energy crisis, countries must take action to handle the situation. The study presented in this paper delves into the challenges faced by Nigeria in adopting building energy-efficient practices. Using the Relative importance index (RII)" approach, the study examines the various elements influencing the adoption of energy-efficient building policies and procedures in Nigeria. The finds find a significant gap in energy-efficiency practices in the country, with residents relying on the national grid, which cannot meet their energy demand. Additionally, most residents do not measure their energy consumption or follow energy efficiency guidelines. Furthermore, the study highlights the crucial role that government supervision and support and technical and economic assistance play in adopting energy efficiency practices in buildings. To address the challenges faced by the country, the study recommends the following measures;

- The government should improve existing policies, implement new ones, and raise residents' awareness of building energy efficiency practices.
- There is an urgent need for the country to incorporate green building concepts into the curricula of its educational institutions to address the country's massive gap in green building awareness.
- Provision and enforcement of mandatory smart grid metering policies for all residential properties.
- The judiciary arm of the government needs to provide solid legal support for the defaulters.
- There is a need for technical assistance from both industries and researchers supported by government grants to develop low-cost materials using locally available resources.
- It is important to increase the utilization of renewable energy sources to decrease expenses and the emission of greenhouse gases.

In conclusion, the presented study highlights the significance of addressing the energy crisis and the need for countries to take action toward energy conservation. The study calls for additional research to establish a structure for energy-efficient design in the sector and to outline ways to enhance the professional code of ethics towards energy conservation practices in the country. We can work toward a greener, more sustainable future for all with the right measures.

6. LIMITATION

This research has some limitations, including the small sample group size and the self-reported nature of the information retrieved from the survey. The sample size of 197 households, while representative of the population in Kano State, may not be generalizable to the entire country. The study also relies on the accuracy of the respondents' self-reported energy consumption patterns and energy efficiency practices, which may be subject to bias or inaccuracies. In addition, it is equally vital to note that the research conducted does not consider the impact of cultural or societal factors on energy efficiency adoption. However, despite the limitations mentioned offers a significant understanding of the present state of building energy efficiency practices in Nigeria and pinpoints key areas that require improvement. Future research should consider expanding the sample size and incorporating a more diverse range of respondents to further examine the barriers and facilitators to energy efficiency adoption in the country. Additionally, further research could also investigate the role of cultural and societal factors in energy efficiency practices.

ETHICS

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

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE

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

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The author confirms sole responsibility and contribution for the study conception and design, analysis and interpretation of results, and manuscript preparation. Further, the author has validated and approved the final manuscript.

PEER-REVIEW

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Research Article

An architectural query of Anthropocene Era: Planned obsolescence

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ABSTRACT

After Modernity, the human has become the subject, and the world redefined by the human has turned into a painting. However, the efforts of human subjectivity to reveal the world in the Anthropocene Era, with negative practices such as the "planned obsolescence theory," which is the research subject, even prepares for the end of its existence. According to the research hypothesis evaluated through the theory's effect on architectural problems, "*secularization should take place against planned obsolete architecture.*" The research aims to show that positive feedback can be provided in society and ecology by reversing architectural consumption. It is to open up for discussion that architecture, which is left in the tension of life and death but revived by the urbanites and nature despite the negativity of decay, can be sustained by becoming secularized. How planned obsolete architectures become secularized is revealed through visual documents and tables and discourse and descriptive analysis methods through architectures of different scales and geographies, which can be reactivated in human-nature activity while in crisis of decay. At the micro and macro scale of architecture, Hawthorne Plaza Shopping Center, Banker Han (Banker Kastelli), Doel Village, and Houtouwan Village were selected as purposeful examples.

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1. INTRODUCTION

According to Henri Lefebvre (1974), the material of the city, namely the "raw material," is nature, and nature is being indecently plundered [1]. Industrial remnants accumulating in geological layers exacerbated ecological crises and pointed to the Industrial Revolution as the beginning of this plunder [2]. According to the British geologist Jan Zalasiewicz et al. (2008), human activities after the Industrial Revolution caused significant changes that could be reflected in the geological record of the world [2]. According to geologist Antonio Stoppani, chemist Paul J. Crutzen, and biologist Eugene F. Stoermer et al., the determining factor on the functioning and physical structure of the planet has been "human" for a long time. Therefore, it has been suggested that the current era be called the "Anthropocene," that is, the "New Human Age," in terms of human being the most significant ecological power on the planet [3].

Swedish scientist Johan Rockström et al. have discussed The Anthropocene, where human actions have become the main driving force in environmental changes since

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the Industrial Revolution; in terms of the context of planetary boundaries, climate change, nitrogen and phosphorus cycles, rate of biodiversity loss and delicate balance [4]. Noel Castree has also stated that the disruptions that may occur in these areas can trigger each other in a chain reaction, and it cannot be predicted what effects the deterioration in one place may cause on other sites [5].

One of the human behaviors that played a direct or indirect role in environmental changes in the Anthropocene Era is planned obsolete, which is the subject of the research. Planned obsolescence, a consumption-oriented strategy recommended to stimulate the economy, leads to concrete piles that cannot degrade in nature, from industrial products to structures. Industrial products, buildings, and even cities are worn out before their biological lifespan, as in the example of Detroit[1], and remain idle and left to the nature of decay [6] because, according to Portzamparc (2003), there is no such thing as "reuse" after the Industrial Revolution, instead "buy-use-throw away" [7].

Wastes that cannot dissolve on their own or take a long time to dissolve and disappear are included in the ecological cycle and trigger deterioration with the chain effect, as Castree says. Inactive architecture, which cannot be eliminated, also continues its existence in the urban environment with the potential to cause physical and psychological dangers. According to McKenzie Wark (2015), God, the underlying idea of self-correcting, balancing, and curing nature, is dead [6]. Nature, and therefore cities, are plundered and consumed by the distinguished subject of Modernity by suppressing the power of self-renewal with various harmful practices. Problems of the Anthropocene Age, such as the COVID-19 virus epidemic that emerged in Wuhan, China, in 2019, show that the subject also objectifies itself and prepares for the end of its existence while transforming cities into places of disaster.

This research, which makes the secularization of reinforced concrete architectures visible, is opening a discussion that life can be positively reversed with human-active practices despite the human-active practices such as planned obsolescence, which are consumption-oriented, affect nature negatively by leaping from micro-scale to macro-scale. According to the research hypothesis, secularization should occur in the human-enabled Anthropocene Age in the face of planned obsolete architecture. How does a planned obsolete architecture become secular and sustainable? The research aims to elucidate the answers to this question through different examples of architectural practices. This study aims to reveal how architecture, pushed into the crisis of decay and remaining in the tension of life and death can be acted upon despite the negativity of refuting the material and to discuss the relationship between these practices of action and architecture in the context of subject-object relationship. The research, rather than the reuse of space, focuses on the reuse of spaces that have been left to the negative consequences of decay in human subjectivity, with their existing potential, that is, without any technical-theoretical intervention from the inside or outside, with reason and creativity or by nature as if they were alive. In the research showing that positive feedback can be provided in society and ecology by reversing consumption in architecture, Hawthorne Plaza Shopping Center and Banker Han (Banker Kastelli) were chosen as purposeful samples of architecture on a micro-scale, Doel Village and Houtouwan Village macro scale.

2. MATERIALS AND METHODS

Systematic consumption, which evolves from micro scale to macro scale from industrial products to buildings/building groups and the plunder of cities and nature in its integrity, is discussed in this study through the effect of planned obsolescence on architecture. The research makes it visible with examples from the world and Turkey that the architectures, pushed into the decay crisis in human subjectivity, are reproduced and maintained with their current potentials without technical-theoretical intervention. The method of the research was determined by questions such as "how? by whom?" addressed to "how and by whom the architectures were obsolete, how and by whom they were reproduced" [8]. In the research universe where one of the qualitative methods is used, namely "explanation with examples," buildings that remain idle despite their usable features and purposeful examples of architecture in micro and macro scales representing secularization were considered. To exemplify the universality of secularization in architecture regardless of geography or scale, Hawthorne Plaza Shopping Center (Hawthorne, California) and Banker Han (Banker Kastelli-Istanbul, Turkey) structures at the micro-scale, Doel Village (Belgium) and Houtouwan Village (China) at macro scale were used as purposeful samples. The research's findings were reached and discussed through discourse and descriptive analysis (Table 1).

3. SUBJECT-OBJECT RELATIONSHIP AFTER MODERNITY

According to David Harvey (2003), being a radical break from the past, Modernity has created a state that allows us to see the world as a blank page on which the new can be written, without any reference to the past - or ignoring the history completely when it is but an obstacle [10]. As a result, human has become a subject, and the world has become a painting. According to Heidegger, the world,

1 Detroit, which is among the poorest cities of the USA today; is one of the country's largest trading centers, with investments from automakers such as Ford, General Motors, and Chrysler in the 1800s. Industry struggles led to the closure of many of these factories, coupled with other problems facing the city, leading to a decades-long decline that has affected Detroit to date [9].

Table 1. Research design

Research Problem	The subject (human), which became apparent with Modernity, consumes nature directly or indirectly systematically, with the negative practices that it exhibits in a way that threatens even its existence in society and ecology while trying to make sense of and define the world again.
Literature Review	Research that questions the negative practices that have evolved into the systematic consumption of cities and, therefore, nature and how they can be affirmed; how? and by whom? Consequently, it was necessary to scan the questions in a way that covers the subject-object relationship that has changed with Modernity.
Research Hypothesis	Secularization should take place opposite of the planned obsolete architecture in the Anthropocene Era
Discourse Analysis and Descriptive Analysis: Presenting Findings	–The changing subject-object relationship and other developments after Modernity also determine future periods. –Systematic changes have evolved into the consumption of the object. –Planned obsolescence is one of the causes of systematic consumption. –Secularization takes place opposite the planned obsolete architecture and affirms the fate of decay.
Conclusion and Discussions	The decay and destruction of the planned obsolete architecture or its ability to act like a living thing has been associated with the practices of the new action and the methods of its unveiling.

which exists with nature and living things in its integrity, exists to the extent that it is taken into human life, entered into the living space, and transformed into life, hence revealed by humans [11].

Modernity, which emerged in the 17th century as a result of the Renaissance, which means rebirth, and the Reformation, which is a religious movement and affected the whole of Europe, removed the divine foundations at the center of society -at best, but leaving a place within private life- and replaced them with science and technology [12]. The products of rational, scientific, technological, and administrative activity conquered all areas of life, and the progress of the Industrial Revolution triggered notable changes in society and ecology, as well as intercontinental life [12; 13]. According to Heidegger (1977), even the field that the peasant regulates to cultivate differs from what it is now, and agriculture is now the mechanized food industry [14].

According to Alain Touraine (1992), it is the “reason” that activates science and technology, and Modernity, which is identified with “the victory of the mind”[2], also means the rebirth of the subject. For Modernity, which clarifies the mind and human as a subject, what matters is the re-interpretation of nature (the world) [12]. Nature, the object the issue tries to reinterpret, began to be perceived as something standing before the subject. It was seen and defined as a measurable, calculable, and reducible field to mathematical principles [15]. However, according to Christian de Portzamparc (2003), nature, reshaped in human subjectivity, has become increasingly artificial and the object of

2 Victory of the mind: The “reason” that distinguishes human beings from other living things, and thus the ability to think and become clear as a subject and re-make sense of the world [12].

calculation and power relations [7]. According to Nietzsche, God had died along with the emergence of Modernity, and he wrote the phrase "God is dead" for the first time in his work "Die Fröhliche Wissenschaft" published in 1882. Values that were valid until that day were destroyed by the "superior person." While the preservation of religious worship for the creation of a culture or the spread of civilization was resolved through encouragement, the creativity peculiar to the God of the holy book turned into the distinctive feature of human actions, and human creativity eventually took a leap into entrepreneurship in business [11]. In Peter Berger's words, the "sacred dome"[3] above us has been lifted, and people have begun to change the world by conquering it with their minds, creativity, and technology, not with the religion attached to the church [16].

With the removal of the sacred from society, there has been a period in which technology has changed the world, and the world has turned into a world-sourced capital area where human actions occur. In this respect, according to Europeans, Modernity necessitates making the past "from scratch," and the spirit of capitalism also bears this tendency [12]. Heidegger (1977) elaborates on this process by comparing the old windmill with modern technology. In the old windmill, the sails turn with the wind, completely surrendering to the wind (nature). However, the windmill does not need to be switched on to store the energy from the air currents.

On the other hand, the discovery of mines that meet the energy of modern technology requires digging the soil and throwing it out, that is, challenging the ground (nature). Therefore, the earth is a coal mine zone, and the soil is a mineral deposit [14]. The use of nature by humans as an unlimited resource by being challenged, carved, eroded, relocated, and transformed into something else, that is, towards its depletion, also reveals human activity. At the same time, reducing nature to measurable dimensions by planning and calculating by human beings indicates the beginning of the human-active Anthropocene Era.

4. CONSUMPTION OF NATURE

The concept of Anthropocene, whose etymological origin is Greek, consists of the combination of "anthropoid," meaning human, and "-cene," meaning new and latest. Anthropocene (anthropo+cene), a hybrid term that establishes a new relationship between nature and human beings, briefly means "New Human Age" [3, p.3]. The concept defines a geographical period in which humans dominate the entire ecosystem of the "world," humans consciously or unconsciously control various ecosystemic movements [17].

Everything attributed to nature (earthquake, flood, epidemics, etc.) in the Anthropocene Age, where the subject human being is active, is actually "human-made" in that the natural is no longer natural [6]. According to Barney Jeffries, human behavior paves the way for and spreads epidemics. People's close contact with livestock activities and wildlife changes in land use facilitate the spread of diseases, including new types of bacteria and viruses. Due to the rapid transformation of pathogens, close contact, deforestation, improper land use, etc., which cause transmission from wild animals to humans, trigger epidemics [18].

In the Anthropocene Era, one of the human practices that negatively affected nature, consciously or unconsciously, was planned obsolescence. Planned obsolescence, which emerged as a component in the revitalization of the economy by taking consumption at its center, has turned into concrete piles that cannot disappear in nature, from industrial products to structures/building groups, due to the uncontrolled speed of consumption. Being exposed to waste piles, nature has also been forced to grind more than it can digest. Industrial and chemical wastes accumulating in the atmosphere, oceans, and lands become dangerous living resources for living and non-living environments by being included in the ecological cycle. Idle buildings/construction groups also pose a problem in the urban environment with their potential to cause physical and psychological hazards. How planned obsolescence negatively affects architecture and ecology is explained in detail in the "Planned Obsolescence" section and is illustrated with visuals (Figure 1. and Figure 2.).

4.1. Planned Obsolescence

"Fashion is a form of ugliness so intolerable that we must alter it every six months."
Oscar Wilde

The concept of planned obsolescence is designing a product's life by its designer to get the consumer to buy the new one a little sooner than necessary. After the period defined by the designer, the product becomes obsolete or outdated. The concept is an economic strategy designed to revive the economy in the USA that collapsed after World War II [19]. Proposed by the economist Bernard London in 1929, it was mentioned for the first time in London's article "Ending the Depression Through Planned Obsolescence," published in 1932. According to London's theory of planned obsolescence, which argues that production can be balanced by consumption, the government should assign a lifespan to shoes, buildings, machinery, cars—all manufacturing, mining, and agricultural products—and these should be recorded. After the allotted time expires, all products (shoes, buildings, machinery, etc.) will be legally "dead." In this way, the difficulties in balancing the budget for the federal government will be easily solved, and it will

3 The removal of the sacred dome: The secularisation of the social universe as "form" and "content", that is, religion being removed from being the spirit and the shaper of politics, economy, science, art, culture etc. [16]

be a permanent source of income [20]. However, London's proposal was not accepted within the framework of the law [21]. Before Bernard London's suggestion, General Motors CEO Alfred Sloan Jr. was also considered for the American automobile industry, which reached saturation in the 1920s [19; 22].

The concept was revived at an advertising conference in 1954 by industrial product designer Brooks Stevens in a talk entitled "planned obsolescence." According to Stevens, who thought that aesthetic features of a product add value besides its quality, "obsolete is psychology based and is triggered by the desire to achieve better and more beautiful in a short time" [21, p.52]. Unlike London's, Stevans' planned obsolescence theory, which aims to revive the purchase impulse with the perception created in the consumer's mind, is not government-oriented. Still, it covers all manufacturers to ensure continuity in their businesses. According to Vance Packard, when modern marketing practices are examined, three different planned obsolescence methods are used to obsolete the product in the consumer's mind. In Packard's book "The Waste Makers," published in 1960, these methods are psychological, functional (or technological), and systematic obsolescence. Psychological obsolescence is the obsolescence of a usable product in terms of performance and quality by making the new one in the market more desirable characteristics. For example, it is psychological obsolescence for a newly purchased car to lose its value in the mind by comparing it with a vehicle of a different brand. Functional (technological) obsolescence is the obsolescence that occurs by determining the useful life of the products at the design stage before they are put on the market to ensure that the consumer receives the new product in a shorter time. Shortening the battery life of mobile phones or laptops is an example of functional obsolescence. Systematic obsolescence is the expiration of the previous product with the introduction of new versions of the products at regular intervals [22]. An example of frequent obsolescence is General Motors's production of new car models in short periods, turning car purchases into a social status rather than a necessity.

Planned obsolescence, which was applied by various manufacturers from automobiles to textile products between 1920 and 1960, has led to the thinning of the boundaries between natural and built environments over time. Industrial and chemical wastes, which started to accumulate in nature due to the unbalanced speed of consumption, began to be included in the natural cycle of living and non-living environments. These wastes that cannot dissolve in nature, occupying the oceans, soil, and air, have become dangerous living resources for the creatures in these environments (Figure 1).

In 1911, Reginald Pelham Bolton's book "Buildings for Profit" was published. The National Association of Buildings Owners and Managers team also prepared a "Building Autopsies" study in 1930. According to Bolton, buildings must be demolished and rebuilt thrice a century. In both studies, the wearing and obsolete periods of the structures are not related to their tectonic features but to the decrease in their economic values [21]. Therefore, the reduction in monetary value leaves the structures/construction groups in a tensity of life and death despite their usable features (Figure 2.). According to Katie Colford (2021), a building is considered worthy of repair if it is alive, and if they have to stand to be active, how their fall can be made meaningful – the aftermath of decay – should be discussed [24]. When the methods of making the decay outcome meaningful are questioned, one is secularization, which is laid down as a hypothesis in the research. It has been made visible through

Figure 1. Negative integration of planned obsolescence practices into the ecological cycle 1-2-3-4-5 [23].

Figure 2. The effect of planned obsolescence on architecture; 1- San Zhi Pod City (Taiwan), 2-Wonderland (China), 3-Wuchan Temple (Taiwan) and 4-5-6-Chisinau State Circus (Moldova) 1-2-3-4-5-6 [9].

purposeful samples that secularized architecture is reproduced by activation despite the negativity of decay in the extinction phase, thus affirming the fate of decay.

4.2. Secularization

The concept of Turkish "dünyevileşme" (secularisation), whose etymological origin is Arabic, is accepted to be a world derived either from the root of "dunuv," meaning "to be close" or from the root "denaet," meaning meanness and evil, [25, p.47]. The concept refers to having a close relationship with the world and taking a particular attitude towards the earth. Therefore, the concept gains meaning according to the meaning attributed to the word "world." It is the counterpart of "secularization". The concept, which has its etymological origin in Latin, the term "speculum" has a meaning that gives the connotations of "time" and "space" together. "Time" indicates that it is present and ready.

In contrast, "space" means earthly and mundane. Therefore, "saeculum" refers to the events in this world in this age and current time. That is, it means "contemporary events." The era to be emphasized is about a specific time and period as a historical process. This time-space connotation was historically formed from practices that arose from the fusion of Greco-Roman and Jewish traditions within Western Christianity. Seculum means "appropriate to earthly time, not divine time," so it is defined as "the liberation of human from religious and then metaphysical control over his mind and language" [25, p.48; 26, p.2]. The process of "secularization" emerged with the religious characterization of the great transformation (Modernity) that occurred with the Enlightenment, Renaissance, and Reformation at the end of the Middle Ages. Religious functions have transformed into secular social parts, and finally, the worldly has replaced the sacred [12]. Therefore, secularization meant for religion to lose its authority in society. The secularization process is when religious beliefs, practices, and institutions lose social importance, especially after the industrial revolution and modernization.

According to Harvey Cox, secularization is the switch of people's fundamental interests and orientations towards this world only, from outside to beyond and above this world [26]. Peter Berger, a sociologist of religion, defines secularization as the process in which the social and cultural spheres are removed from the influence of religious institutions and symbols [16]. Max Weber's definition of secularization as rationalization means opening the eye, or in other words, getting away from magic or mystery. Opening the eye also means that mystery or mysterious concepts become worthless. Mystery is also seen as something that needs to be conquered with the human mind, creativity, and products of technology [27].

As the religious worldview lost its social authority along with Modernity, the social and political organization has wholly ceased to be holy. Secularization has become worldly and a period in which technology changes the world by removing the sacred from society. It is the mind that drives science and its applications [12]. Science and technology are driven by reason, with the loss of authority of the sacred in the setting of order, the invention of machines to support human power, the increase of transportation networks, new business areas, etc. With innovations, it has started to reshape and make sense of the world socially and physically by advancing from daily life to intercontinental continents. In short, with the abolition of the sacred, the world has become a worldly-sourced production and capital area where human actions occur.

When giving examples of architecture becoming worldly, the Southbank area of London, where cultural buildings built between 1950 and 1960, now used as theatres, concert halls, and art galleries, come to mind. Three architects were appointed to evaluate the lower floor of the triple cultural complex, which consists of Queen Elizabeth Hall, Purcell Room, and Hayward Gallery. A concrete "landscape" consisting of slopes, steps, and planes was designed and built by the architects, but for various reasons, Southbank has fallen out of favor and begun to be used by the "others" of

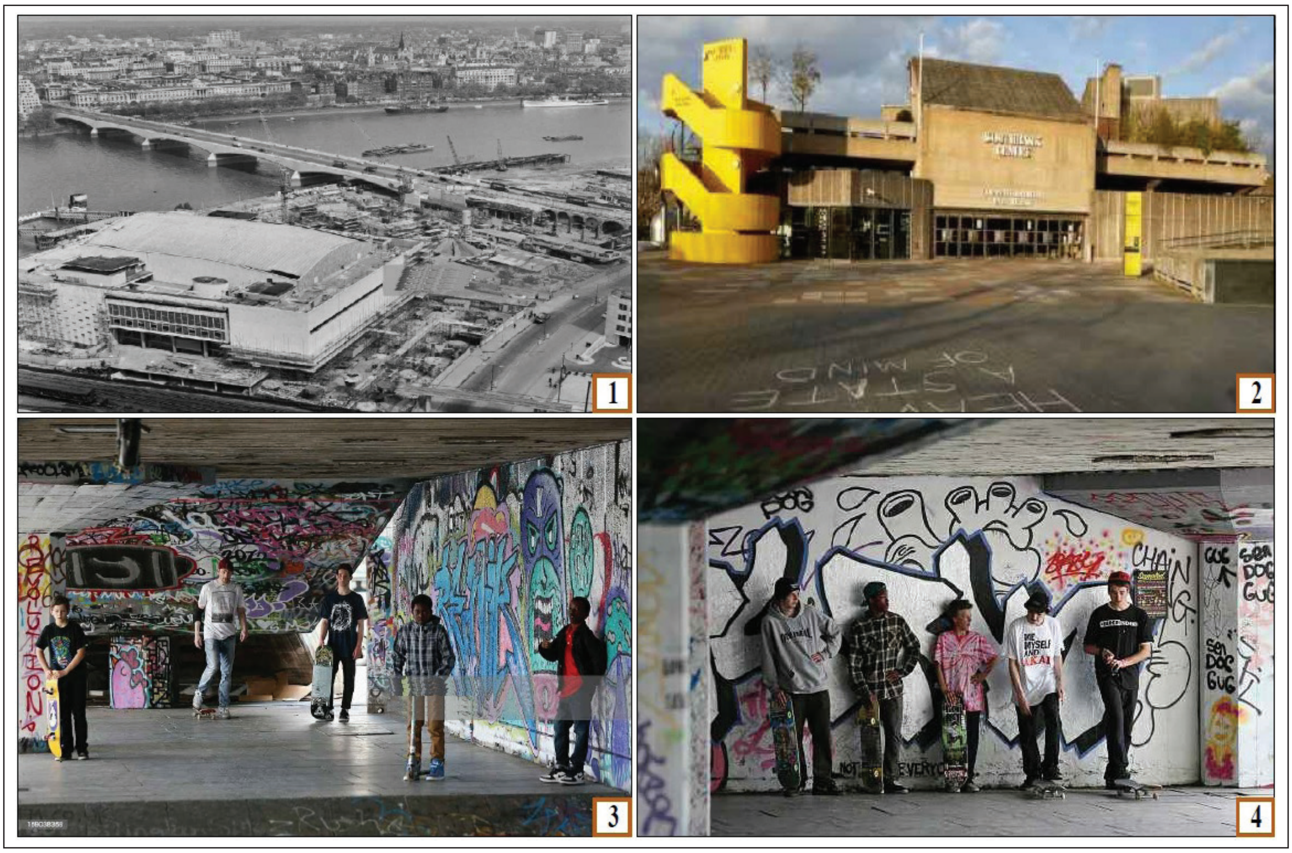


Figure 3. Activisation of Queen Elizabeth Hall in the Southbank area through graffiti art and skateboarding from construction to its current use 1-2-3-4 [28].

the city (Figure 3.). These "others" include skateboarders who inhabit this place specifically to do Undercroft. The origin of skateboarding is based on surfing, a nature sport. It proves that it can become "natural" instantly through the bodily relations allowed by the "artificial" one by taking place on concrete waves. Thus, while the manifestation of the public-private symbiosis resurrects an urban commonality that the parks try to forget, it also shows that greenery may not be enough for naturalness. While street skateboarding reproduces the urban space in unpredictable ways, it does this not by affirming a "public" space that Modernity constructs to legitimize the private space but by objecting to the symbiotic opposition [6]. Therefore, the actions and practices that enable re-activation by secularizing the architecture reproduce them despite the intangible-concrete negativities in their idle state.

5. PLANNED OBSOLETE OF MATERIAL

Buildings: wood, reinforced concrete, steel, masonry, adobe etc. They are named according to the material they are produced from and the production techniques. The average lifespan, production and modification costs, relations with the ecological environment, etc., vary according to the material produced and the production techniques. However, no matter what material or how they are made, even when all structures are built according to their technical/theoretical basic requirements, they encounter the fate of decay, which is the result of time, and unite on a common ground. The causes and durations of decay also vary according to the material produced and the production techniques.

On the other hand, planned obsolescence pushes architectures to a crisis of decay despite their usable features, regardless of material construction technique, and accelerates the depletion of their useful life. In terms of the quality of the materials they are produced in, etc., it is being planned, designed, and pushed into a decay crisis. For example, with the spread of industrial production after the Industrial Revolution, reinforced concrete technology became a material suitable for the obsolescence mentality of Modernity, and therefore, reinforced concrete structures with an average lifespan of 50 years were integrated with the destructiveness of Modernity.

According to John Urry (1995), places, especially visually, and things people find meaningful about a place, such as industry, history, building, literature, and environment, are reduced, finished, or consumed over time [29]. Planned obsolete, which is the subject of this research, pushes the reinforced concrete structures into a decay crisis before their biological life is over and is consumed due to various

Figure 4. The social and physical change of the city of Boston North End read from its facades; the image of everyday life overflowing the streets was replaced by landscape elements 1-2 [28].

reasons of deterioration from the inside and outside by leaving them out of use (Figure 4).

According to Katie Colford (2021), decay, the first step of planned obsolescence, means that the built environment is in a perpetual crisis. That is, by "decay crisis," it means that there is a turning point between recovery (life) and death in the built environment. She argues that the economic, cultural, and social values of the context determine how the "decay," which she calls a "decisive moment," is defined, validated, and handled - resulting in recovery (life) or death. Therefore, different stakeholders support signs of "vitality" such as structural resilience, vitality of the real estate market, historical significance, and cultural capital [24]. Space, whose consumption, like production, depends on social dynamics such as economy, capital, and culture, is continuously redefined, organized, and destroyed if necessary, creating environments where new relations can occur [30].

Jane Jacobs mentions in her book "The Death and Life of Great American Cities," published in 1961, that Boston's North End neighborhood is the city's worst slum, bad enough to be taught to planning and architecture students as a "megalopolis" in Harvard and North End MIT. However, the rotten neighborhood has become a place where liveliness is felt on its facades and streets over time (Figure 4.). While it is one of the districts with high tuberculosis death rates, It has turned into a district where crime, disease, and infant mortality are the least. But even though Boston North End is a livable place, it has to be transformed one day, according to planners and bureaucrats, because it's still a slum! [31]. As can be understood from the example, the government's capital, profit, and market-oriented capitalist approach plays a decisive role in the fate of the space.

5.1. The Secularization of Planned Obsolete Architectures

Economist Clarence Long, in his book titled "Building Cycles and the Theory of Investment," published in 1940, talked about the psychological life of buildings and stated that a building can fall out of favor even because of the style it carries [21]. For example, until the 19th century, architecture adopted the principle that buildings survive thanks to load-bearing walls. Although various decorative elements were applied to these surfaces, the walls played a crucial role in the structure. However, with Modernity, "solidity," the symbolic feature of stone and wall, fell out of favor, and architecture suddenly consisted of a building skeleton holding glass surfaces. When the logic of industrial construction became dominant, the human scale lost its importance, and the human proportions in the Classicism and Humanism eras were quickly replaced by cages and modular systems [32].

According to Tschumi (1994), architects do not like the death-like side of life. Hence, decaying constructions are incompatible with both the ideology of Modernity and what can be called conceptual aesthetics. But the Modern movement loved both life and death. Life has been counted as the denial of death, which goes beyond the idea of death and encompasses the mold of rotting flesh. However, the painful aspect of death is due only to the phase of decomposition because the appearance of white bones is not like the unbearable sight of rotting flesh, and architecture has begun to reflect these deep-seated feelings. Decaying buildings were deemed unacceptable, but the dry, white remnants were well received. Villa Savoye was not as attractive when the gypsum plaster on the concrete blocks was shedded [32].

According to sociologists such as Henri Lefebvre (1974), city space is social and is produced by society in that it is shaped by the culture of their geography and the communities in which they exist [1]. For this reason, in this research, random examples were selected from around the world and from Turkey to make it visible that planned obsolete architectures have become secularized, regardless of material, production technique, location, geography, and scale. Therefore, buildings/building groups produced from

Figure 5. Interior and exterior images of the first use of Hawthorne Plaza Mall 1-2 [34].

Figure 6. The current state of the building and its re-activation practices: movie set, graffiti art, and skateboarding 1-2-3-4-5 [35].

different geographies, scales, and materials were selected. Hawthorne Plaza Shopping Center (California) and Banker Han -Banker Kastelli- (Turkey) were chosen as purposeful samples on the micro, i.e., building scale, and Doel Village (Belgium) and Houtouwan Village (China), on the macro, i.e. urban scale. While selecting examples, Being idle due to human-determined situations such as economy or fashion, being produced spontaneously (by human nature) without technical-theoretical intervention, and being maintained as living things with their current potential were used as criteria.

5.1.1. Hawthorne Plaza Mall, Hawthorne, California

Hawthorne Plaza Mall is located in Hawthorne, California, one of the third most significant cities in the USA. The shopping center opened in 1977 (Figure 5.) to revive the city of Hawthorne and has 134 stores. It was closed entirely in 1999 due to the economic crisis in the 90s. The shopping center, which was closed due to the decline in the socioeconomic values of the region where it is located, started to be used as a movie set after it was closed. The building, which first appeared in Evolution in 2001 and then in Minority Report in 2002, was saved from destruction thanks to these two films, which enabled it to be used as a center of attraction. Many movies and television programs, such as The Fast and the Furious: Tokyo Drift (2006), Teen Wolf (2011), Beyoncé's "Superpower" music video (2013), Taylor Swift's "…Ready?" the music video (2017), were shot here as well. Apart from being a movie set, it is also used by graffiti artists and skateboarders (Figure 6.) [33].

5.1.2. Banker Han (Banker Kastelli), Istanbul, Turkey

Banker Han (Banker Kastelli), the financial center of bankers in Galata, home to many banks and insurers in the beginning and lent to the state during the Ottoman period in the late 19th century and 20th century, is located on Banker Street. Banker Han (Banker Kastelli) (Figure 7.), located on the street that was the financial center of

Figure 7. The first use of Banker Han (Banker Kastelli) [37].

Figure 8. Banker Han (Banker Kastelli) interior use by graffiti and stencil artists 1-2 [36].

the Ottoman period, lost its vitality in its early stages and became out of use. In its derelict state, it was conquered by graffiti and stencil (spray paint) artists (Figure 8.). The relevant municipality (Beyoğlu Municipality) decided to transform the space into a gallery space by supporting the methods of graffiti and stencil artists to reproduce the space. With the support of Beyoğlu Municipality, Akçalı Boya, Koridor Contemporary Art, and StreetArt Istanbul, each floor of the seven-floor building was turned into an exhibition space by a team of approximately 30 graffiti and stencil artists. The exhibition called Morphosis lasted from June to July 2009. The building, which was for sale at the time of the exhibition, has been restored and is used as a hotel today [36].

5.1.3. Doel Village, Belgium

Doel Village is an island surrounded by land deliberately flooded until the 1700s. At its peak by the 1970s, the village was home to around 1,300 people and several historic

Figure 9. Images of the period when Doel Village began to be abandoned 1-2-3 [38].

Figure 10. Village of Doel, whose streets were conquered by graffiti art, Belgium 1-2-3-4-5 [9].

buildings, including some of the oldest in Belgium. The country's oldest stone windmill also resides in a historical inn and a village school. In 1965, the Belgian government announced plans to expand the Port of Antwerp, Europe's second largest port, but Doel residents had to leave the area for the project to materialize. From the 1970s to the mid-1990s, as the government and residents debated plans for the village to be demolished, the village was revived in 1995, only to be formally demolished four years later (Figure 9.). In 2007, a group called "Doel 2020" decided that the best way to save the village, which had about 350 residents, was to turn it into a street art venue. This effort has transformed many of Doel's abandoned buildings into blank canvases for those wishing to showcase their creativity through graffiti, works of art that have made it a popular place for urban explorers to visit as well (Fig. 10.) [9].

5.1.4. Houtouwan Village, China

Houtouwan Village is located in eastern China in the Shengsi Archipelago. The village, consisting of families engaged in fishing, had a population of more than 2000 in the 1980s (Figure 11.). However, in the 1990s, it was abandoned due to its distance from the city. For example, to get from Houtowan to Shanghai, one needs to take a taxi over the Sanqiaoshan Great Bridge connecting Shengshan Island and Gouqi Island, then take a three-and-a-half hour boat ride from Ganxie Port on Gouqi Island to Shengjiawan Port, followed by an additional two-hour journey is required to reach Shanghai. This makes it difficult for the villagers to access basic needs such as food and health, so transportation has created the beginning of the village being abandoned and idle. In addition to transportation, changing demands in the fishing industry have also required fishermen and their families to move. Abandoned due to transport and changing current needs, Houtouwan Village was conquered by nature over time and turned into a center of attraction for photographers and tourists (Figure 12.) [9].

5.2. Destruction of The Object in The Subject Activity

According to Lefebvre (1968), a starting point is required to present and reveal the urban problem, and this is the industrialization process. When a distinction is made between the determiner and the determined, industrialization appears to be the determiner, while the incrementally intensifying problems of urban culture are selected [40].

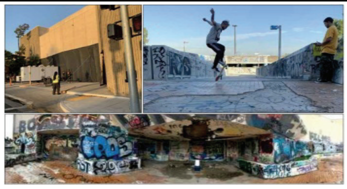
Figure 11. The situation of Houtouwan Village before it was conquered first by nature and then by humans [40].

Figure 12. Houtouwan Village, China 1-2-3-4 [9] was conquered by nature before human actions such as hiking photography.

The industrialization process has deepened and clarified the detachment from nature. However, to understand the beginning of the rupture and the subject-object relationship, which has an active role in the process that evolves into the systematic consumption of nature, the research has found it appropriate to start with Modernity, which has an active role in the process that develops into the frequent consumption of nature.

According to Modernity, the subject is the one who seizes power, gives meaning, names, dominates, and oppresses [15]. Seeing the object as a field that is measurable, calculable, and reducible to mathematical principles by the subject has led to the process of being systematically

Table 2. Findings

Purposeful Samples	Subject (Human) Object (Nature)	Subject (Human) Object (Object)	Subject (Object) Object (Object)	Objectification of All Components Process
Micro and Macro Scale Examples of Architecture	**Planning Strategies**	**Obsolescence Reasons**	**Re-Activation Practices**	**Objectification Actions**
	Hawthorne Plaza Mall	Problems associated with the social and economic decline of its position	-Film set -Skateboarding sport -Graffiti art	
	Banker Han (Banker Kastelli)	Regional economic downturn	-Graffiti art -Stencil art -Exhibition Gallery	
	Doel Village	Authority pressure to pave the way for port expansion project	-Photography -Walking sport -Graffiti art	
	Houtouwan Village	Problems with its location and changing business trends	-Landscape -Photography -Walking sport -Graffiti art	
He plans →		**He obsolescences**	→ **He makes secular**	

shaped by the subject. However, when even the aspects specific to the nature of the object are determined by the issue, the shaping process has started to objectify the subject while bringing the object to a state of exhaustion. The answer to how planned obsolete architecture becomes secular is explained with discourse and descriptive analysis through purposeful samples (Table 2)

Table 2. shows the findings of 1-Hawthorne Plaza Shopping Center and 2-Banker Han (Banker Kastelli) on the micro-scale, 3-Doel Village, and 4-Houtouwan Village on the macro scale, which are the purposeful samples of the research. Objects (buildings/construction groups) designed by the subject and put out of use due to wear and tear again by the subject, regardless of its scale, be it micro or macro, were able to be reproduced and acted upon with the subject's mind and creativity, despite the abstract and concrete negativities, in contrast to the technical-theoretical applications of architecture and engineering. Actionable states are associated with reproduction methods and practices. The facades are used as the canvas for graffiti artists, the landscape for professional or non-professional photographers, the floors as a platform for skateboarders, a set for film crews, a stage for those dealing with street music, and a landscape for those who love nature walks. Activation practices are usually independent of periodic periods, specific rules, and rules, that is, by the nature of the freedom of the space. The practices that revealed the re-activation in Hawthorne Plaza Shopping Center and Banker Han (Banker Kastelli) were not limited to the building in Doel Village. They also brought the reproduction to the urban scale with

its streets and avenues. In the example of the Houtouman Village, unlike the others, the building group produced by the human subject was objectified by nature and then again objectified and acted upon by the human. The village has been transformed into landscape art by nature, forming the basis for human activities such as hiking and photography.

In the research, it is seen how idle spaces are transformed spontaneously through daily activities and nature itself, that is, how places that are out of use are revitalized by humans or nature. The concept of secularization has also defined revival. In the face of the planned designers, architects, politicians, etc., urbanites and nature reproduce the space. These natural, spontaneous new uses of space provide an inquiry into the abandonment of buildings through the obsolescence of building technologies.

6. RESULTS AND DISCUSSION

Existing and worsening problems in society and ecology, such as inequality in access to basic needs such as education, shelter, and food, climate change and global warming, depletion of natural resources, and environmental and economic crises, require new searches in the discipline of architecture, which is responsible for the production of built environments, as in other fields (materials, construction techniques, land use, etc.) While social and ecological problems that trigger each other turn cities into disaster places, they also systematically consume nature, which has no alternative. Therefore, approaches such as equal access to basic needs, effective and efficient use of existing resources, and minimizing wastes preventing nature from renewing itself are central to contemporary architectural understanding.

It has been demonstrated that negative practices in human activity, such as planned obsolescence, which evolves into the consumption of buildings/building groups from industrial products, and cities and nature in their integrity, can be affirmed with solutions in human activity with reason and creativity. The topics discussed in the research are visible through four examples of how modern buildings built in the destructive understanding of Modernity but obsolete and abandoned over time were revived in the Post-Modern period and are reminiscent of anarchistic or guerrilla architecture. Buildings and residential areas occupied by humans and nature are similar to the examples discussed. The transformation and reproduction of buildings open to destruction by non-architect actors such as skateboarders, graffiti artists, and nature, in other words, the new usage forms that emerged in the face of current neoliberal policies and the economic system, offer an inquiry about cities that are in the process of continuous destruction and construction. Therefore, this research exhibits that by reversing the consumption of architecture, positive feedback can be achieved in society and ecology through the spaces that can be reproduced despite their unpredictable uses in architecture, engineering, and other fields -especially with the richness of science and current technology- it has opened up the questioning of the reverse of how the material or function are rendered dysfunctional.

ETHICS

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

DATA AVAILABILITY STATEMENT

The authors confirm that the article's data supporting this study's findings are available. Raw data supporting this study's result are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The author declares that they have no conflict of interest.

FINANCIAL DISCLOSURE

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Research Article

The influence of microwave curing on the strength of silica fume-added fly ash-based geopolymer mortars

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ABSTRACT

Geopolymer concretes a substitute for traditional Portland cement as a more environmentally sustainable alternative. In addition, one of the most significant advantages of geopolymer concrete is the high setting speed that can be achieved with thermal curing, that is, the short curing period. Research on geopolymer concrete has focused on curing, where curing is usually done with conventional ovens. Microwave curing initiates heat generation at the molecular level, which results in a minimal heat increase on the surface of the specimens compared to traditional thermal curing methods. In addition, it provides internal, rapid, and homogeneous heating and rapid strength development. This study is based on research that examined the effect of microwave cure on the compressive strength of silica füme-modified geopolymer mortar. In the study, sodium silicate and sodium hydroxide were used for activation, and first of all, fly ash substituted geopolymer mortar specimens were subjected to conventional thermal curing in an oven. On the other hand, the mortar specimens with the same composition were subjected to short-duration (10 minutes) microwave curing at power levels of between 200-600 W. When the results were compared regarding compressive strength, void and percent water absorption, UPV, and SEM-internal structure examination, it was revealed that microwave curing could be used faster than the conventional oven curing method in silica füme-added fly ash-based geopolymer mortars. This research can be considered an essential step for further optimizing and popularising geopolymer concrete and microwave curing and proposes a method that should be considered in the future development of more sustainable construction materials.

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1. INTRODUCTION

Concrete has long been a fundamental building material extensively utilized in the construction and building sectors. Traditionally, concrete is formed by blending aggregates, water, and Portland cement through a process known as hydration. However, the production of Portland cement is associated with a significant release of CO_2 into the environment, posing environmental hazards and sustainability concerns. It's estimated that every 1 kg of cement production emits 0.87 kg CO_2 [1]. Consequently, the quest for alternative binding agents has become crucial, attracting

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the attention of numerous researchers. At this juncture, geopolymer mortars have emerged as a solution, reducing carbon emissions by up to eighty percent.

Additionally, they lower the energy consumption related to cement production by around thirty percent [2]. Another advantage is its contribution to sustainability. Geopolymer concretes can be produced by activating many waste materials such as fly ash (FA), metakaolin, blast furnace slag, silica füme (SF), and rice husk ash [2–5]. Moreover, the most frequently used ones are FA, metakaolin, and slag. FA and slag SF, which can be used in geopolymer mortars, are recyclable materials obtained as by-products.

Fly ash, a fine powder derived from burned coal or coal slag typically forms during thermal power generation and serves as a primary binder component in geopolymer concrete production. Using fly ash in geopolymer concrete helps two primary purposes: it aligns with sustainability goals, providing an advantage to geopolymer concretes. Secondly, it exhibits activatable binder properties. By repurposing burnt coal or coal slag—otherwise considered waste—fly ash's incorporation in geopolymer concrete production aids in conserving natural resources and mitigating environmental impacts. Simultaneously, as a binding material in geopolymer concrete, fly ash actively solidifies through hydraulic reactions, resulting in a durable structure. The aluminosilicate compounds within fly ash interact with alkali activators, generating a polymeric structure that fortifies the concrete. Consequently, geopolymer concrete boasts elevated compressive strength, improved chemical resistance, and reduced permeability.

FA standards (ASTM C 618 and TS EN 197-1) divide FA material into two groups. ASTM C 618 defines pozzolanic ash with a CaO percentage below 10% (low calcareous and $SiO_2+Al_2O_3+Fe_2O_3>70\%$) for class F FA, while the percentage of CaO for class C FA is more than 10% (high calcareous). And $SiO_2+Al_2O_3+Fe_2O_3 >50\%$). Class C FAs are pozzolanic and binder [6]. Conversely, TSE divides FAs into siliceous (V) and calcareous (W) groups. While V class FA is defined as reactive lime and active silica (CaO<10%, SiO2>25%), W class FA is defined as containing active limestone and reactive silica (CaO>10%, SiO2<25%) [7].

Like FA, SF can be used at different rates in geopolymer mortars. It has advantages such as improving the mortar's mechanical properties, reducing its porosity, improving its properties, and contributing to thermal comfort, depending on the purpose. Silica fume is a fine powder in which silica or silicon dioxide (SiO_2) particles are suspended in the air. It is usually formed by the oxidation of silicon or silicon compounds at high temperatures. Silica fume consists of very fine particles; this fine particle structure provides a homogeneous material distribution. High surface area increases chemical reactivity and improves adhesion. This increases the adherence, making the concrete more durable and cracking-resistant. In addition, since it is generally a chemically inert material, it contributes to the chemical stability of conventional concrete at high temperatures compared to geopolymer concrete. The SF used in this study was added to the mixture due to this thermal stability feature. Microwave curing tends to increase in temperature at high powers, causing the specimen to crack. Adding SF to the mortar is aimed at partially preventing these microcracks. In addition to all these material properties, the use of FA and SF in this study supports research to help reduce the amount of environmental waste and increase environmental sustainability.

The most frequently used activators are sodium hydroxide, potassium hydroxide, and sodium silicate.

The reaction takes place in the following steps in FA-added geopolymer mortars.

- Use of activators to activate Al and Si atoms
- Combination of solid FA particles with Al and Si atoms to form aluminosilicate gel
- Polymerization formation
- Condensation

Calcium silicate hydrate gels are also found in conventional Portland cement products. For example, the most common activators in the gels that provide the binder hydration process are sodium hydroxide, potassium hydroxide, and sodium silicate [8].

The reaction and geopolymerization process is directly affected by the curing temperature and activator concentration [9]. Polymerization takes place very slowly in geopolymer mortars that are left to cure with their heat of hydration. For this reason, in most cases, the curing environment is heated by an external heat source without losing the moisture of the mortar. However, these methods generally require 1-7 days of curing. On the other hand, microwave ovens use electromagnetic microwave energy to emit vibrations from the inside out at the molecular level and provide heating very quickly. This makes them much more suitable for prefabrication. The general working process of microwave ovens starts with generating microwave energy by a microwave generator inside the oven. Next, an unloader (magnetron) tube inside the oven receives the generated microwave energy. The magnetron tube converts electrical energy into microwave energy and spreads this energy inside the oven, creating a microwave field. The microwave field focuses on the food or material and creates a vibration at the molecular level. This molecular vibration causes the water molecules in food or materials to accelerate and heat up. The heated water molecules also heat the other molecules in their surroundings, heating the material or food [10–12].

Among the thermal curing methods used in the literature, there are studies of oven curing, hot water curing, autoclave curing, steam curing, curing methods, and a few microwave curing methods [5, 13, 14]. However, there needs to be a more detailed investigation in the literature regarding the strength aspects of FA-based geopolymers, and no research has been found that specifically explores the reaction of SF-incorporated and FA-based geopolymers with microwave curing. In this sense, this study will likely fill an essential gap in the literature and make a strong contribution. For this purpose, FA-based geopolymer mortars containing SF additive were prepared in the study. It was determined that the effects of conventional oven curing and microwave curing on compressive strength were revealed, and optimum microwave power was determined.

2. EXPERIMENTAL WORK

Geopolymer mortars represent resilient and ecologically sound construction components that offer a viable substitute for conventional cementitious materials. These matrices are engendered through the amalgamation of fly ash, commonly augmented by alkali activators sourced from industrial residuals. In the context of this investigation, fly ash (FA) and silica fume (SF) were harnessed as principal binders. The activation process involves the introduction of sodium silicate and sodium hydroxide, serving as pivotal alkali activators, while the geopolymer mortars are constituted utilizing RILEM sand. The Class F variant of fly ash employed herein is a derivative stemming from the operational endeavors of Cenal Elektrik Üretim A.Ş. The chemical attributes of the fly ash are enumerated in Table 1 for reference and scrutiny.

Antalya Eti Krom furnished the SF. The chemical characteristics of the SF are shown in Table 2.

Other materials used in mortar are CEN-Standard RILEM Sand (EN 196-1) as aggregate. Table 3 shows the granulometry of the sand. NaOH (%99 purity, prepared in 12 moles by water dissolving with water) and Na_2SiO_3 (ρ:1,35 g/cm^3 at 20°C) are the activators. The specimens were prepared using fly ash+silica fume=1 part (90% FA+10%SF), 3 parts sand, and 0.5 part activator ratio. After allowing a 12 M NaOH solution made with water to calm fully, NaOH and Na_2SiO_3 were combined at the room's temperature in a 1:2 ratio.

First, mortar specimens were prepared for conventional and microwave oven curing. For this purpose, sand and pozzolans put into the mixer were mixed for 1 minute, then activators were added and mixed for two more minutes. It was placed in 50x50x50 mm molds for compressive strength

Table 3. The granulometry of the sand

Sieve Square Mesh (mm)	Cumulative Remainder (%)
2	0
1,6	7
1	30
0,5	67
0,16	87
0,08	99

Table 1. Chemical analysis of the FA

Chemical Components	SiO_2 (%)	Al_2O_3 (%)	MgO (%)	SO_3 (%)	Fe_2O_3 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Total Alkali	Specific Gravity	Activity Index 28 days (%)
Analysis Results	59.37	21.40	2.108	0.202	8.620	3.237	1.267	1.804	2.45	2.38	78.8

Table 2. Chemical properties of the SF

Chemical Components	C_2O3	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Analysis Results	%3,5-5	%70-80	%1,17-5,0	%2,55-4,10	%1,06-1,80	%8,05-9,9

Figure 1. Images from the preparation stages of the specimens.

Figure 2. The conventional oven.

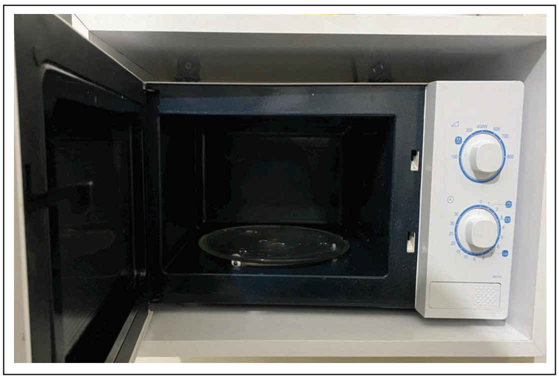


Figure 3. The microwave oven.

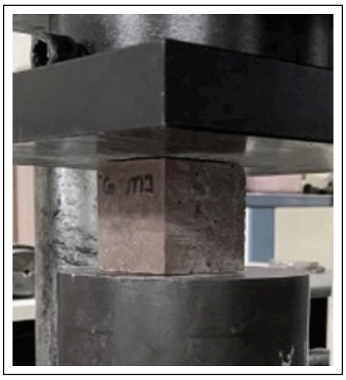


Figure 4. The compression testing machines.

testing (Fig. 1). It was kept in the mold for 24 hours at room temperature and wrapped airtightly. Afterward, some of the specimens removed from the mold were cured in a conventional oven at 60°C for 30 minutes, 60 minutes, 90 minutes, 24 hours, and 48 hours. Other specimens that needed to be cured in a microwave oven were kept for 10 minutes at 200 W, 300 W, 400 W, 500 W, and 600 W (Fig 2 and 3).

All cured geopolymer mortars were kept at room temperature without losing their moisture until the 7th day. They were subjected to a compressive strength test on the seventh day (Fig. 4). After this stage, all specimens subjected to microwave curing were compared with those cured in a conventional oven for 24 hours regarding void ratio, water absorption percentage, and UPV transmission rate.

Only the 24-hour curing comparison is considered adequate after this section, as many conventional oven-curing studies have been conducted in the literature. The experiments were performed according to TS-EN 12504-4 and TS EN 1015 -11 standards, respectively. These experiments aim to see the changes in the specimens' void ratios and water absorption values after microwave curing at different powers. Then, the samples exposed to conventional and microwave curing were examined by SEM images.

Compressive strength tests of 50 mm cube geopolymer mortars were performed at a load rate of 0.5 N/mm^2/second and on the 7th day according to TS EN 12390-3 [21] standard. Three specimens were tested for each, and mean values were used to indicate the results. The standard deviation between specimens was 2.5% (Fig. 4)

3. RESULTS AND DISCUSSION

In this study, which aims to investigate the strengthening of geopolymer mortars with the help of microwave ovens, the prepared mortars were first cured in the microwave oven at different Powers, and the temperatures of the hardened mortar specimens were measured. These temperatures are significant for the interpretation of the results. Then, these geopolymer mortars, cured in conventional ovens at different times and different powers in the microwave oven, were compared in terms of their compressive strength. Afterward, the analysis of the internal structure of the mortars after hydration was made by SEM internal structure imaging method, and all the results are given below.

As a result of the measurements made with an infrared thermometer, the temperatures of the specimens rise above 200 degrees after 10 minutes of microwave curing. Since temperatures above this degree are thought to damage the mortar's microstructure, the microwave oven's cure time is limited to 10 minutes. This effect is confirmed by compressive strength results (Fig. 5).

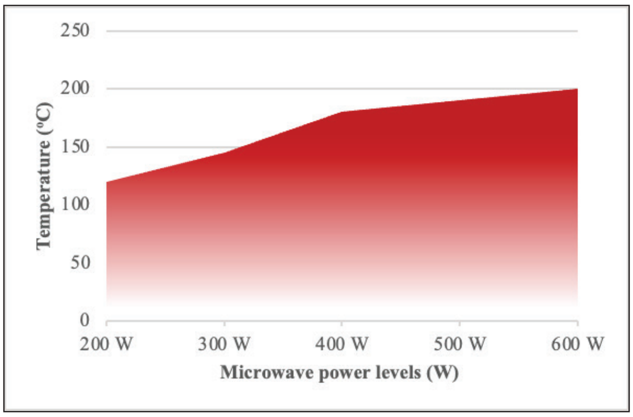


Figure 5. Final temperatures of the specimens after 10 minutes of microwave cure.

Fig. 6 shows the compressive strength test results of the specimens cured at 60°C in conventional ovens for 30 min, 60 min, 90 min, 24 h, and 48 h. According to these results, the strength only reached 15.8 MPa after 30 minutes of oven curing, while it reached 73.1 MPa after 48 hours of thermal curing. The regression between the curing time and compressive strength showed a positive increase. This situation has been demonstrated in many studies as the positive contribution of kiln curing to the hydration process in geopolymer mortars [3, 15].

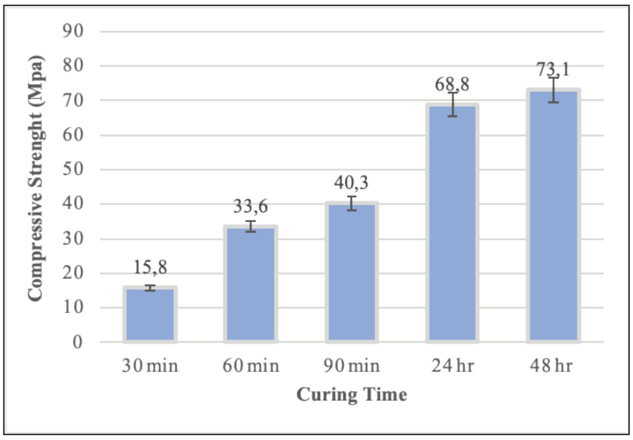


Figure 6. Compressive strength-curing time graph of the specimens after 60°C oven cure.

However, this effect corresponds to a limited point. Even in 90-degree oven curing, the maximum strength could slightly exceed 80 MPa, and the final strength ended in this range for any curing method [1, 16–18]. This situation revealed that the values obtained at the end of the traditional thermal curing given here could be affected by a maximum of 40%, independent of the content and curing temperature, but depending on the curing time variable [19, 20].

Graytee et al. (2018) found the conventional curing strength for 24 hours to 52 MPa without adding silica fume, which was measured as 68.8 MPa in this study (Fig. 7). This difference is due to the substitution of silica fume. The 48-hour strengths in both studies are closer to each other.

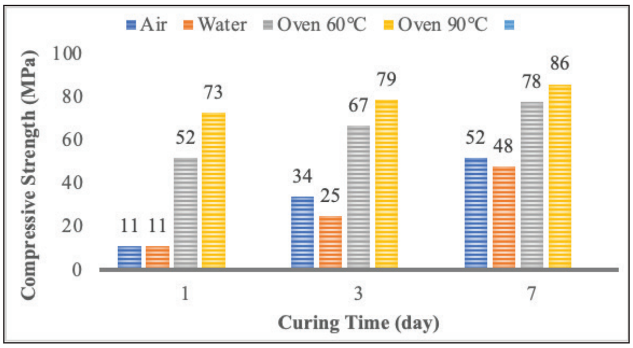


Figure 7. Compressive strength of fly ash-based geopolymers treated with different cures [18].

The compressive strength values given in Fig. 8 and measured after 200W, 300W, 400W, 500W, and 600W microwave curing did not distort this general view. The specimens cured in a microwave oven at 200 W for 10 minutes reached a strength of 39.5 MPa, while the other values were 67.7 MPa, 58.7 MPa, 50.2 MPa, and 44.8 MPa, respectively. The specimens with the highest compressive strength were cured at 300 W power. This value is approximately 8% below the strength created by the 48-hour thermal curing value, which shows the highest strength in conventional thermal curing.

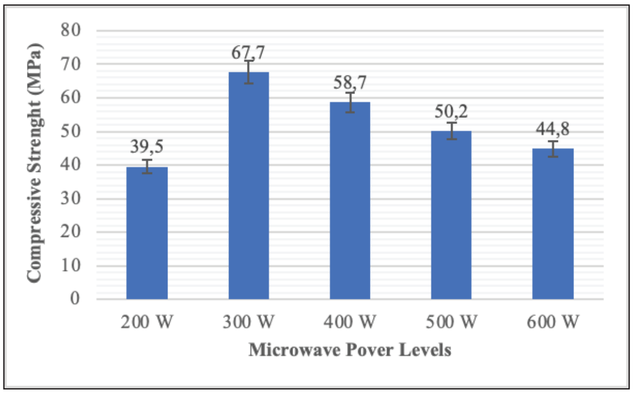


Figure 8. Compressive strengths after microwave cure of the specimens.

In another study where microwave curing was applied for 15 minutes on a geopolymer mortar specimen containing only fly ash, strengths of 59, 72, 67, and 54 MPa were obtained at 200, 300, 400, and 600 W, respectively. [18]. These strength differences have shown us that it is important to do the curing in sufficient time and at the optimum temperature and that it can change the initial and final strengths. Still, it has been observed that the curing time is similar between the specimens at maximum strength. When the two studies are compared, it is thought that the difference between the compressive strengths due to curing times is 5-10% at most. Since no research in the literature includes mixing ratios that match precisely with this study, it is necessary to conduct more comprehensive research to obtain more detailed information on this subject.

According to the experimental data of the study, curing at 400, 500, and 600 W power values above 300 W resulted in reductions in compressive strength exceeding 10%. El-Feky et al. (2020) reported that a 25-30 MPa compressive strength occurred in microwave-curing slag-based geopolymer specimens performed for 6 minutes with a power value of 720 W [21]. This result shows that high-power curing damages the structure of geopolymer mortar, consistent with our study. In addition, in cases where the curing exceeds 300 W, the increase in temperature to values close to 150 degrees causes the moisture loss of the specimens to be high, which leads to the formation of cracks in the specimens (Fig. 9). Crack formation is possible due to rapid moisture loss at high temperatures. In cases where curing is done much faster than the conventional method, such as microwave curing, it may pose serious risks and affect the concrete strength [22]. When this risk is controlled, microwave curing can provide an alternative to the traditional method for silica fume-added fly ash-based geopolymer mortars.

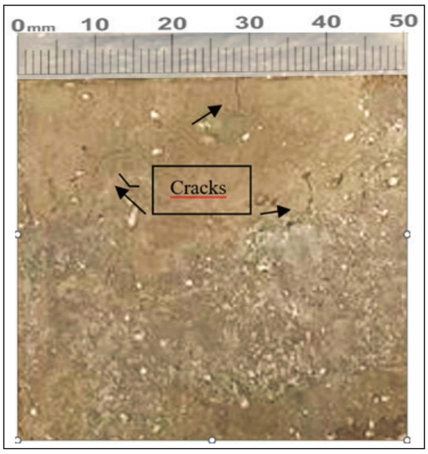


Figure 9. Crack image of specimen cured at 600 W.

Considering the compressive strength test results of curing the specimens with microwaves at different powers, Fig. 7 and 9 show that the activation of fly ash-based silica fume-added geopolymer mortars could develop faster and better strength with microwave oven curing without heat cure.

The measured void percentages, water absorption percentages, and UPV values of the specimens are shown in Figure 10. The void ratios vary between 14.33% and 20.12%, the water absorption ratios vary between 6.90% and 11.47%, and the UPV values range between 2388 and 2734. As seen in Figure 10, while the highest UPV value is in 300-watt microwave curing, this curing condition also shows a close correlation with the lowest void and water absorption values (Figure 11). This value also gave the highest value in terms of compressive strength. The second best-performing specimen was 24-hour oven curing for all four parameters. The compressive strength-UPV correlation graph of the specimens also confirmed a relationship between the void amount and strength of the specimens, together with the high correlation value in this sense. As it is known, as the UPV value increases, the material's void ratio increases in the compressive strength [23–25].

The specimens that gave the worst results in these tests were those cured at 200-watt power and those cured at 600-watt power. According to this result, 200-watt power is insufficient for hydration, and 600-watt power overheats the specimen, causing cracks and disrupting stable calcite structures. SEM images of critical specimens were taken to support this interpretation.

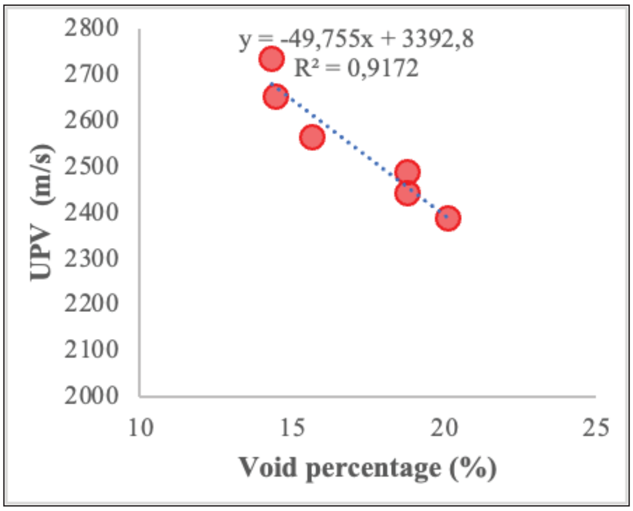
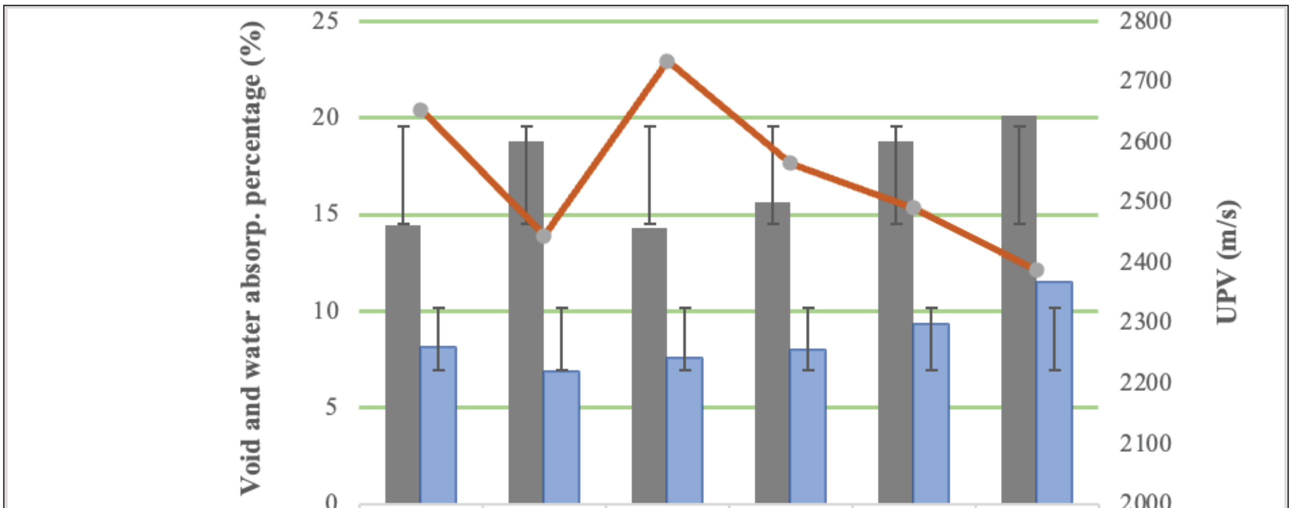


Figure 11. Correlation between void percentage and UPV of specimens.



	24 h OC	200 W MC	300 W MC	400 W MC	500 W MC	600 W MC
Void percentage (%)"	14,45	18,8	14,33	15,64	18,78	20,12
Water absorp. perc. (%)	8,13	6,90	7,55	7,96	9,36	11,47
UPV (m/s)	2653	2445	2734	2565	2491	2388

Figure 10. Void, water absorption, and UVP pass rates of the specimens.

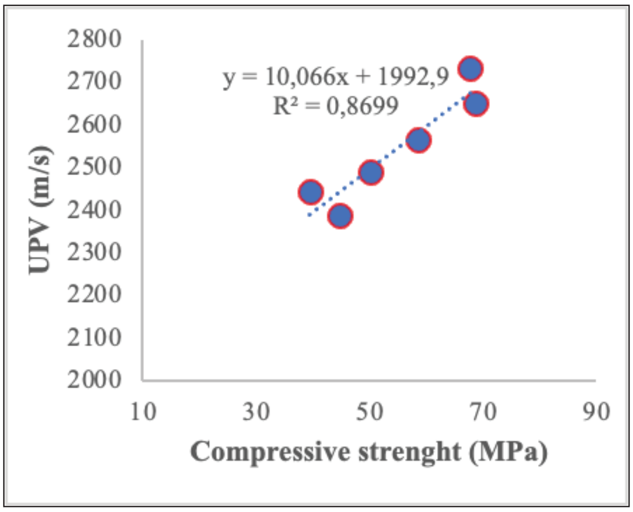


Figure 12. Correlation between compressive strength and UPV of specimens.

SEM micrographs of the specimens are shown in Fig. 13, 14, 15, and 16. SEM analysis was performed after the compressive strength tests to examine the microstructural changes of the geopolymer specimens.

In the control specimen, whose internal structure is shown in Fig. 13, gel formation on fly ash particles and hardened structure with micro gaps filled with silica fume have indicated the breakdown of the glassy phase in the alkali solution. Additionally, partly reacted fly ash particles were also seen.

As shown in Fig. 14, in the specimens with the highest strength cured 300 W, there are $CaCO_3$ structures that have hardened due to microwave radiation from fly ash and accelerated dissolution of Si and Al species. This explains the increase in compressive strength.

Figures 15 and 16 show that fissures, dissolved structures, and a constant accumulation of geopolymer products filled fly ash voids were detected. Moreover, rapid curing and evaporation caused cracks to appear.

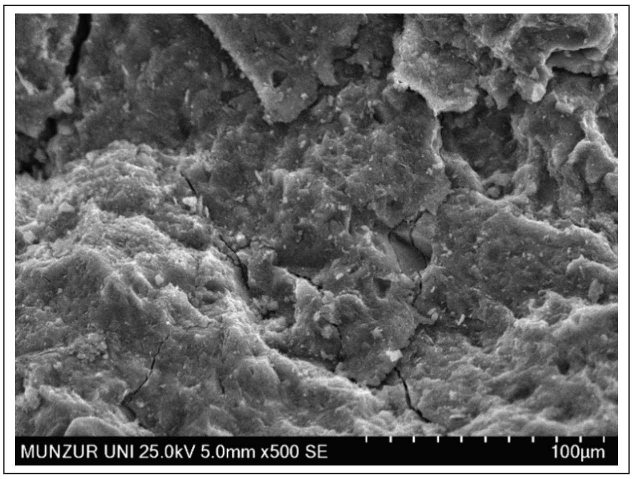


Figure 13. 60°C oven cure.

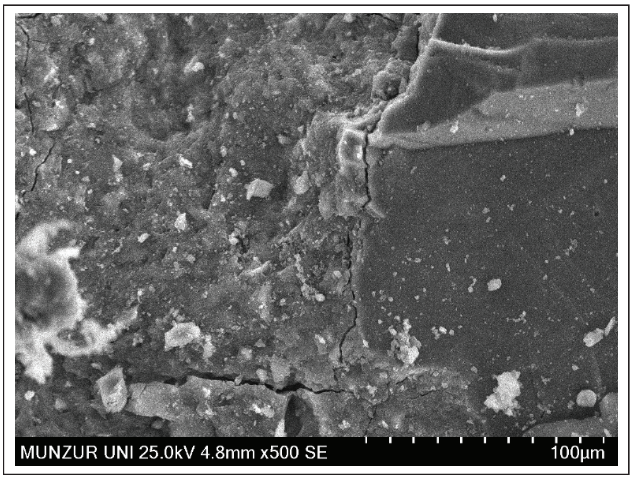


Figure 14. Microwave cure-200 W.

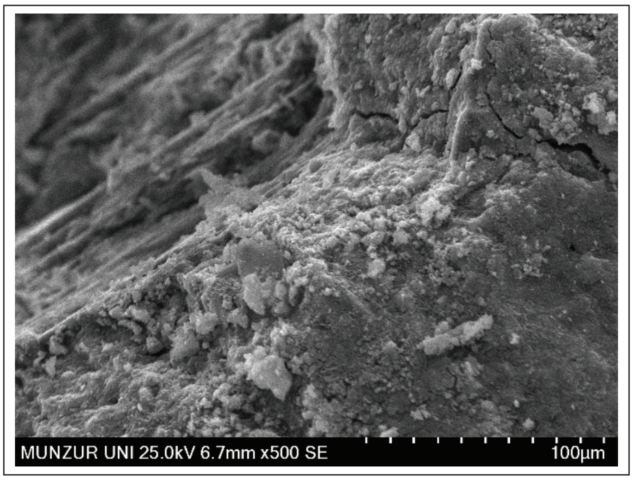


Figure 15. Microwave cure-400 W.

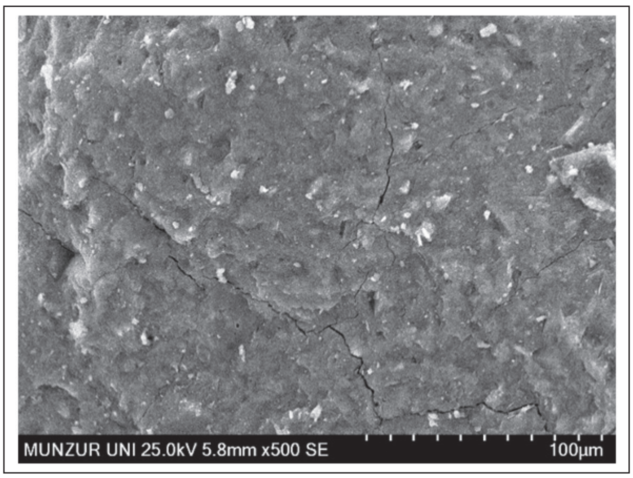


Figure 16. Microwave cure-600 W.

The following might describe the mechanism of microwave radiation's contribution to geopolymer cure. Microwave radiation affects the strength development of geopolymer before conventional heat curing. The geopolymer gel was made in part because of early microwave radiation. Because the aqueous solution heated up fast, using the microwave on specimens increased the solubility for Si and Al species from fly ash.

4. CONCLUSIONS

This research investigated the strength and internal structure properties of silica fume additive fly ash-based alkali active mortars after curing with microwave radiation. As a result, the following findings were revealed:

- It is a fast and convenient curing regime for fly ash-based geopolymer mortars reinforced with silica fume in microwave curing. In addition, 200 W power and 10 minutes of curing time are the optimum rates for this research. When these mortars are cured in the microwave, they reach high early strength values of 67.7 MPa. At the same time, this form of curing improves the microstructure. However, strength loss begins due to a high-temperature increase in high-power curing over 300 W. As it rises to 600 Watts, the mortar loses approximately 20% of its maximum strength.
- It was understood from the study results that silica fume increases the compressive strength of geopolymer mortar. Still, more detailed internal structure examination and experimental studies at different curing times are required to learn the reasons for the real contribution of silica fume on microwave curing.

The traditional curing method complicates the production process of geopolymer concrete, which is very suitable for prefabrication production. The 1- or 2-day periods spent in the furnaces for curing necessitate creating many large furnaces. This limits mass production. However, this time can be reduced to 10 minutes in curing with the microwave method. This provides a faster, less costly, and energy-efficient process for producing geopolymer mortars. In addition, this concrete, produced with waste materials such as silica fume and fly ash, can take its place in sustainable building materials and be widely used as a more environmentally friendly concrete with less energy.

In future studies, the effects of microwave curing on the internal structure and durability of fly ash-based mortars or all other geopolymer mortars should be investigated in detail. Thus, a more detailed discussion can be carried out on the subject before production.

ETHICS

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

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

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Research Article

Energy demand reduction for Nigeria housing stock through innovative materials, methods and technologies

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ABSTRACT

Energy utilisation has recently become a highly sought-after commodity on a global scale. This situation is not limited to Nigeria, where the national grid's supply of electricity has been severely inadequate. This has hampered the country's ability to meet the mounting needs of its large population and expanding economy. Aside from the global challenges of rising energy costs and environmental disasters, a number of factors such as a lack of interest in indigenous building technologies and materials have contributed to the Nigerian construction industry's slow pace of meeting energy demand and achieving energy efficiency. This study investigates the possibility of achieving energy conservation through innovative materials, methods, and technology to increase energy efficiency and minimise energy demand in Nigeria's residential housing. The objective is to determine the variables that influence energy usage in residential house design, select methods and technologies to reduce energy demand, and assess the best materials and processes. A quantitative approach to data collection was used by distributing questionnaires to respondents in the Minna metropolis. A hundred and forty (140) questionnaires were distributed, and 117 of them were returned. Secondary data were obtained from literature reviews, journal articles, and conference papers. According to the findings, the most energy efficient residential buildings would result from the appropriate use of innovative materials, methods, and technology to reduce the energy demand of the building. In order to decrease energy demand, the study suggests that built environment professionals should focus largely on changing energy-consuming devices and their end uses for energy efficiency. It concluded that, in order to reduce overlap between the applications of these elements and better meet the needs of building occupants in terms of energy usage in Nigeria, energy demand should be considered from the design stage.

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1. INTRODUCTION

Globally, due to rising population and income, energy consumption will increase by 15% from 2021 to nearly 660 quadrillion Btu in 2050 [1]. The Global Energy Review evaluates the trajectory of carbon dioxide emissions and energy consumption in recent years, and almost 55% of all electricity consumed worldwide is used for building

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operations [2]. The building and construction sectors combined form the highest CO_2 emissions recorded, accounting for 30% of total global final energy consumption and 38% of total global energy sector CO_2 emissions [3]. Energy demand from buildings and building construction continues to rise, driven by improved access to energy in developing countries, growing demand for air conditioning in tropical countries, greater ownership and use of energy-consuming appliances, and rapid growth in global building floor area [4].

Several studies [5-8] conducted in several regions of Africa, Europe, and Asia suggest that successful energy demand reduction is possible when approached from the correct angles. Buildings are responsible for significant energy use because individuals spend most of their waking hours indoors [9]. An energy-efficient design and technical characteristics that allow for good living standards and comfort with little energy use define a low-energy building [10]. In Africa, millions lack primary access to electricity due to rising energy demand, which challenges nations to maintain GDP development, forcing them to use polluted fuels to cook and light their houses. Estimate by [11] shows that 770 million people worldwide lack access to electricity, with 75% residing in sub-Saharan Africa. The majority of businesses in this area rely on fossil fuels, which are expensive and exacerbate climate change.

In Nigeria, population growth has rapidly increased reliance on fossil fuels due to a massive energy crisis that has plagued the country for over 20 years. In addition, industrial and commercial activity has been severely restricted, significantly increasing energy poverty. Based on the report by Nigerian Council for Renewable Energy, power disruptions cost Nigeria 126 billion naira ($984.38 million) yearly [12]. Nigeria experienced severe energy poverty due to the country's high demand and absence of a well-established energy supply network. Nearly 90 million Nigerians, according to [13] will not have access to grid energy in the coming years beyond 2020; while those that do will only have it for fewer than 12 hours each day. Despite the country's abundance of conventional energy resources, the leading cause of Nigeria's energy crisis is an insufficient supply of distribution to match the country's growing population. Additionally, due to unemployment and the inability to pay energy bills, literature has demonstrated the considerable effects of energy poverty on vulnerable households [14].

Energy poverty is a problem caused by the increasing energy demand and has become increasingly challenging to assess and characterize precisely. According to [15] the accepted definition of energy poverty is defined as the situation in which a household finds it difficult or impossible to secure adequate heating in the home at an affordable price. Similarly, it is when a household is unable to ensure a sufficient level and quality of domestic energy services for its social and material needs [16]. Against this backdrop, this paper investigates the possibility of achieving energy conservation in residential housing estates through innovative materials, methods, and technology with a view to increase residential housing energy efficiency and minimise energy demand in Nigeria housing stock. Its objectives are to: (i) identify factors influencing energy consumption in residential housing design. (ii) determine energy conservation strategies for energy use reduction in residential housing and (iii) assess suitable materials, methods, and technologies for reducing energy demand in residential housing provision.

2. LITERATURE REVIEW

Nigeria is projected to have a population of 195.87 million people and a GDP of $397.27 billion in 2021 [17]; however, its average annual energy consumption is only 144 kWh per person. The energy demand required for proper economic growth is lacking when taking into account the 16 GW installation capacity (which is made up of 75% gas and 13.5% hydro), at production of about 33%, with a transmission capacity of 2.9 GW and transmission losses of 22% from generation to distribution, and with only about 55% of the population known to have access to electricity [18 -19]. The assumption for the size of Nigeria's energy demand is that it is based on the country's high population, an annual GDP growth rate of about 2.2%, a high rate of power shortages, an energy consumption that is roughly twice to thirty times lower than that of its peers on the continent, and a World Bank ranking of 131 for ease of doing business [19-22]. Therefore, it is estimated that Nigeria requires more than 63,000 MW to address the gap in energy demand. This is based on estimations, assertions, and available data.

The demand for grid-powered energy distribution in Nigeria is estimated to be around 3200 MW [22-23]. There is a general view that many families in the nation have insufficient access to electricity since several elements, including a home's energy access, location in relation to electricity infrastructure, and administrative capability, have been neglected [24]. An average Nigerian household spends 27% of its income on energy, primarily on cooking, lighting, and cooling (91% of energy is used for cooking, 6% for lighting, and 3% for other electrical appliances); 72% of homes use fossil fuel because it is readily available; 69% do so out of convenience; 58% do so out of efficiency; and 52% do so out of cost [25].

Furthermore, Nigeria's energy poverty is extremely of concern [26] with some reports describing the electricity's performance records as abhorrent [27]. Hence, it is essential to conduct ongoing research on the energy situation in order to identify potential solutions to the issue. Additionally, several Nigerians lack access to the national grid, creating a very worrisome scenario that impacts the nation's residents and economic development. Various forms of research have been carried out to investigate Nigeria's potential for clean and dependable energy. According to [28] cited by [29] clean energy is the solution to Nigeria's severe energy crisis, particularly in rural areas. Ajayi and Ajayi [30] pointed out that by-products from fossil fuels are dangerous for both the environment and people. Aliyu *et al.* [31] posited that renewable energy technology must be aggressively pursued to address Nigeria's ongoing energy shortage and advance. Hence, considerable possibilities for sustainable electricity production in Nigeria should include renewable resources like clean energy.

Migration from the country's rural parts, where only 34% of people have access to power, to the nation's already highly energy-demanding urban centres, where 86% do, has also contributed to Nigeria's rising population and energy consumption [17, 32]. To ensure energy efficiency in Nigeria's building industry, deliberate efforts are required to halt the grid's energy supply which is insufficient, unstable and unbalanced [33]. Although, the decline over time has been due to the dominance of fossil fuels, which are well-known to be non-sustainable, non-renewable, and unfriendly to the environment.

Energy Efficiency Evaluation and Adoption Strategies

Reducing the use of energy-intensive building materials and technology is one of the sustainable methods for improving energy efficiency in residential buildings in Nigeria [34]. Any residential buildings that consume less energy than a typical one is energy efficient. It is generally accepted that low-energy buildings should use much less energy to deliver the same service [35]. Energy consumption optimization and making the most use of the energy that is available are not novel concepts. For instance, humans in ancient times struggled to build structures with adequate thermal comfort. The critical issue was keeping a house cool in the summer and warm in the winter [36]. There is no universally accepted definition of a low-energy house due to the vast disparity between national regulations; "low-energy" developments in one nation might not comply with "normal practice" in another. One primary federal and worldwide initiative to reduce greenhouse gas emissions with reasonable economic costs is improving energy efficiency [37].

Between 2000 and 2016, Germany's total energy consumption (or primary energy, not temperature-corrected) fell by 6%, from around 344 to 322 million or mega tonnes of oil equivalent (MTOE) in 2016 [38]. To a considerable extent, heat gains from occupants, equipment, lighting, and solar radiation are employed in low-energy buildings to maintain a comfortable indoor climate [39]. Low-energy buildings typically use high insulation, energy-efficient windows, low levels of air infiltration, and heat recovery ventilation to reduce the energy required for heating and cooling. They may also use passive solar building design methods or active solar technologies [36]. There are two key approaches to ensuring that buildings are using energy efficiently. The technological approach is the first, and the behavioral method is the second [40].

Adopting sustainable technologies is the technological strategy for increased energy efficiency to help meet growing energy demands without harming the environment [41]. Any technology that reduces energy more efficiently than conventional systems can be considered sustainable [42]. Therefore, Smith [43] offers a variety of sustainable methods. They comprise solar thermal energy, low-energy cooling methods, geothermal energy, wind energy, photovoltaics, and bioenergy. Green roofs and renewable technologies like solar panels and solar hot water systems are examples of further sustainable technologies [44-45].

Green roof technology is generally considered a passive strategy for lowering building energy demand [41]. The following are some examples of technological approaches: (i) Introduction of solar architecture and solar passive systems, which include energy-efficient light bulbs, refrigerators, water pumps, fans, and other devices. (ii) The utilization of contemporary, energy-efficient heating and cooling systems. (iii) Incentives for buying energy-efficient items have been used to influence customer behavior to advance energy efficiency. (iv) Reducing the amount of electrical energy used to heat water in the home through Renewable Energy Technologies (RETs), such as a solar heater.

Energy efficiency is all about performance and product improvements that reduce the energy needed for service delivery and other activities like lighting, cooling, heating, manufacturing, and cooking. Activities like indiscriminate electricity use by urban dwellers, gas flaring, inefficient, traditional three-stone fuel wood stoves, buying reasonably used appliances, and low fuel efficiency vehicles fall under this category [46]. Devices that ensure little energy is wasted are created and constructed to help achieve energy efficiency in electrical systems.

Automatic power factor controllers, electronic ballasts, energy-efficient lighting controls, energy-efficient motors, energy-efficient transformers, maximum demand controllers, occupancy sensors, soft starters with energy savers, and variable speed drivers are some gadgets that help with energy efficiency. Energy efficiency appliances, sensor-based modeling, and thermal insulators on panels, walls, and floors to help regulate the indoor thermal environment are a few technologies that can reduce overall energy use and achieve energy conservation [47-48].

Innovative Materials, Methods and Technologies

When it comes to the envelope performance, the elements of the materials, thermal mass, geometrical surface-to-volume ratio, shading devices, and the building orientation, the usage of the OTTV idea in place of glass has been quite established [49]. Innovative approaches to reducing energy demand include the use of programmable thermostats in homes with settings that are appropriate for the local weather at any given time, the use of renewable energy sources, and the intentional use of CFL bulbs [50].

Adjusting external shading devices to control interior lighting and thermal comfort, using wireless sensors through automated control panels to reduce energy usage, and using reflective roofing materials and modern building insulation [51].

It has been shown that using bioclimatic design to insulate a building's mass appropriately is the first step in improving energy efficiency [52]. This is accomplished by starting with a compact building shape, appropriate orientation, applying passive shading techniques, using high thermal resistant insulators for external walls within acceptable dimensions, and reducing air leakages through an airtight design through proper detailing [53-54]. Additionally, to save energy, it has been found that using earthen walls, insulating concrete forms, Low-e windows, plant-based polyurethane foam (the fiberglass insulation), plastic composite lumber, recycled steel, straw bales, structural insulation panels in structural systems, and vacuum insulation panels can all help create low energy buildings [48]. A design that closely connects to the heating influence of the sun on the house and effective insulation of the thermal mass is credited with contributing to energy conservation in the built environment.

Solar Energy Technologies

Solar energy is an excellent prospective option for producing clean electricity because it is unrenewable and pollutant-free. Several developing nations, including Nigeria, experience trouble utilizing the resources despite the enormous amount of solar energy that strikes the globe's surface. Mohammed [55] claims that several industrialized nations experienced electrical stability after investing in solar. Investing in solar energy collection technologies can assist developing countries in ending energy poverty and reducing greenhouse gas emissions (GHG). Solar photovoltaic, solar thermal, and concentrated solar power conversion are the three main processes that turn solar energy into electricity [3]. These innovations are machines that transform solar energy into usable energy. In the following section, these technologies are briefly discussed, focusing on photovoltaic technology because it is the most widely used solar technology in Nigeria and the rest of the world.

Solar Photovoltaic

This device uses photovoltaic effects when exposed to solar radiation to produce energy. When exposed to solar radiation, photons become stimulated and release electrons that are then captured by wires to produce direct electricity that must be converted to alternating current using converters [56]. The generated energy can be delivered to a load or stored using a storage device like a battery. As long as the device is exposed to sunlight, it will continue to produce energy.

Hydro

The process of releasing energy to turn mechanical turbines and produce electricity is known as hydropower energy generating [57]. The water's volume and descent velocity affect how much power is made. Hydropower is the first and only renewable energy source supplying electricity to Nigeria's national utility grid [3].

Energy Demand Reduction Conceptual Framework

A conceptual framework (Figure 1) was developed to study the concepts derived from the theoretical framework found in the literature in connection to energy demand reduction. This is to accomplish demand reduction in energy consumption in housing provision in Nigeria. The approach implies that climatic conditions, building design, and building operations impact the energy demand in housing. These three factors could worsen and increase the demand for energy in housing if they are not adequately considered while designing housing provisions. This would unavoidably call for innovative techniques (Figure 1) that might lower housing energy use. The framework is built on a model that illustrates several strategies for reducing energy usage.

Figure 1 depicts the study's hypothesis that energy reduction strategies center on technological, building-specific, and behavioral methods that, when integrated and sufficiently considered, would call for an innovative strategy to reduce energy consumption in buildings. Sustainable construction, which includes eco-friendly methods and integration of renewable energy, is a component of the technological approach. The building attributes had bioclimatic designs, year of construction, window type, and building materials. The behavioral method focuses on the occupant's behavior, which includes comfort-seeking, perceived norms, mixed habits, and conscious and unconscious drivers. Using smart home hubs, LED lighting, smart thermostats, energy-efficient insulation, smart plugs, and power strips, cool roofing, high-efficiency heat pumps, and smart HVAC systems are all part of the innovative and green energy reduction strategy.

3. RESEARCH METHODOLOGY

The research methodology used in this study is a quantitative method that specifies the investigation into a social or human problem regarding the responses to specific questions. A cross-sectional survey approach using a questionnaire's respondents' statistical data as the primary instrument. The respondents who live in Minna City comprise the sample population of users. Data collected from pertinent literature and published articles from journals, conferences, and national newspapers were combined using the qualitative technique.

Study Area

The research is conducted in Minna, Nigeria's north-central geopolitical zone. Minna connects Abuja, Kano, Ibadan, and Lagos and covers an area of 76,363 square kilometers. It is geographically located between the Latitude and Longitude coordinates of 9.58 and 6.54 east

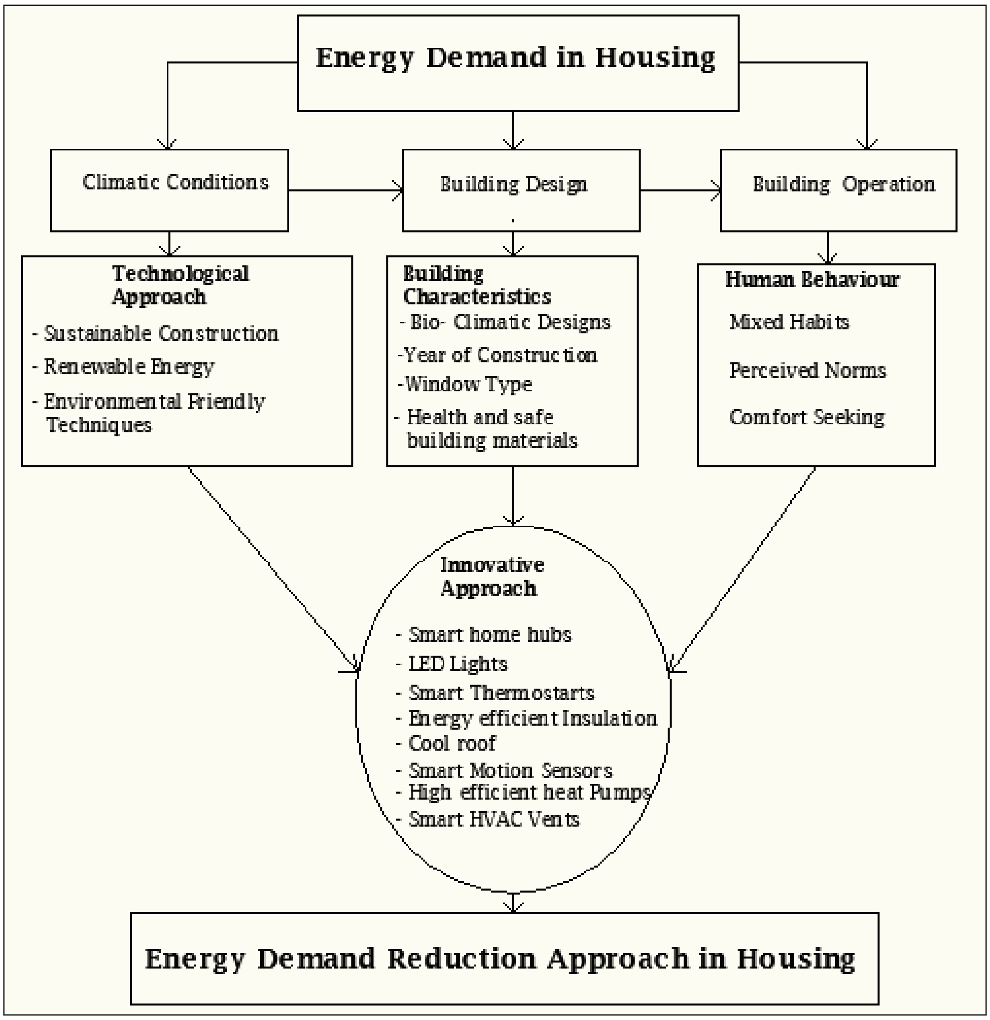

Figure 1. Conceptual framework of energy demand reduction approach in housing.

of the Greenwich Meridian, respectively (Figures 2 and 3). Minna is emerging as one of Nigeria's fastest-growing cities, with a population density of 56 people per square kilometer. Minna's residential land use exhibits three characteristics: high, medium, and low densities, with a combination of these densities except for the low density, which is delimited. Several densely populated communities can be found in the inner city. It has an estimated land area of 1,000

Figure 2: Map of Nigeria showing Niger State

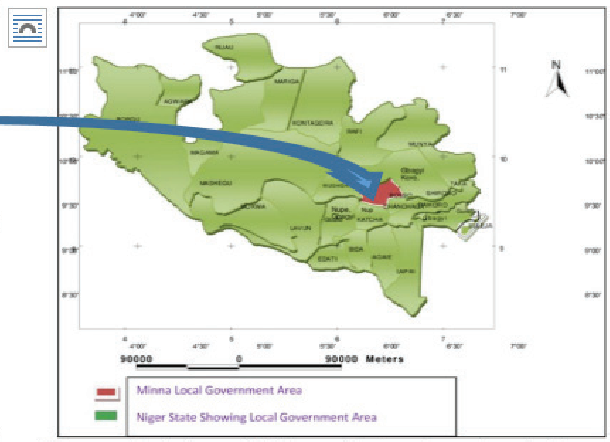

Figure 3: Map of Niger State showing Minna

square kilometers [58]. Minna's population has increased dramatically, from 192,437 in 1991 to almost 300,000 in 2006 [59]. Sulyman *et al.* [60] stated that there is a lack of energy supply in the Minna metropolis, and electricity usage accounts for 25.0% of total energy consumption in the city, typically used for lighting and cooking.

The Survey

The study used a quantitative survey approach using a questionnaire as an instrument is considered efficient and effective by [61] in sampling a wide population. The questionnaire was recognized as the most appropriate instrument the respondents could easily reach in the most inexpensive, efficient, and popular way to obtain essential information. Within the study area, it was reported by [58] that domestic energy increased by 72.6% in 2012, resulting in a significant demand for energy supply. The questionnaire was distributed to the residents in the study area. Before administering the questionnaire, a pilot study was conducted in which some respondents were interviewed using the intended, structured questionnaire to check that the respondents comprehended the questions.

Sample size

The sample size is determined by the study's need for reliable and authentic findings to establish conclusions [62]. According to [63], the size of the sample is more a question of convenience and a compromise among various criteria (e.g., expenses and precision) as supported by [64]. The sample size for this study was determined using the formulas from [65] and [66], which are as follows:

$$ss = \frac{Z^2*(p)*(1-p)}{C^2}$$

Where:

Z = Z value (e.g., 1.96 for 95% confidence level)
P = percentage picking a choice, expressed as decimal (.5 used for sample size needed)
C = confidence interval, expressed as decimal

In surveys, it is a common practice to aim for a 95% confidence level or a precision level of 5%. As a result, a 95% confidence level was assumed, as is customary in other research [65] while z = 1.96 for a 95% confidence level (i.e., significance threshold of = 0.05). Based on the requirement to balance precision, available resources, and the utility of the research findings, a confidence interval (c) of 10% was deemed sufficient for this investigation. To calculate the sample size for a particular degree of accuracy, Czaja and Blair [66] proposed that the worst-case percentage of picking a choice (p) be assumed, which is 50% or 0.5. The sample size was estimated using the following assumptions:

$$ss = \frac{1.96^2 \text{ x } 0.5\ (1 - 0.5)}{0.1^2}$$

$$ss = 96.04$$

The sample size for the questionnaire survey will be 96 respondents. However, the calculated value requires further modification for limited populations. As a result, the formula for calculating finite populations was taken from [66] as follows:

$$\text{new ss} = \frac{ss}{1 + \frac{ss - 1}{pop}}$$

Where: Pop = population

$$\text{new ss} = \frac{96.04}{1 + \frac{96.04 - 1}{300{,}000}}$$

$$\text{new ss} = 96.00$$

This formula can be used to determine the finite populations, and it can be seen that 96 samples are the bare minimum needed. The nonresponse rate, typical with questionnaire surveys, was nevertheless considered vital when determining the sample size. Therefore, it was crucial to modify the sample size to consider nonresponse. The suitable sample size to be surveyed was consequently determined using the method adapted from [67] based on the assumption of a cautious response rate of 85% as proposed by [68] for in-person (i.e., Face to Face) surveys:

$$\text{survey ss} = \frac{\text{new ss}}{\text{response rate}}$$

$$\text{survey ss} = \frac{95}{0.85} = 113$$

In order to conduct the survey, a minimum of 113 respondents with an 85% response rate were required.

4. RESULTS AND DISCUSSION

One hundred and forty (140) questionnaires were sent out in total, and 117 of them were returned giving an 83% response rate. A reliability score of 0.826 and a frequency of 85 male and 36 female respondents were recorded. The reliability value of 0.826 and the response rate percentage were deemed satisfactory for the study. Most respondents are 25-34 years old, while others are 55 years and above. Half (50.4%) of the respondents live in rented houses, while 49.6 % live in owned houses, as shown in Table 1.

Table 1. Demography information of the Respondents

Characteristics	Frequency	Percentage	Characteristics	Frequency	Percentage
Gender			Number of bedrooms		
Male	85	70.2	1	36	29.8
Female	36	29.8	2	32	26.4
			3	28	23.1
			4	25	20.7
Age			Number of occupants		
15-24	23	19	1	17	14
25-34	45	37.2	2	23	19
35-44	31	25.8	3	17	14
44-54	14	11.6	4	64	52.9
55 and above	8	6.6			
Do you own or rent the building			Occupation		
Rent	61	50.4	Self-employed	33	27.3
Own	60	49.6	Regular salary	62	51.2
			Casual/daily wage	10	8.3
			Student	11	9.1
			Unemployed	3	2.5
			Retired	2	1.7

The majority (27.4%) of the respondents receive a monthly income of N100,000 ($131.18) and above, closely followed by 25.6% having an income of N20,000 ($26.24) - N50,000 ($65.59). About 22.2% earned N81,000 ($106.26) - N100,000 ($131.18) while just 10.25% earned N51,000 ($57.06) - N80,000 ($105.19) while 17.95% earned below N20,000 ($26.30) (see Figure 2 recorded according to the number of the respondents in each category). This shows that the majority of the users battle with poor income to meet up with the energy demand.

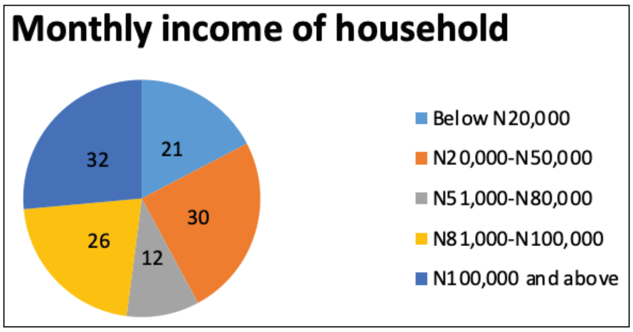

Figure 2. Shows the Monthly income of the Respondents.

It has been observed that there is a lot of energy consumption on use of 2 out of 6 appliances: Refrigerators and fans. Figure 3 illustrates that most respondents constantly leave their refrigerators, ceiling, and standing fans on. This is due to the importance of both devices

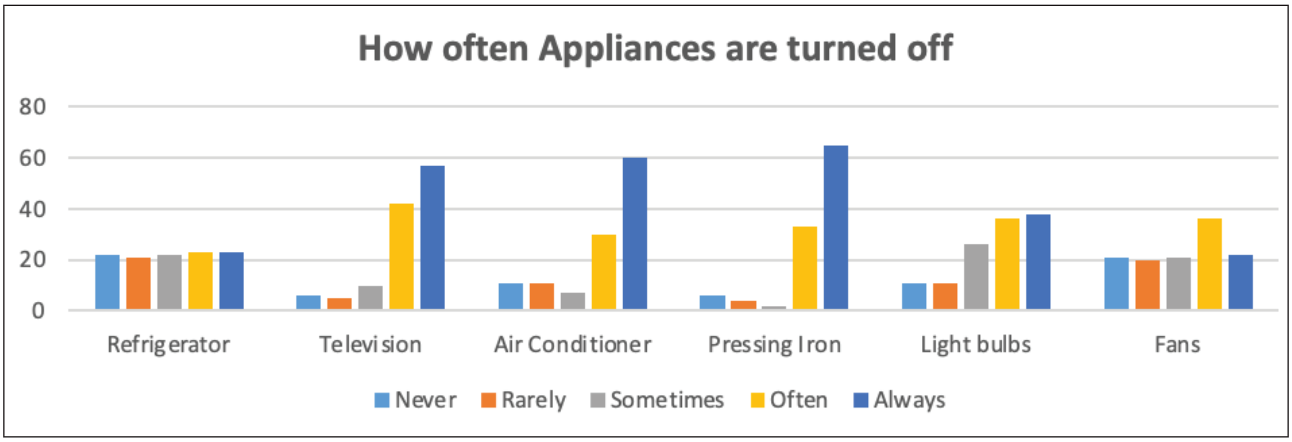

Figure 3. Showing human behavior on ways of energy conservation in the household.

For sustaining the occupants' comfort. This finding reflects the opinion of [10] on the overreliance on more mechanical and electrical devices to produce thermal heating, which results in more energy consumption and acts as a barrier to low energy—the respondents' solutions for reducing energy waste while in use are presented in Figure 4. According to the figure, 88%, 85%, and 88% of the users of appliances such as phones, laptops, and rechargeable fans responded to switching off their gadgets when fully charged. In comparison, 33%, 36%, and 33% of phones, laptops, and rechargeable fans do not switch off when fully charged. This result corroborates the views of [69], who opined that a sharp growth in the number of electrical appliances has been one of the main factors driving rising electricity consumption in homes, especially when they are not turned off when they are ultimately charged or not in use.

Figure 5 reveals the year of construction of the building. Forty-five percent of the respondents' facilities were constructed between 2000 and 2010, while the fewest were dwellings completed in 1990 or earlier. Structures built in the 1990s typically combine local and modern elements, whereas buildings constructed in the 20th century have a preponderance of modern materials. In the view of [70] occupants of buildings built in earlier years relied significantly on wood and coal to keep them warm, cook their food, and light their homes, which results in using less energy. However, in the modern age, the discovery of electricity ushered in a new age of technology that claims to provide comfort in any building by invariably incorporating high energy-consuming technologies. Though the new age technology has significantly impacted how people live, it has increased fossil fuel-based energy prices over the past two decades. This has created more awareness of the need to preserve energy and practice energy efficiency in modern buildings.

According to Table 2, 84.3% of respondents utilize hollow sandcrete blocks for their building's walls, compared to 8.3% who use stone and 7.4% who use mud blocks. This demonstrates that sandcrete hollow blocks are the material most frequently used for wall construction in residential constructions. This finding aligns with [71] who indicated that most residential buildings in Nigeria's hot-dry climate rely on sandcrete hollow blocks to build respective of their climatic environment. Meanwhile, only a small number of

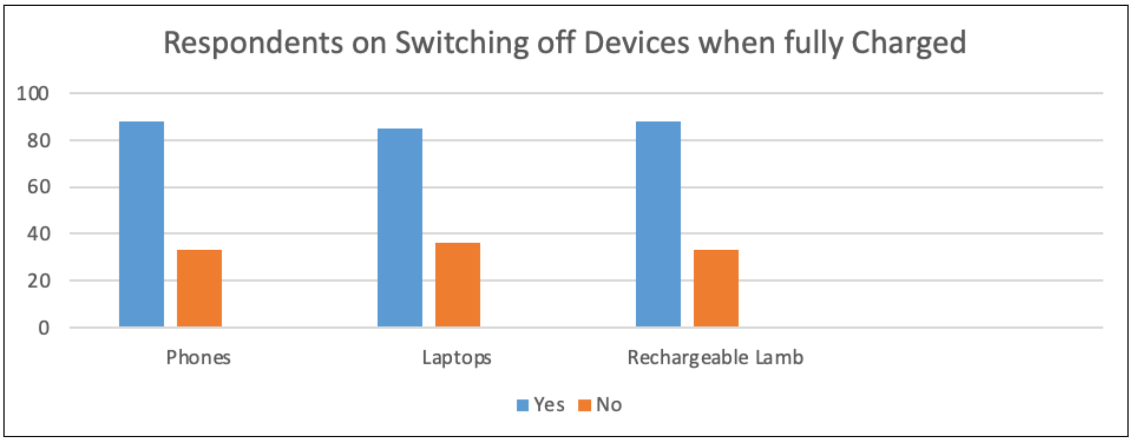

Figure 4. Showing human behavior on switching off devices when fully charged.

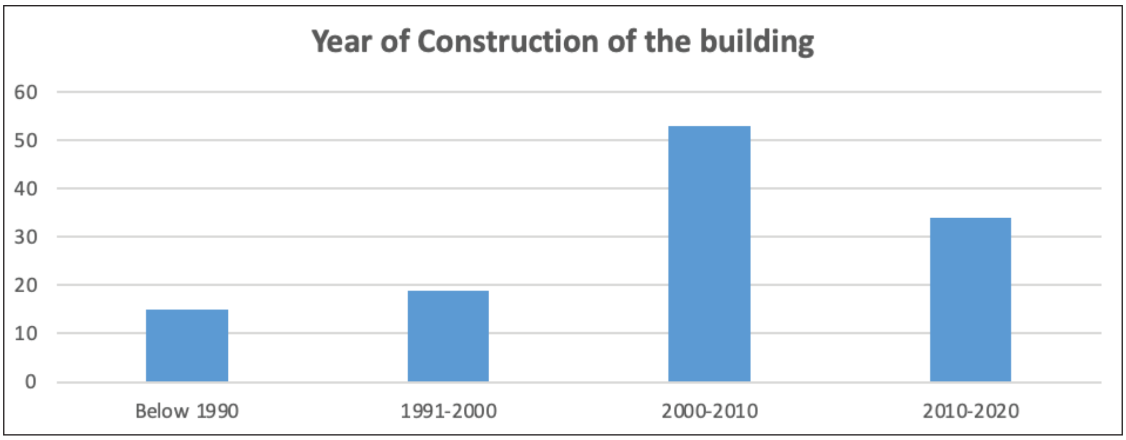

Figure 5. Showing the year of construction of the building.

Table 2. External materials (walls) used in construction

Variable		Frequency	Percentage
What building material was used for the wall of your building	Stone	10	8.3
	Sandcrete hollow blocks	102	84.3
	Mud blocks	9	7.4
	Wood	0	0
	Others	0	0

houses employ mud and stone blocks. While [72] and [73] argued that sustainable residential building construction in Nigeria is the goal of the low-energy architecture idea. Lembi *et al.* [74] further emphasize that traditional building materials are a significant resource for architecture which could take the form of clay bricks, compressed earth blocks, rammed earth, and other types of earthen construction. Thus, it could be argued that utilizing these materials, which are readily and naturally available, would lower the amount of fossil fuel energy used.

Figure 6 and Table 3 show the usage of the window types by the respondents. Casement windows are used in 31.4% of residences, sliding windows in 38.5%, louvers in 17.4%, and projecting windows in 12.4%. This result shows that the majority of residences utilized sliding windows more than any other type of windows. It could be argued that inappropriate window types in residential houses, such as sliding windows and projected windows in the tropics, could result in more energy use for adequate ventilation as these would limit the extent of the openings required for a more significant percentage of airflow needed for natural ventilation. Although [75] argued that up to 25% of a home's total heat loss through windows can come from window units and frames, losses from heat conduction and convection airflows between the panes, and heat loss from heat radiation. In contrast to this argument, this view only applies to buildings in temperate regions or climates where residential buildings need window types to limit the rate of heat loss.

Figure 7 illustrates the type of ventilation in the sampled household. The data shows that the household uses 33% natural, 27% mechanical, and 61% of the available ventilation types. This shows the household depends mainly on mechanical ventilation for adequate comfort due to poor designs. Knowing that the study location records high temperatures and hot seasons will result in the use of more energy by the household to seek adequate comfort, thereby causing an increase in energy demand. Wargocki [76] speculated that health risks may occur when ventilation rates in residential properties fall below 0.4 air changes per hour.

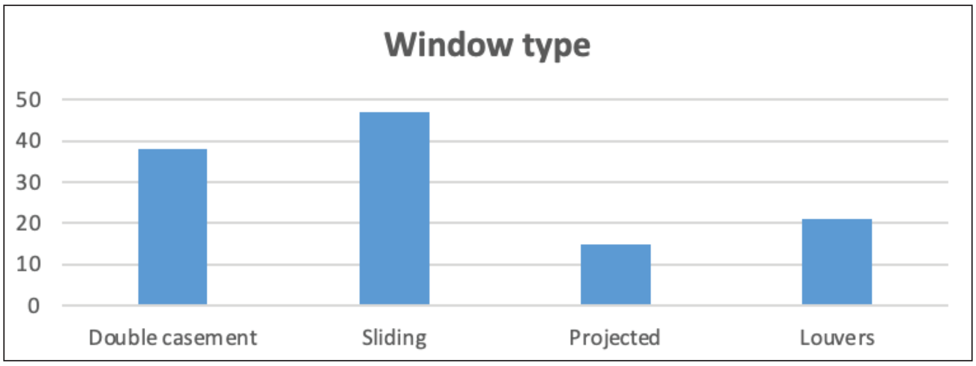

Figure 6. Chart showing window types used in the households.

Table 3. Energy conservation strategies suitable for energy use reduction for appliances

Variable		Frequency	Percentage
Window types	Double casement	38	31.4
	Sliding	47	38.5
	Projected	15	12.4
	Louvers	21	17.4

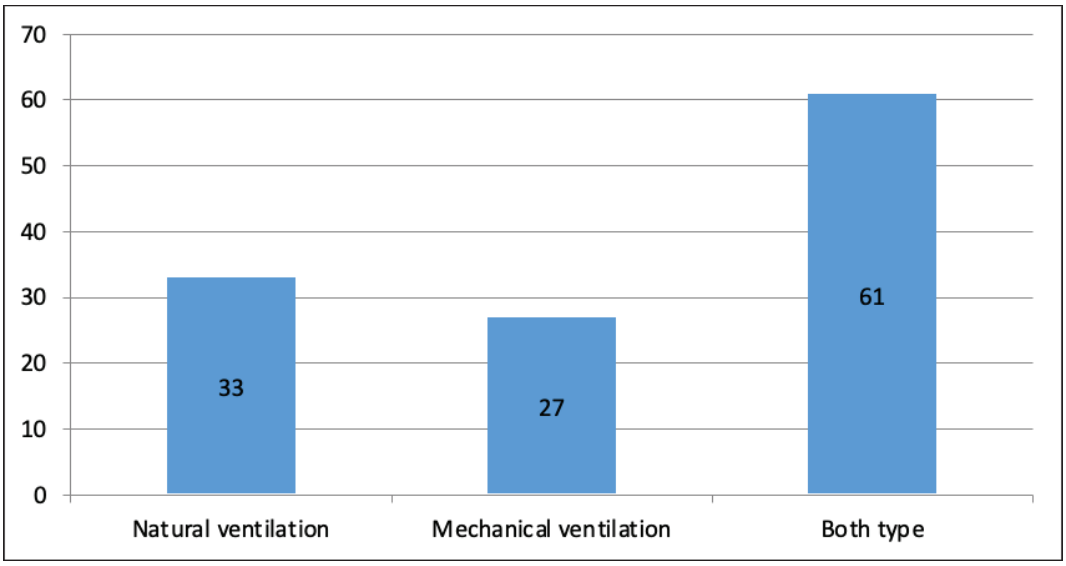

Figure 7. Chart showing ventilation types in the households.

Sherman and Matson [77] proposed that energy use is a factor of building attributes. According to the study, a typical residence's average yearly ventilation energy demand is approximately 61 GJ (almost 50% of total space conditioning energy usage); the cost-effective savings potential is approximately 38 GJ. This means that housing requires a lot of energy to offer acceptable comfort for the residents, and adequate measures to ensure proper ventilation must be in place from the design stage to minimize energy use.

Energy Conservation Strategies

Regarding energy conservation strategy, 49.4% of the respondents use ceiling fans in their bedrooms, 31.6% use air conditioning, and 19% use standing fans. As for sitting rooms, 49% of the respondents use ceiling fans in their living rooms, while 28.9% use air conditioning and 22.1% use standing fans. Lastly, 73.6% of respondents use energy-saving bulbs, 18.1% use incandescent light bulbs, and 8.3% use standard fluorescent tubes in their houses (Table 4). From the findings, it is instructive that most respondents use energy-saving bulbs for lighting. However, the use of air-conditioning would result in higher consumption of energy for cooling, as opined by [78], who expressed that air conditioners use the most electricity excluding lighting. In addition to the energy conservation strategies employed by the respondents, 80% unplugged their refrigerators, while only 19.8% never unplugged their refrigerators.

Meanwhile, 72.7% of the respondents switched off their phones when they were fully charged, while only 27.3% did not switch off their phones. 70.2% of the respondents switched off their laptops when fully charged, while only 29.8% did not switch off their computers. 72.7% of the respondents switched off their rechargeable lamps when fully charged, while only 27.3 did not switch off their rechargeable lights (See Table 5). To adequately use energy in buildings, Monacchi *et al.* [79] recommended prepaid billing as an easy technique to raise energy awareness and convert appliances into pay-as-you-go devices which could result in average savings of 11% regardless of grid disconnections. This step could regulate household behavior

Table 4. Energy conservation strategies suitable for energy use reduction for appliances

Variable		Frequency	Percentage
What cooling devices are used in the bedroom	Air condition	50	31.6
	Ceiling fan	78	49.4
	Stand fan	30	19
What cooling devices are used in the living room	Air condition	43	28.9
	Ceiling fan	73	49
	Standing fan	33	22.1
Types of lighting devices/systems used in the house	Standard fluorescent tubes	12	8.3
	Energy saving bulbs	106	73.6
	Incandescent light bulbs	26	18.1

Table 5. Strategies of household energy conservation in residential housing design

Variable		Frequency	Percentage
How often do you unplug your refrigerator	Never	24	19.8
	Rarely	23	19
	Sometimes	24	19.8
	Often	25	20.7
	Always	25	20.7
How often do you unplug your television	Never	6	5
	Rarely	5	4.1
	Sometimes	10	8.3
	Often	43	35.5
	Always	57	47.1
How often do you unplug your AC	Never	11	9.1
	Rarely	11	9.1
	Sometimes	8	6.6
	Often	30	24.8
	Always	60	49.6
How often do you unplug your Pressing iron	Never	5	4.1
	Rarely	3	2.5
	Sometimes	1	0.8
	Often	33	27.3
	Always	66	54.5
How often do you unplug your light bulbs	Never	11	9.1
	Rarely	11	9.1
	Sometimes	26	21.5
	Often	36	29.8
	Always	37	30.6
How often do you unplug your fans	Never	21	7.4
	Rarely	20	16.5
	Sometimes	21	17.4
	Often	36	29.8
	Always	23	19.0
Do you switch off your phones when it fully charged	Yes	88	72.7
	No	33	27.3
Do you switch off your laptops when it is fully charged	Yes	85	70.2
	No	36	29.8
Do you switch off your rechargeable lamp when it is fully charged	Yes	88	72.7
	No	33	27.3

regarding unnecessary energy consumption arising from users' behavior, and it would prompt users to turn off appliances to avoid racking up large utility bills.

Table 6 shows some design parameters that aid in reducing energy demand in residential housing. 39.7% of the respondents admitted having high airflow in their bedrooms, while 9.9% and 12.4% recorded very low and low airflow, respectively. 38% of the respondents admitted having high airflow in their living rooms, while 3.1% and 4.2% recorded very low and low airflow, respectively. 27.3% of the respondents attest to using more natural ventilation, while 22.3% use mechanical ventilation. 38.5% of the respondents use sliding windows, while 12.4% use projected windows. Adequate ventilation is a key measure to reducing energy demand in buildings. As suggested by [80] several strategies for reducing energy consumption include features in buildings such as appropriate design strategies, proper placement of fresh air intakes, efficient air distribution in rooms through improved ventilation efficiency, and using ventilation for night cooling.

Table 6. Design parameters for reducing energy demand in residential housing

Variable		Frequency	Percentage
Quality of airflow in the bedroom	Very low	12	9.9
	Low	15	12.4
	Moderate	40	33.1
	High	48	39.7
	Very high	6	5
Quality of airflow in the living room	Very low	5	4.1
	Low	16	3.2
	Moderate	45	37.2
	High	46	38
	Very high	9	7.4
Quality of airflow in the kitchen	Very low	12	9.9
	Low	20	16.5
	Moderate	57	47.1
	High	28	23.1
	Very high	4	3.3
Types of ventilation in the bedroom	Natural ventilation	33	27.3
	Mechanical ventilation	27	22.3
	Both	61	50.4
Window types	Double casement	38	31.4
	Sliding	47	38.5
	Projected	15	12.4
	Louvers	21	17.4

The amount of space in the bedroom and living room is shown in Table 7, along with its impact on natural lighting, thermal comfort, light brightness, and natural ventilation. Natural ventilation in living rooms stands at 38% moderate and 35.5% high, while natural lighting in living rooms moves to be moderate and high with a 38% reduction in energy use. Living rooms have intermediate thermal comfort (40.5%) and high thermal comfort (23.1%). The bedroom had extremely high natural ventilation (9.1) and low natural ventilation (5.8% airflow).

The living room's light brightness was 6.6% extremely high and 19.8% extremely poor conservation. These are the frequencies and percentages of the Minna, Nigeria, housing stock sampled for energy efficiency.

From Table 8, saving monthly costs and reducing greenhouse gas emissions appear to be the most important

Table 7. Contributing factors to energy reduction/conservation strategy

Questions relative to the contributing elements to energy conservation tactic	Very low (1)		Low (2)		Moderate (3)		High (4)		Very high (5)	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	Frequency	%
Level of space in the living room (Natural lighting)	12	9.9	9	7.4	46	38.0	46	38.0	8	6.6
Level of space in the living room (Thermal comfort)	9	7.4	27	22.3	49	40.5	28	23.1	8	6.6
Level of space in the living room (Light brightness)	24	19.8	36	29.8	37	30.6	16	13.2	8	6.6
Level of space in the bedroom (Natural ventilation)	7	5.8	14	11.6	46	38.0	43	35.5	11	9.1
Level of space in the living room (Natural ventilation)	7	5.8	10	8.3	50	41.3	50	41.3	4	3.3

Table 8. Perception of energy use reduction in the residential buildings

Questions relative to the perception of energy use reduction in the residential buildings	Not important (1)		Least important (2)		Neutral (3)		Important (4)		Very important (5)	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	Frequency	%
Response to having a less negative impact on the environment	14	11.6	18	14.9	24	19.8	35	28.9	30	24.8
Response to saving monthly operating cost	12	9.9	10	8.3	14	11.6	38	31.4	47	38.8
Response to adding value to the house	11	9.1	11	9.1	23	19.0	36	29.8	40	33.1
Response to minimizing the effect of climate change	13	10.7	9	7.4	25	20.7	39	32.2	35	28.9
Answer to reducing greenhouse gases	12	9.9	8	6.6	17	14.0	51	42.1	33	27.3

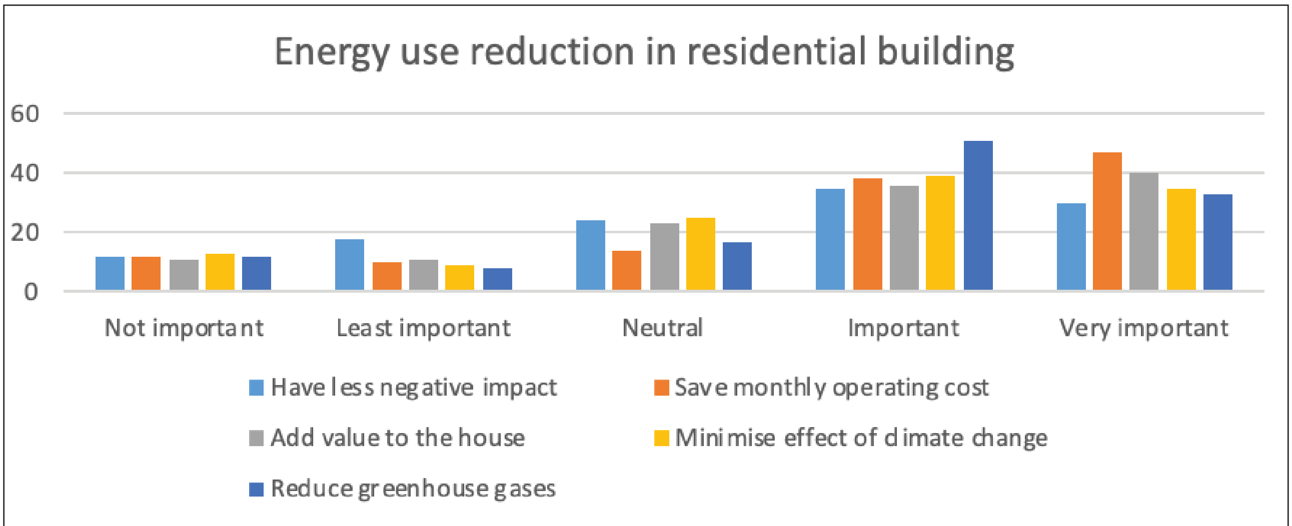

Figure 8. Chart showing perception of energy use reduction in the residential building.

aspects of energy reduction benefits, with less negative impact being the least important overall.

Recommendations

1. Energy use demand should be considered right from the design stage in helping to reduce the synergy between applying these elements and even more innovation to bridging the gap of building occupants' need for energy in Nigeria.
2. Professionals and researchers in the field can focus primarily on directly influencing the demand by modifying the energy-using devices or their end use for energy efficiency.
3. To help reduce the energy demand load, there is a need to employ both the energy efficient and energy conservative approach of saving monthly costs and minimizing the effect of climate change with a definite action on innovative materials, methods, and technology.
4. There should be more clay bricks for wall construction to reduce thermal heat in housing interiors, double casements for windows to allow maximum free air flow and practical applications of energy-saving appliances.
5. There should be a constitutional amendment in Nigeria by laws of power generation to allow the individual state to generate its power and consume with the prospect of selling out to another neighboring state.

Contribution to knowledge

The study advances knowledge by encouraging the reduction of energy demand through energy-efficient building strategies to enhance energy performance in housing provision and innovative building design to address energy consumption in housing design, especially in mass housing provision in Nigeria.

5. CONCLUSION

Reducing energy demand in Nigeria's housing stock is essential. The demand for energy in the country, though, cannot be particularly articulated, but it can be ascertained that it is high, and the need for a measure of meeting those needs is expedient. Therefore, design parameters with indications of energy conservation must be implemented on various building codes and requirements to achieve the desired reduction in household energy demand. Energy efficiency and energy conservation are vital in driving a reduction in Nigeria's energy demand. In line with this, the professionals and researchers in the field can focus primarily on directly influencing the demand by modifying the energy-using devices or their end use for energy efficiency. Or focus more on the indirect influences of "what causes users to need energy." The various elements discussed in this study would guide homeowners, designers, and builders on how to be innovative with materials, technologies, and methods to reduce energy demand. The study's findings will aid in the economic improvement of the users by reducing energy demand and ensuring adequate energy supply. This will significantly help in energy savings in residential buildings. This can be achieved using cost-effective technologies and an innovative and behavioral approach. Energy use in the residential sector can be significantly reduced.

Areas of Future Research

This study is an ongoing contribution to the body of knowledge rather than a final answer. As a result, future research should focus on the following:

- To improve more on the technological approach to reduce energy demand and make the supply more sustainable,
- To develop passive design features and to promote an adequate environment that will be comfortable for the users and reduce energy demand,
- To alert the users on the occupants' behaviour regarding energy use to achieve energy reduction,
- To sensitize the users on the benefits of the Innovative approach of using renewable energy in households to conserve energy.

ETHICS

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

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

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Research Article

Assessment of a new rigid wall permeameter for the slurry like barrier materials: zeolite example

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ABSTRACT

Areas vulnerable to catastrophic disasters such as hurricane, landslide and earthquake require ready and sustainable solutions for the post-pollution scenarios. Clinoptilolite type zeolite resources of Türkiye can serve economical and sustainable solutions as a quick response. While the studies on compacted zeolite-bentonite mixture at optimum water content for the landfill liners applications or dry zeolite-sand mixtures in permeable reactive barrier (PRB)s are common, the slurry form of zeolite emplacement at subsurface reactive barriers has not received an attention by the researchers. In this context, this experimental study presents the preliminary findings on one-dimensional consolidation and hydraulic conductivity tests performed on crushed zeolite samples S1 and S2 with fine contents of 33 and 84%, respectively. The results indicate that S2 has a higher compression index than S1, without a significant change in swelling index attributed to less than 4% clay contents. A self-designed rigid wall type permeameter was used to study on reconstituted slurry like materials under the benefit of back pressure saturation without the consolidation during testing that encountered in flexible wall permeameter. Falling head – rising tail water procedure was adopted under the back pressure in between 200 and 700 kN/m^2. S2 samples reconstituted under 25, 50, 100 and 200 kN/m^2 show a gradual decrease in k_v from 3×10^{-8} to 2×10^{-9} m/s. Previous observations on the sample of S1 revealed 8 times higher k_v values under the same σ_v'. Since the fine content of zeolite limits k_v, the proposed permeameter will be beneficial to determine the proper grain size distribution of fill materials considering the barrier height and in-situ stress conditions before the environmental studies with leachate.

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1. INTRODUCTION

Hurricanes, landslides and earthquakes are one of the catastrophic disasters that result in economical and human losses globally. Decision makers are responsible to define and get precautions against this type of natural events that may affect their region locally. Since past, engineers have been conducting scientific studies in geoenvironmental projects to reduce risk of loss of life and property. In this context, waste management strategies are discussed on sustainable solutions for post pollution events [1-7]. Based on the contamination scenarios, the barriers against the site-specific pollutants were previously studied considering

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the constructability, and readily available or near sources of the reactive fill material in the region for a quick and economical response.

Soil-bentonite (SB) and cement-bentonite (CB) based impermeable reactive walls are widely used to prevent the spread of contamination in the soil environment [8]. Fly ash [9] and steel slag [10] may also be used as ingredients that are effective to immobilize the contamination and increase the shear strength of the wall section. On the contrary, sand can be added to reduce the cost or increase the permeability of the barrier [11, 12] in case the permeable reactive barrier (PRB) methodology requires a more permeable material used in the barrier than the aquifer soil [8, 13-19] to control and treat the contaminated groundwater while passing through, based on its reactivity against the heavy metals [20, 21], chlorinated organics [22], radionuclides [23] etc in the soil. This alternative passive technology may involve one or more reactive materials in a barrier such as zero-valent iron (ZVI) [24-27], hydroxyapatite [28], and activated carbon [29] or natural rocks; limestone [30], attapulgite [31], sepiolite [32-34], zeolite [12, 33-36] which have been mechanically brought to a certain grain size or processed minerals such as organoclay [37-38] and organo-zeolite [38].

The constructability, stability and permeability of the wall section are reported to be related to the local geological and groundwater conditions [15, 39-41]. Emplacement methodology of a reactive material in an excavated trench defines the initial porosity along the barrier. However, it can be changed by inundation or in-situ stress conditions based on the initial moisture content (e.g. placement at dry state, a predesignated water content, or in slurry form). In literature, there are limited number of studies about the stress distribution on the SB slurry trench cutoff walls [42-44]. The measured horizontal effective stresses within a 7 m high SB wall were pointed out to be considerably less than the expected geostatic stresses [43]. The hydraulic conductivity of SB is highly stress-dependent and increases with increasing fines content [43]. The stress dependency on hydraulic conductivity needs to be taken into consideration during design stage and this issue can be overcome by utilization of well graded backfill material [41]. However, it should be noted that these properties can change significantly when the fill material or construction methodology changes. Therefore, the environmental studies based on a single porosity value may not be sufficient to simulate the in-situ conditions of the reactive material especially when the barrier height increases, thus the porosity value decreases with increasing overburden stress. The performance of the barrier may be optimized by interpreting the porosity-overburden pressure-hydraulic conductivity relationship of a reactive material prepared at different grain size distributions. The breakthrough curves developed using the proper grain size of reactive material prepared at the designated porosity values will be beneficial to predict the longevity of the barrier.

Zeolite is one of the sustainable reactive materials applicable in remediation projects for groundwater pollution due to the high cation exchange capacity (CEC). [34-43]. Clinoptilolite-type zeolite showed more than 80% removal efficiency against the contaminants NH_4^+, Pb^{+2} and Cu^{+2} ions in column and batch trials [12]. In that study, zeolite with a particle size range of 0.42–0.85 mm was amended with a local sand at a ratio of 20:80 (w/w) by mass to reduce the construction costs. Clinoptilolite-type washed zeolite had been found to be a suitable material for PRB considering the comparable shear strength of the mixture (ϕ=28.9°) with the aquifer soil (ϕ=27.3°), and higher permeability coefficient values of zeolite ($k=2 \times 10^{-5}$m/s) than the aquifer soil ($k= 7 \times 10^{-6}$ m/s). The field column tests were conducted to predict changes in the barrier during operation and to verify the longevity of barrier under the field conditions [12]. Villalobos et al. [45] performed compaction, consolidation and direct shear tests on compacted tuff zeolite with particle size of coarse sand, fine sand, silt and 15% clay reporting that the increase in fine fraction reduced the shear strength related to the higher water content which was attributed to the chemical structure of zeolite.

A significant portion of the world's zeolite reserves are in Türkiye [46, 47], thus there are a number of studies about the use of local zeolite in geoenvironmental practice [33-36, 48-51]. Tuncan et.al. [51] performed geotechnical tests on the compacted mixtures of bentonite, sand and fine size crushed natural zeolite and investigated the environmental characteristics when waste disposal leachate is used as an influent by analyzing Pb, Ni, Zn, Cu and Cr concentrations. The zeolite additive at 10% by weight was suggested for the landfill bentonite liners under municipal waste, which benefits from the high cation exchange capacity compared to the lean bentonite. Cevikbilen [35] compared the compression behavior of dry and inundated 67% sand, 33% fine particle size fraction of a local raw zeolite, and performed permeability tests to predict the hydraulic conductivity of a zeolite barrier along the depth of a trench by performing experimental and numerical analyses. The numerical models predicted that the hydraulic conductivity of the barrier would significantly decrease below 20 m depth considering the relationship observed experimentally between overburden pressure, void ratio and permeability. The shear strength of the inundated zeolite exhibits conservative values compared with the dry zeolite regarding to the result of the direct shear tests in which the shear strength angle ϕ decreased from 38 to 35° even though a slight increase of cohesion is observed.

Use of slurry form of the zeolite may be a proper emplacement methodology considering the observed values of high consolidation coefficients and the lower values of secondary compression and swelling indexes. Even though chemically identical composition and microscopic structure results in similar affinity towards pollutant removal from aqueous sources, the increase in the fine-grained fraction of zeolite may significantly reduce the seepage velocity through a permeable barrier that may result in a scenario where the contaminated water bypasses the PRB. Hence, the effect of fine-grained fraction on the behavior of slurry-like zeolite should be discussed in advance to control the hydraulic conductivity along the barrier. In this respect, this study fills a gap about the effect of gradation on the permeability of a locally supplied raw Clinoptilolite-type zeolite rock prepared with mechanical crushers to be used as a reactive material at the sub-surface barrier. The hydraulic conductivity of zeolite emplaced in a trench at the slurry form was modelled experimentally after the consolidation stage under its self-weight using a rigid wall permeameter specifically designed for this study. Fine-grained zeolite was prepared at 1.5 times the liquid limit and applying one-dimensional compression allowed the consolidation of the samples under the overburden pressures within the range of 25 to 200 kN/m^2 to simulate the specimens in the deeper depths of the subsurface barrier with lower values of porosity. The permeability tests were conducted on these samples in the self-designed permeameter, which offered the advantage to apply a back pressure up to 700 kN/m^2 after the fully saturation had been verified. The comparison of void ratio - vertical effective pressure - the hydraulic conductivity relationship observed for the two specimens of crushed zeolite with different gradations presented that any increase in the fine particle size fraction or the overburden pressure decreased the hydraulic conductivity significantly. Consequently, an arrangement in grain size distribution of the same source reactive material from finer through coarser proportional with overburden pressure was proposed to improve the remediation performance along the depth of a subsurface barrier in harmony with the hydraulic conductivity of the adjacent soil profile.

2. MATERIALS AND METHODS

The source of the zeolite was from the Gördes district of Manisa province in Türkiye. Commercially available two fractions of the raw samples were supplied from the Gördes Zeolite Company. Fig. 1 shows the grain size distribution of samples S1 and S2 which have the particle sizes in between 0 - 2.0 mm, and 0 - 0.2 mm, respectively. The index properties of the samples were determined with respect to the relevant standards summarized in Table 1. Swelling potential of the zeolite was 3.5 mL/2g according to the ASTM D5890 method [52].

The zeolite specimens of the region are mostly reported to contain hydrated K, Ca, Mg, Na alumina-silicates [57]. Studies on identification and the origin, mineralogical and petrographic analysis of the rock samples of the source material with X-Ray Diffractometer illustrates that the major chemical compositions of the zeolite of this study are 71.6% SiO_2, 11.3% Al_2O_3, 3.67% K_2O, 2.27% CaO and the others are less than 1% by weight [35, 58]. Consequently, it is classified in 70~85 % Clinoptilolite-type zeolite group with the ratio of SiO_2/Al_2O_3 in between 5.0~6.3% at the source.

Table 1. Index properties of zeolite

Sample	S1	S2	Standard
Gravel (%) (>4.76 mm)	-	-	ASTM D6913 [53]
Sand (%) (4.76-0.075 mm)	67	16	ASTM D6913 [53]
Silt (%) (0.075-0.002 mm)	29	82	ASTM D7928 [54]
Clay (%) (<0.002 mm)	4	2	ASTM D7928 [54]
D_{85} (mm)	0.600	0.077	
D_{50} (mm)	0.164	0.030	
D_{15} (mm)	0.014	0.008	
D_{10} (mm)	0.0069	0.0055	
Liquid limit, *LL* (%)	58	55	ASTM D4318 [55]
Plastic limit, *PL* (%)	39	38	ASTM D4318 [55]
Plasticity index, *PI* (%)	19	17	ASTM D4318 [55]
Specific unit weight, *Gs*	2.39	2.38	ASTM D854 [56]

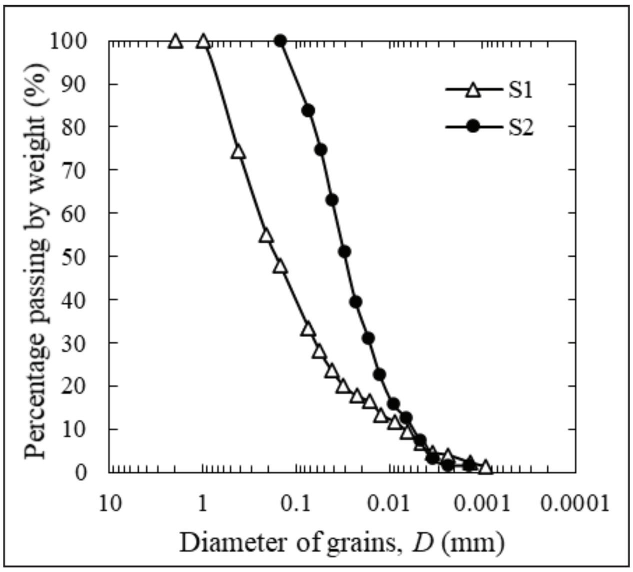

Figure 1. Grain size distribution of the samples.

Uygur et.al [57] compared the zeolites of two mining companies in Gördes region and presented that Gördes Zeolite Company had more impurities and involved tectosilicates such as 5% cristobalite and tridymite. The Scanning Electron Microscope (SEM) image taken at 3000 magnification factors of the zeolite sample used in the study (Fig. 2) confirms that the shape of the particles is varying from needle-shaped zeolite fibers to spherical-shaped amorphous structures.

The zeolite samples were prepared in the slurry form at water contents equal to 1.5 times the liquid limit. After the 24 hours of conditioning period of the slurry in a sealed container, a glass funnel was used while placing the remixed slurry samples in the test molds. Keeping the tip of the funnel inside the slurry, the tip was gradually raised from bottom to top. Thereafter, lateral light strokes were applied to the mold to minimize the air voids and finally a stainless-steel spatula was used to level the surface of the slurry.

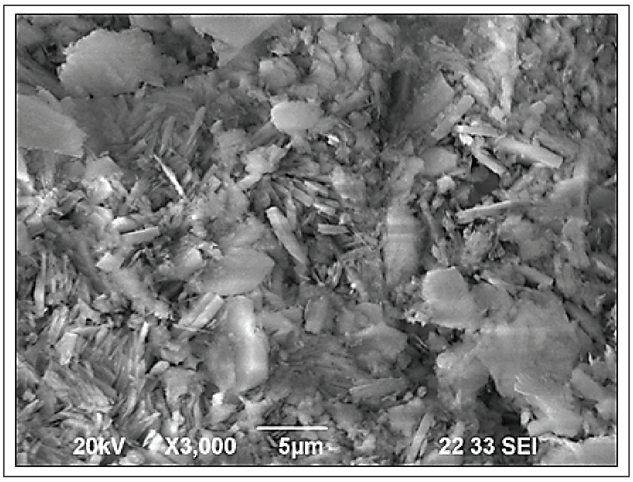

Figure 2. SEM image of Zeolite (x3000) [59].

One dimensional consolidation behavior of the samples was investigated in a consolidometer with an inner diameter of 63 mm and height of 40 mm. Two-way drainage was allowed at the top and bottom ends with the porous stones. The vertical loading was applied with a unit increment ratio in accordance with ASTM D2435 [60]. Time dependent vertical displacement were recorded by LVDT to check the end of primary consolidation at each load increment in a predesignated load duration of 24 hours.

Permeability tests of the zeolite samples were conducted in a new rigid wall stainless steel mold within the 45×45×45 mm inner dimensions. A front-loading arm type conventional consolidation test frame was modified to reconstitute the slurry at a predesignated overburden pressure in the mold on which an extension collar was initially attached. After a seating pressure of less than 5 kN/m^2 had been applied, the vertical load was gradually increased up to final effective consolidation pressure σ_v' values of 25, 50, 100 or 200 kN/m^2. During the reconstituting, a unit load increment ratio was adapted and the load increment durations were at least 24 hours. As in consolidometer, two-way drainage was allowed through the top and bottom porous ends. After the primary consolidation had finalized with respect to the settlement versus time data recordings, the cell chamber and the collar were removed. Then the excess height of each sample was trimmed, and the top cover of the mold was closed which has a porous end mounted inside. The vertical permeability test with respect to falling head – rising tail water procedure was performed with respect to Method C of ASTM D5084 [61] on the reconstituted samples in the mold which were connected to a Trautwein M100000 standard pressure panel through the top and bottom ends. Time dependent influent and effluent volumes of water passing through the sample was followed through the burettes on the panel during the test. The experiments were repeated at least 4 times under condition at which the hydraulic gradient was less than 5. Fig. 3 summarises the steps of the sample preparation and testing procedure.

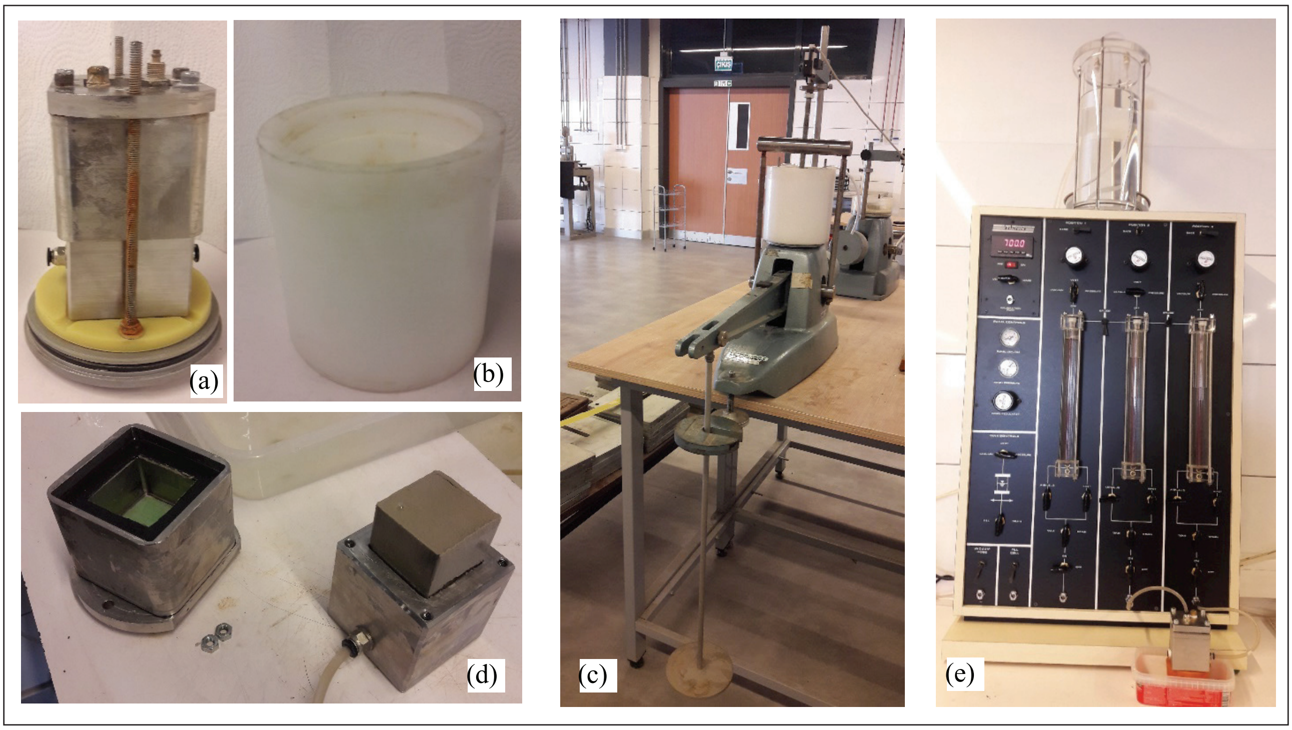

Figure 3. (a) Mold with collar piece (b) consolidation cell chamber (c) reconstituting S2 sample under 50 kN/m^2 consolidation pressure at modified front loading arm consolidation test setup (d) the sample before trimming after the collar piece was removed (e) the permeability test under 700 kN/m^2 back pressure.

3. RESULTS AND DISCUSSION

The subsurface barriers can be constructed as impermeable, permeable or the combination of both to limit, direct or treat the pollution in a contaminated region. While the k values of SB below 1×10^{-7}m/s are assumed to be sufficient for slurry cut off walls, in case of PRBs the k value of the reactive barrier should be higher than the aquifer soil. The fine content in fill material plays an important role on the hydraulic conductivity of the barriers. Since the construction methods and economic factors limits the installed thickness of the barriers less than 2 m in the direction of the groundwater flow for the zeolite-based barriers [14, 39], the use of proper graded samples in testing programs is essential. The sorption capacity and residence time inputs used in the mathematical models to predict the necessity in reactive material replacement will have a significantly impact on the economics of the system.

Before the long-term laboratory tests, the index properties of the fill material and the aquifer soil may be used for preliminary assessments to determine the interaction between them. Based on their grain size distribution, the filtration criteria stated by [62] as

$$D_{15\,filter} < 5\times D_{85\,soil} \quad (1)$$

$$4 < \frac{D_{15\,filter}}{D_{15\,soil}} < 20 \quad (2)$$

$$D_{50\,filter} < 25\times D_{50\,soil} \quad (3)$$

can be used to arrange the gradation of fill material considering the soil environment. Contrary, designating the soil type of the environment for a specific filler is applicable. In this context, the listed values in Table 1 presents that sample S1 will be a proper filter material for a soil stratum in which D_{85}>0.0028 mm, D_{50}>0.0065 mm, 0.0035 mm>D_{15}>0.0007 mm. while sample S2 is proper for a soil with D_{85}>0.0016 mm, D_{50}>0.0012 mm, 0.0020 mm>D_{15}>0.0004 mm. Hence, S2 offers a better filtration potential if the soil stratum has higher fine size particle content.

Since the zeolite in the slurry form at the initial case has direct contact with the aquifer soil, seepage property of zeolite can also be checked. The solid particles in the slurry, cannot permeate or can permeate the soil stratum or can flow out through the pores in soil stratum with respect to the n parameter $n<2$ or $2<n<4$ or $n>4$ respectively which is defined by

$$n = \frac{0.2\times D_{15\,soil}}{D_{85\,solid\,in\,slurry}} \quad (4)$$

In case of a slurry composed of S1 and S2 samples, the zeolite particles cannot seep, can seep, or flow out through the pores in the soil stratum which has D_{15}<6 mm, 6 mm<D_{15}<12 mm or D_{15}>12 mm, and D_{15}<0.77 mm, 0.77 mm<D_{15}<1.54 mm or D_{15}>1.54 mm, respectively. Considering a homogenous aquifer soil condition, S1 has lower seepage potential than S2 that S1 is properly used in sand and fine-grained soils, while S2 is applicable in only fine-grained soils.

The consistency limit tests presented that S1 has slightly higher value of liquid limit than S2 due to the higher amount of clay size particle. Practically, the change in fine fraction did not result in a significant change at plasticity and specific unit weight of the zeolite samples.

One dimensional consolidation behavior of the zeolite slurry samples S1 and S2, which have 33% and 84% fine fraction respectively, was determined. Fig 4 presents an example for the compression ratio versus logarithm of time plot observed under 100 kN/m^2 vertical pressure at S1. These recordings showed that primary consolidation duration is approximately 10 minutes for S1 under 100 kN/m^2 vertical stress. It was attributed to the predominant sand or silt size particles with the clay fraction below 4% for both of the samples. Therefore, it might be projected that zeolite-based barrier system in the field will settle under its own weight in a limited time domain which would consequently result in an apparent change in void volumes through the barrier with a direct impact on the performance of the barrier.

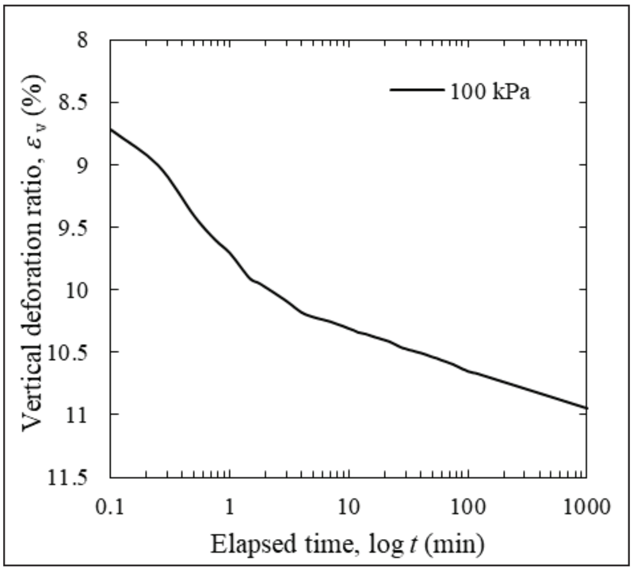

Figure 4. Consolidation behavior of S1 sample under 100 kN/m^2 stress level with time.

Consolidation curves of both S1 and S2 are presented in Figure 5. During loading stages, the void ratio values for S2 were observed higher than S1 at the same stress levels. However, at approximately 800 kN/m^2, both consolidation curves converge to each other, indicating that the effect of fine fraction by weight was negligible. The compression index, C_c of S1 and S2 was calculated to be 0.225 and 0.264, respectively. Compression indices of Clinoptilolite type zeolite remolded at its liquid limit has been reported as 0.194, with an initial void ratio of 1.184, which is in agreement with the results, since the initial void ratio of S2 is 1.47, hence a larger compression index is expected. For Terzaghi [63] proposed the compression index, C_c value for natural undisturbed soils as

$$C_c = 0.009 \times (LL - 10) \quad (5)$$

where *LL*: the liquid limit (in %). However, the predicted values around 0.400 by Equation 5 was lower than the observed values. In unloading stage performed after 800 kN/m^2, the swelling index, C_s of S1 and S2 was determined as 0.015 and 0.026, respectively in which S2 showed slightly higher values attributed to the higher fine content (Fig. 5).

The back pressure application is commonly used technique in triaxial testing to enhance the high degree of saturation of soil samples [64]. However, the saturation technique adopted in flexible wall testing cause an error considering the consolidation of the problematic soils sample due to the increase in effective stress under a constant total stress condition. Therefore, new permeameters were introduced such as low-compliance double cell/burette permeameter to track all volumetric changes during testing stages [65]. The rigid wall permeability cell proposed in this study is one of the permeameters that has the benefits of the back pressure application for the reliable characterization of saturated permeability and the constant void ratio of the reconstituted sample during testing. The vertical permeability tests were performed at several back pressure values. The higher back pressures present the faster saturation of the sample. Fig 6 shows the values of k_v versus back pressure observed in S2 sample under the back pressures in between 200 and 700 kN/m^2 when the hydraulic conductivity is steady.

The ratio of inflow and outflow rate was controlled to be in the range of 0.75~1.25 as mentioned in ASTM D 5084 [60], which was slightly out of the limits at the back pressures below 400 kN/m^2 and in the range of 0.9~1.1 above 500 kN/m^2. So, the values of k_v observed at the back pressures above 500 kN/m^2 was assumed to be sufficient for fully saturation of the samples and taken into consideration which decreased slightly with back pressure.

Besides, the vertical permeability coefficient, k_v values versus back pressures did not change significantly, the average values of k_v observed above 500 kN/m^2 were used in this study. Fig. 7 illustrates k_v values of S2 samples reconstituted at 25, 50, 100 and 200 kN/m^2. The k_v-σ_v' relationship of the sample S1 in the previous study of Cevikbilen & Camtakan [34] is also plotted in Fig. 7. The permeability tests of that study were also performed under constant volume conditions in a ELE brand odeometer cell specialized to determine the vertical permeability. It was obvious that the k_v values were gradually decreased when σ_v' increased for both of the samples. Contrast to the values of *e* of the same source zeolite, the S2 sample with higher fine size particles revealed approximately 10 times lower values of k_v at the same σ_v'. The greater change in *e* values at higher fine fractions cause the greater reduction in k_v at the relevant σ_v'. On the contrary, the same values of k_v were determined at around 8 times lower σ_v' for S2 compared with S1. It is seen that the grain size distribution controls the hydraulic conductivity of crushed zeolite in slurry trench applications, which will affect the performance of the barrier. Ören and Özdamar [48] reported comparable hydraulic conductivity values for a compacted zeolite sample having a clay content of 3%.

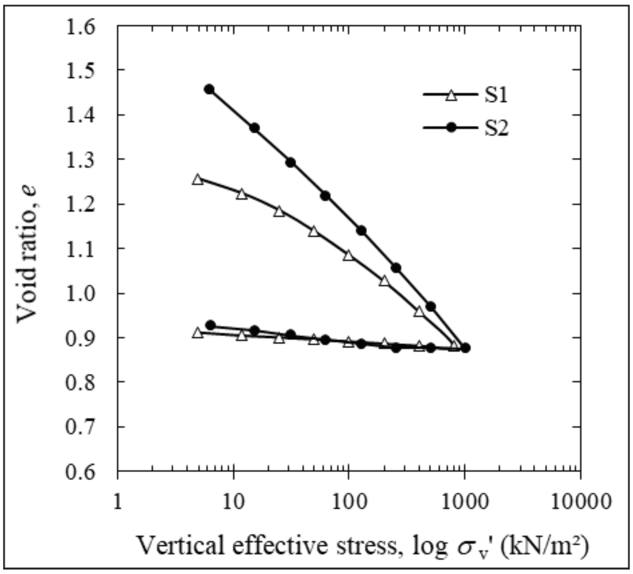

Figure 5. Consolidation behavior of the samples with vertical effective stress.

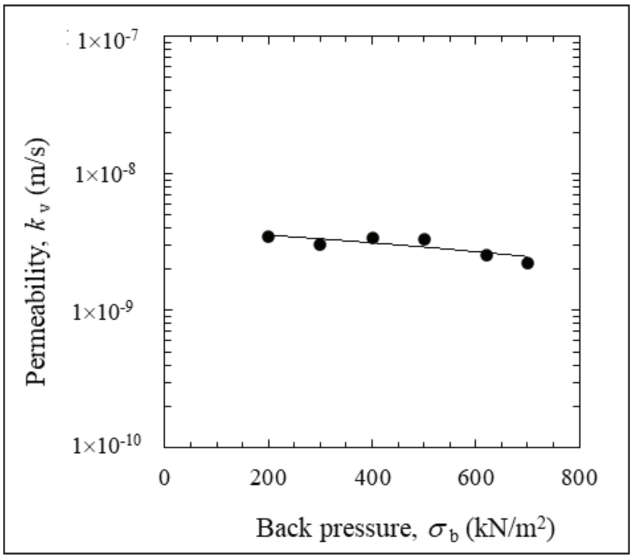

Figure 6. Permeability of S2 sample prepared at 200 kN/m^2 under several back pressures.

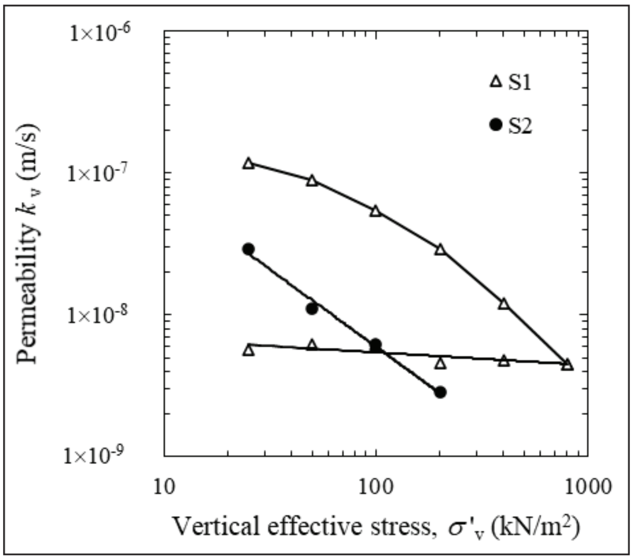

Figure 7. Permeability versus vertical effective stress for zeolite samples S1 and S2.

Hazen's equation [66] for clean uniformly graded materials between permeability coefficient k (in m/s) was defined by

$$k = \frac{(D_{10})^2}{100} \quad (6)$$

where D_{10}: effective grain diameter (in mm) at which the soil weight. The predicted k values of S1 and S2 by Equation 6 are 4.7×10^{-7} and 3.0×10^{-7}m/s, respectively, which are higher than the observed values under any stress condition. So, environmental testing programs should involve the hydraulic conductivity tests on the final product at relevant overburden pressures for sustainable solutions.

In situ conditions, the reduction in effective overburden pressure along the barrier column is observed in the limited cases when the groundwater level rises or when an excavation is required. The low values of C_s for zeolite samples exhibit the swelling will be limited even though a slight increase was shown in Fig. 5 with an increase in fine fraction. Accordingly, unloading result no significant change in k_v for S1 sample despite the reduction in σ_v' from 800 to 25 kN/m^2 (Fig. 7). So, permeability tests at the unloading stage of S2 were not performed with respect to the low C_s value and the low swelling potential of the zeolite source material determined by ASTM D5890 [51].

4. CONCLUSION

The use of local reactive resources against environmental problems will reduce the application costs and enable quick response in case of a post-pollution scenario after a predictable disaster. The subsurface barriers offer sustainable solutions to limit, direct, immobilize or treat the site-specific pollutants that requires short- and long-term laboratorial studies to predict the performance and longevity of the barrier before the construction. In this context a new rigid wall permeability cell was proposed for slurry like reactive materials that allow to study with the reconstituted samples under a vertical overburden pressure and eliminate the consolidation effect encountered during the flexible wall permeability tests. Following findings were obtained:

- The tests performed on S2 presented that k reduces with σ_v' which are below 10^{-7} m/s above 25 kN/m^2 overburden pressures and sufficient for impermeable wall sections. Further studies on thickening or dispersing agents will improve the flexibility, workability and sealing property of the slurry like fine grained zeolite for impermeable barrier applications.
- The comparison of the findings with the literature indicates that the higher k values are applicable by increasing the coarse particle size fraction of crushed zeolite. When the fine fraction in the slurry is reduced to 33%, k values are increased approximately 10 times than the zeolite with 84% fines under the same σ_v' conditions. Nevertheless, the use of slurry form of coarse-grained zeolite with 33% fines in PRB applications requires further investigation in which the k values are still lower than 10^{-7} m/s at σ_v' above 50 kN/m^2.
- This study further proposes hydraulic conductivity tests on the slurry like barrier material reconstituted at the relevant overburden pressures with respect to the height of the barrier to be involved in environmental testing programs.
- The new permeameter has promising advantages for the future works by helping to compose the porosity related breakthrough curves of a barrier material that may later be subjected to a site-specific leachate testing program for sustainable solutions.

ETHICS

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

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article.

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Research Article

Mechanical behavior of large-diameter pipe elbows under low-cyclic loading

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ABSTRACT

Large-diameter steel pipes are often used for transmitting and distributing water, gas, and oil products from the source to the end user. These pipelines are mainly oriented by using pipe elbows due to their high flexibility along their routes. It is important to understand the mechanical behavior of these critical infrastructure components to promote material sustainability. For this purpose, a rigorous 3D finite element model is employed to investigate the mechanical behavior of large-diameter pipe elbows with varying elbow angles such as 90°, 60°, and 30°. Moreover, geometrical and material nonlinearities capture the pipes' ratcheting behavior even under pressurized and unpressurized scenarios. It is seen that the pipes with a larger elbow angle can endure a higher number of cycles before they reach their limit states. In addition, pipe elbows behave similarly to straight pipes as the elbow angle decreases and becomes more vulnerable to plastic deformations such as kink and buckling under bending loads.

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1. INTRODUCTION

Curved pipes, also often referred to as pipe bends or elbows, are critical infrastructure components used for orienting buried pipelines [1] along their route (Fig. 1). In addition, these components are also used in a wide range of applications, including critical piping of storage tanks [2], power plants [3], industrial facilities [4], and even offshore platforms [5-6]. When these critical components are subjected to extreme events such as fault ruptures, lands, and repeated loadings, the pipeline network becomes highly vulnerable, resulting in service disruptions and economic losses. In addition to the failures of the pipelines, loss of containment of these storage tanks, power plants, and industrial facilities can be experienced due to the uplift effect under repeated loads at tank surfaces, tee connections, and nozzles. It can be hazardous to the environment and human health.

Due to the complexity of these pipeline networks, the stresses and deformations these systems undergo might be quite different from the conventional straight pipes due to their flexible characteristics. In case of severe loading conditions, cross-sectional ovalization and ratcheting failures govern the bending capacity and failure modes that are directly associated with the ratio of (D/t) and (R/D) where the pipe diameter is D, the wall thickness is t, and the radius of elbow curvature is R.

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Figure 1. (a) pipe elbow [7] used for; (b) routing of natural gas pipeline [8].

In the literature, most of the studies on pipe elbows are focused on variational *D*/*t* and *R*/*D* ratios. Much research [9-13] focused on *D*/*t* ratios ranging from 10 to 97. Among these studies, Sobel and Newman [9] tested a 90° seamless pipe elbow and verified the results using the finite element method considering large displacements and material nonlinearity. Suzuki and Nasu [10] studied a welded 90^0 elbow component under in-plane bending loads. Another research study [11] employed a 90° pipe elbow with a bending curvature-to-diameter ratio of *R*/*D* = 3. A comprehensive research study [12] elaborated on the mechanical behavior of 90° pipe elbows focused on failure modes depending on the effects of *D*/*t* ratio and internal pressure levels. The studies are lately evolved into promoting material sustainability and life estimation for pipe elbows [13] to increase the fatigue life of pipe elbows.

Most of these studies address toe pipe elbows when used for industrial piping systems with relatively small pipe diameters. As for the large-diameter buried steel pipelines, *D*/*t* and *R*/*D* ratios are expected to be higher due to the practicing devices for cleaning, inspection, dimensioning, and testing purposes [14]. In literature, the diameters of pipe elbows, which have been studied experimentally and numerically for the transmitting pipeline systems, remained limited in a range of 100 [15] to 400 mm [16] for a 90° elbow pipe.

Oil, gas, and especially water transmission pipelines are made of large-diameter steel pipes starting from 450 mm up to 2540 mm due to the high amounts of products to be transported. In this study, the geometrical parameters of a well-documented steel water transmission line [17-20] with a diameter of 2200 mm are chosen to reveal the mechanical behavior of large-diameter steel pipe elbows under cyclic loading. The main parameters to be investigated within this research study are the elbow angles (90°, 60°, and 30°) and internal pressure, p_y as per operating conditions reported in related documents [17]. The bending curvature-to-diameter ratio, *R*/*D,* is chosen as five, which is the mode that allows proper pigging operations for the buried pipelines in practical applications.

Preliminary calibration studies are conducted based on a given experimental research study [4], as detailed in the following section. Geometrical and material assumptions are made in accorded reference. After verification studies, the results of the numerical studies are explained.

2. NUMERICAL SIMULATION

2.1. Finite Element Modeling

This study uses a finite element (FE) model by software. Geometrical and material nonlinearities are taken into unconsidered predicting the post-buckling behavior and the failure modes. For this purpose, calibration studies were performed before this on previous experimental and numerical research work [4]. A 203 mm long SCH40 pipe elbow with a diameter of *D* = 219.1 mm and a wall thickness of *t* = 8.18 mm was tested under cyclic loading with an elbow curvature radius of *R* = 305 mm. Steel pipe material was employed as P355N following EN 10216-3 code corresponding to ANSI/API 5L X52 steel grade. The FE model consists of two straight parts with a length of 5D connected to the pipe elbow by tie connection (Fig. 2). Both pipe elbow and straight parts are C3D8R solid elements with equal wall thickness. A kinematic coupling algorithm specifies boundary conditions at the center

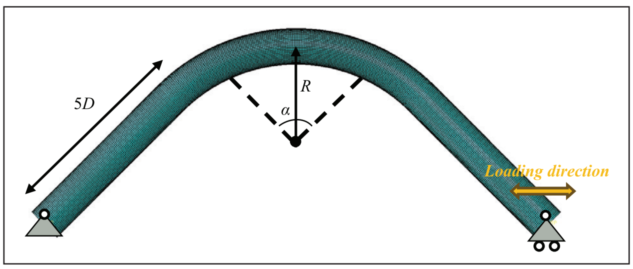

Figure 2. The radius of pipe curvature, *R,* and boundary conditions of a 90° elbow.

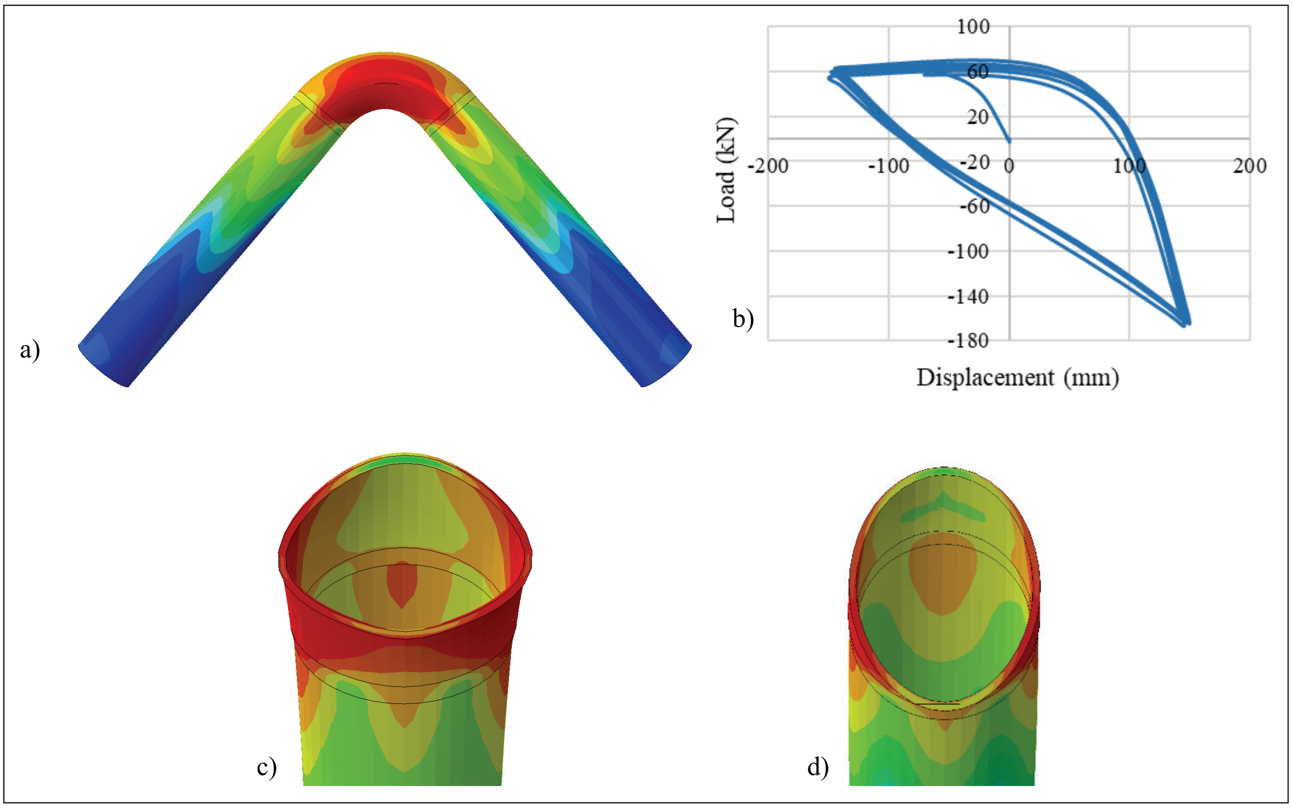

Figure 3. (a) pipe deflection at elbow crown due to material plasticity (b) hysteresis curve (c) closing and (d) opening ovalization.

of straight pipe ends with pinned and roller supports. A displacement boundary condition is defined on the right side as roller support (in-plane) with a cyclic loading protocol of 1.0 to 3.0 meters. For this purpose, numerical analyses were conducted using a low-cyclic loading procedure under a general static step after applying internal pressure.

The results were obtained for the pipe elbow under 3.2 MPa operating pressure with ± 150 mm of loading amplitude. The model captured the similar ratcheting behavior of the pipe elbow when a combined isotropic/kinematic hardening model was employed. The pipe deflection (Fig. 3.a) was formed due to accumulated stresses at the elbow crown after 61 cycles. The hysteresis curve (Fig. 3.b) was obtained at the released end of the pipe constraint and verified with the related research work about material nonlinearity. The von-misses stress contours depict the yielded area, including failure of the pipe elbow due to repeated closing (Fig. 3.c) and opening (Fig. 3.d) forms under cyclic loading.

As for the mechanical behavior of a large-diameter water pipeline, Kullar water steel pipeline (D = 2200 mm) properties were investigated under three different cases of elbow angle, α such as 90°, 60°, and 30°. The steel grade utilized in this research study was chosen API 5L Grade B steel grade by the properties of the actual water pipeline [17]. Besides, the internal pressure p_y was taken at 1.0 MPa, corresponding to the operating pressure specified in the reference. The R/D ratio is also chosen as 5 for the buried pipelines that allow proper pigging operations [14], whereas the pipe has an 18 mm thickness (D/t = 122).

2.2. Material Model

An inelastic material property, Armstrong-Frederic (AF) nonlinear kinematic hardening model, is defined through the ABAQUS material library that allows to capture Bauschinger effect and accumulated plastic strain (ratcheting effect) for metals subjected to cyclic loading [21]. The combined isotropic/kinematic hardening algorithm introduces the concept of change in the center of yield surface for the metals under cyclic loading, allowing the main difference between yield and back stresses. The kinematic hardening component is given as:

$$\dot{a} = C\dot{\varepsilon}^{p} - \gamma\alpha\dot{\varepsilon}_{q} \tag{1}$$

Where C stands for kinematic hardening modulus, γ is the decreasing rate due to increasing plastic strain, $\dot{\varepsilon}^{p}$ And α is back stress. In addition, the equivalent plastic strain $\dot{\varepsilon}_{q}$ It also is defined as:

$$\dot{\varepsilon}_{q} = \sqrt{\frac{3}{2}\dot{\varepsilon}^{p} : \dot{\varepsilon}^{p}} \tag{2}$$

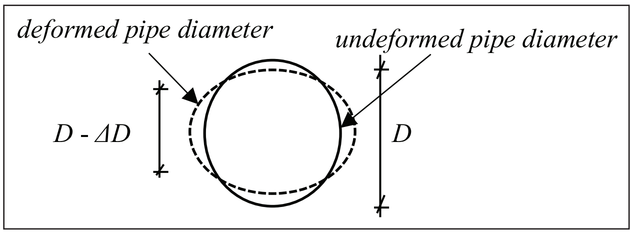

Figure 4. Cross-sectional distortion-based ovalization.

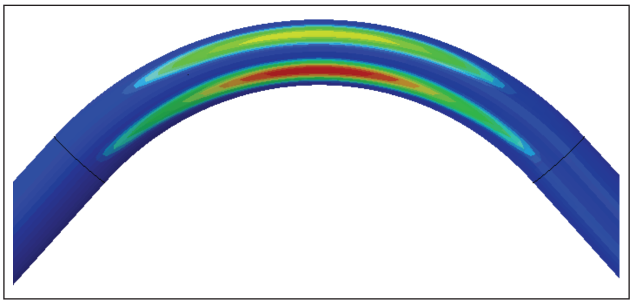

Figure 6. Plastic zone formation of 90° pipe elbow under 1.0-meter cyclic loading.

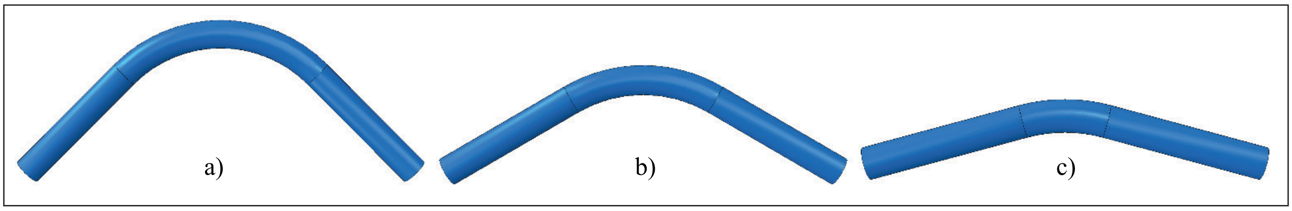

Figure 5. a) 90°, b) 60° and c) 30° pipe elbows.

Due to the lack of experimental data, the mechanical properties of the water pipe are taken by the API 5L Grade B with a modulus of elasticity, E = 221.37 GPa, yield stress of σ_y = 293.27 MPa, and ultimate tensile strength of σ_u = 480.13 MPa as given in the reference study [22]. The relevant stress-strain curve is also integrated into the combined isotropic/kinematic hardening model using data type aa s half cycle.

2.3. Performance Criteria of Steel Pipes

According to the American Lifeline Alliance (ALA) guideline [23] tensile strain limit is 4% to maintain n pressure integrity of the pipe. Besides, the Pipeline Research Council International (PRCI) guideline [24] suggests limiting tensile strain to 2-4% for pressure integrity and 1-2% for normal operability. On the other hand, the compressive strain limit state, which corresponds to the pressure loss, is reached when the plastic strain rate is equal to 1.76 t/D in both guidelines. Moreover, Gresnigt [25] suggested a flattening parameter, f, to clearly describe cross-sectional distortions as an ovalization limit state which is:

$$f = \Delta D/D \tag{3}$$

And it is assumed that the cross-sectional limit state is reached when the flattening parameter equals 0.15 (Fig. 4).

3. NUMERICAL RESULTS

The mechanical behavior of steel pipe elbows is investigated for three different elbow angles, as given in Fig. 5. The hysteresis curves are obtained for each pipe elbow for the case of both pressurized and unpressurized under different ranges of lateral cyclic movements. And the results are discussed in terms of the performance mentioned above criteria and limit states.

3.1. 90° Pipe Elbow

For two cases, 1.0, 2.0, and 3.0 meters of cyclic loading protocol are subjected to the 90° pipe elbow. As for the pressurized pipe elbow, it is seen that the compressive strain limit state was reached after 32 cycles with a plastic strain value of 1.46% under 1.0 meters of lateral cyclic loading. When the pipe undergoes cyclic loading without having internal pressure, the pipe distortion and ovalization become more critical, and the limit state is reached due to the flattening parameter. However, there was no buckling formation for 2.0 and 3.0 meters of cyclic loading for 90° pipe elbows. The plastic formation zone was observed close to the elbow crown, especially on the intrados side of the pipe elbow (Fig. 6).

Besides, the limit plastic strain levels were reached under fewer cycles as the lateral displacement range increased. The hysteresis curves are given in Fig. 7 for both pressurized and unpressurized cases under 1.0, 2.0, and 3.0 meters of cyclic loading.

3.2. 60° Pipe Elbow

According to the numerical result of the 60° pipe elbow, the limit plastic strain levels are reached at earlier stages (fewer cycles) compared to the 90° pipe elbow. It is seen that the plastic zone is shifted from the elbow flank to intrados under 1.0 meters of cyclic loading (Fig. 8). Moreover, the more the pipe elbow angle decreases, the more the pipe system becomes vulnerable to kink or buckling effect under same repeated displacements. The hysteresis curves obtained for 60° pipe elbow are given in Fig. 9 below. The tensile strain limit state is reached at the 4th cycle with a

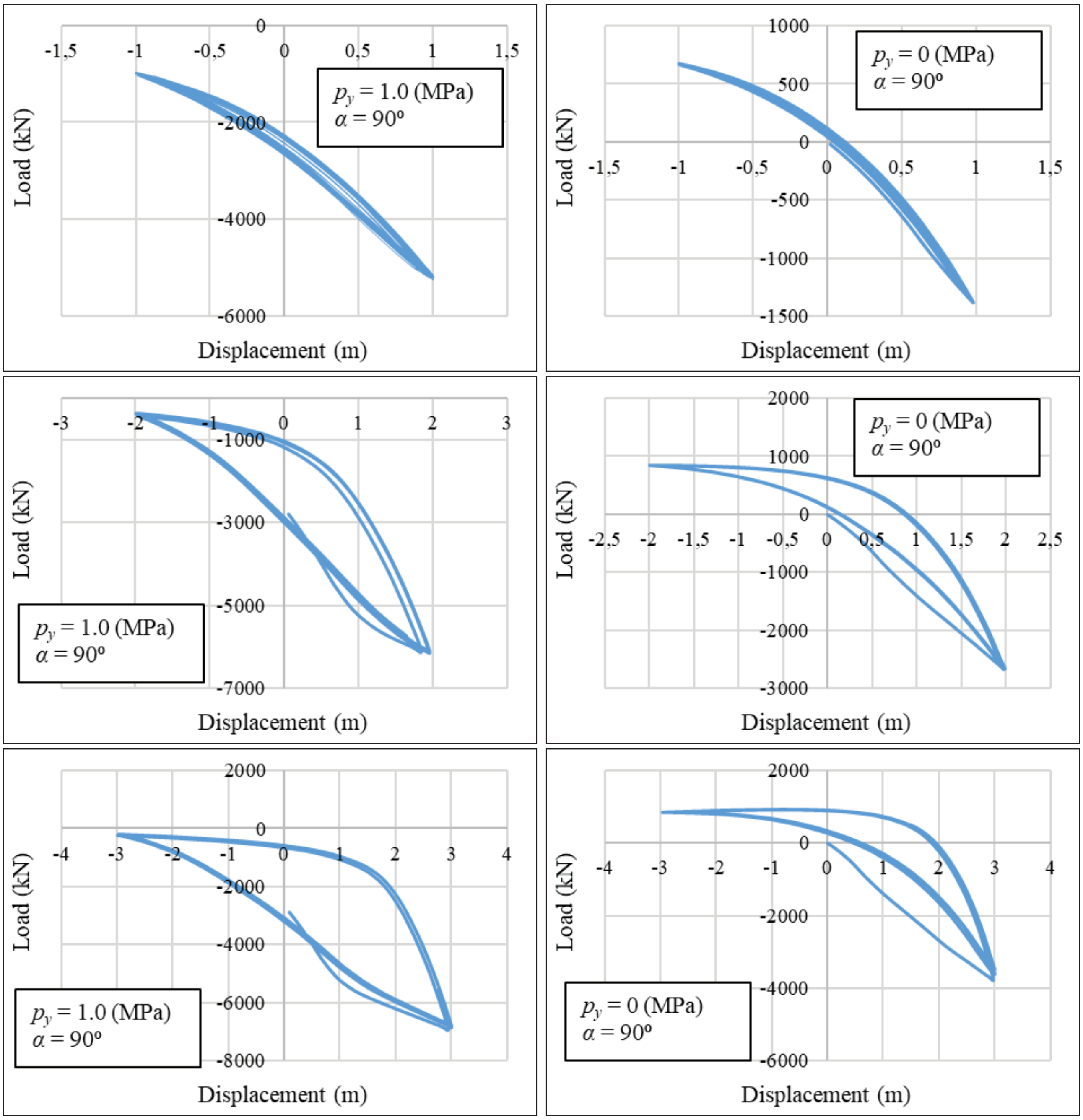

Figure 7. Hysteresis curves for 90° pipe elbow.

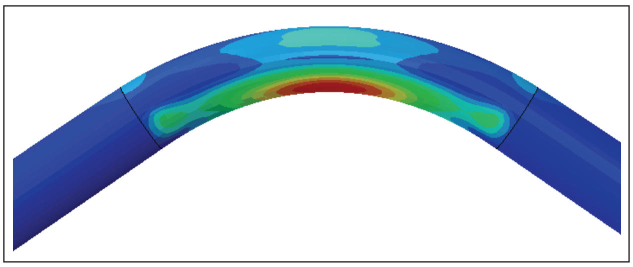

Figure 8. Plastic zone formation of 60° pipe elbow under 1.0-meter cyclic loading.

plastic strain value of 1.63%, and the flattening ratio is exceeded the critical value of 0.15. Similar to the 90° pipe elbow, the formation of plastic deformation is delayed under operating pressure. However, there was no sight of buckling formation under 1.0 and 2.0 meters of cyclic loading but only under 3.0 meters of repeated loads.

3.3. 30° Pipe Elbow

As for the 30° pipe elbow, the pipe's flexibility has remarkably reduced due to a decrease in the elbow angle, and yield strains were reached at the beginning of the

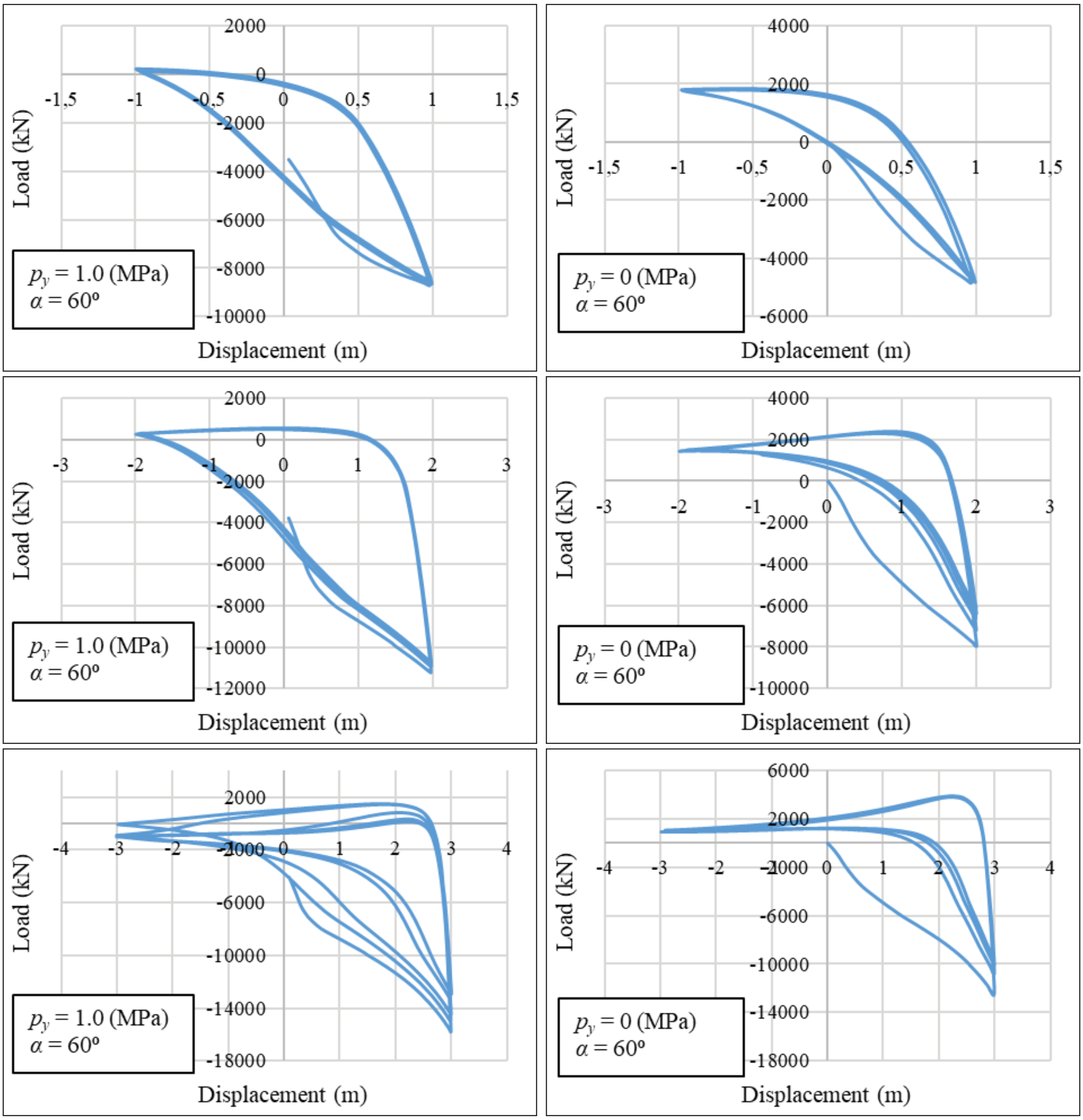

Figure 9. Hysteresis curves for 60° pipe elbow.

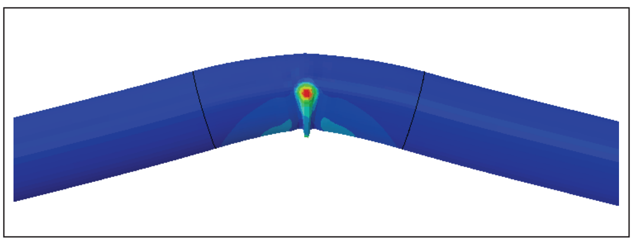

Figure 10. Plastic zone of 30° pipe elbow under 1.0-meter cyclic loading.

loading protocol. It is seen that the pipe elbow behaves similarly to the straight pipes, where tensile and compression limit states are mainly governed. Due to high plastic strain values, only 1.0 meter of cyclic loading results were obtained for the 30° pipe elbow, where the buckling formation was observed as in Fig. 10. Also, the decrease in the number of cycles before the plastic strains were observed in Fig. 11.

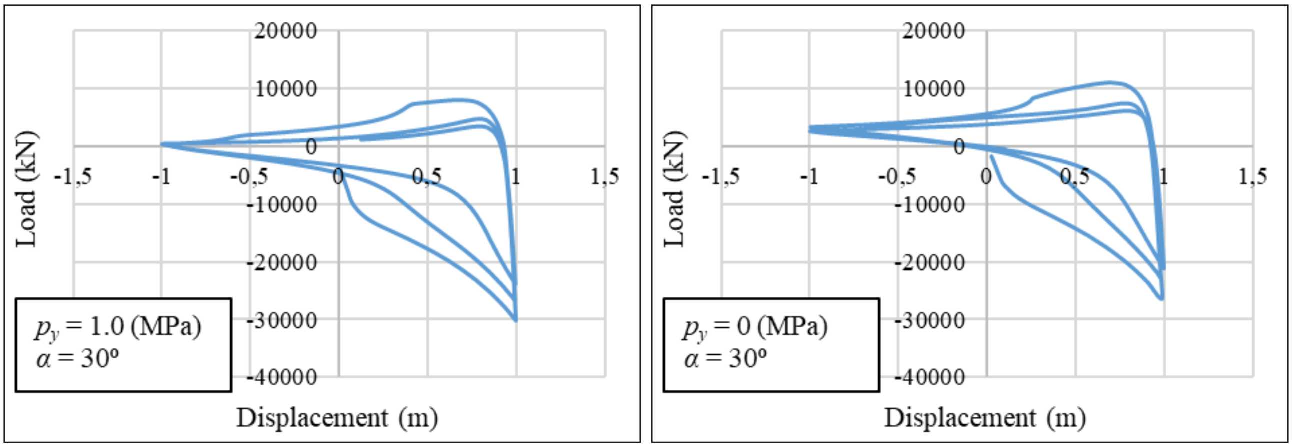

Figure 11. Hysteresis curves for 30^0 pipe elbow under 1.0 meters of cyclic loading.

The numerical results have verified the relation between pipe elbow angle and flexibility which might become critical in providing the structural integrity of pipeline systems. It should be noted that the pipe elbows behave similarly to the straight pipes as the elbow angle decreases and become more vulnerable to plastic deformations. Moreover, the fatigue life of pipe elbows with a higher angle expands due to their higher tolerance for repeated loads before reaching limit state values.

The findings of this study can be applied to pipelines, pipe-tank connections and industrial facilities, power plants, and many other practical scenarios. However, the surrounding soil effect for buried pipelines should also be considered in predicting local strains, which might easily be affected by soil conditions (stiff and soft soil) and seismic hazard regions. Therefore, further study recommendations are provided in the conclusion section.

4. CONCLUSION

Steel pipe elbows are critical infrastructure components for orienting pipelines along their routes. Promoting these systems' fatigue life and material sustainability is important, which may result in large-scale economic losses and service disruptions due to seismically induced cyclic loadings. This study investigates the mechanical behavior of large-diameter steel pipe elbows, which behaves differently from conventional straight pipes due to the stresses and deformations they undergo based on their flexible characteristics. For this purpose, a 3D nonlinear finite element model is employed and calibrated before the numerical studies. Geometrical and material nonlinearities are considered for the numerical models by adopting the Armstrong-Frederick plasticity model. Three types of pipe elbow, such as 90°, 60°, and 30°, are subjected to 1.0, 2.0, and 3.0 meters of low-cyclic loading protocol for pressed and unpressurized cases.

The results revealed that the pipes with a larger elbow angle could undergo a ignores before reaching their limit states. In addition, steel pipe elbows with small angles behave similarly to straight pipes (with less flexibility under opening and closing bending loads) in terms of mechanical behavior, as tensile and compression limit states are mainly governed. Moreover, the vulnerability to plastic deformations, such as the formation of kink and buckling deformations, is increased compared to pipe elbows with larger angles. Unpressurized pipe elbows were also found more vulnerable to pipe distortion and ovalization.

As for further studies, the mechanical behavior of steel pipe elbows can be elaborated on the surrounding soil conditions by adopting soil-pipe interaction or equivalent soil springs for different types of soil (stiff and soft soil) and D/t ratios. Considering the distance between the fault line and pipelines supported with elbow components, local strain values, and pull-out forces can be elaborated. In addition, innovative and advanced materials, including geometrically improved flexible joints, can improve the seismic performance of steel pipe elbows under severe ground motions.

ETHICS

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

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE

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

AUTHOR'S CONTRIBUTIONS

The author confirms sole responsibility and contribution for the study conception and design, analysis and interpretation of results, and manuscript preparation. Further, the author has validated and approved the final manuscript.

PEER-REVIEW

Externally peer-reviewed.

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