



Enhancing the Sustainability of Foamed Concrete Using Industrial By-Products and Pozzolanic Additives

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ABSTRACT

This research investigates the effect of various pozzolanic materials on the physical, mechanical, and thermal properties of foamed concrete. An extensive experimental plan was designed for this purpose, consisting of foamed concrete mixtures with five pozzolanic additives (silica fume, glass powder, fly ash, leaf stem ash, and slag), all of which were used as a 15% substitute for cement. Porcelanite was used as a fine, lightweight aggregate for all mixtures with the exception of the reference mix. A 3:1 foaming agent-to-water ratio was used for all mixtures, which resulted in a foam density of 42 kg/m³. The test results confirmed that foamed concrete with a density of 1100 to 1290 kg/m³ would have a compressive strength of nearly 16 to 20 MPa at 28 days when pozzolanic additives are used. The use of these materials as additives also significantly reduced thermal conductivity. Specifically, the mix containing 15% leaf stem ash performed better than the other pozzolanic replacements, exhibiting the best thermal, mechanical, and physical properties.

Keywords: Foamed concrete, Glass powder, Lightweight concrete, Pozzolanic materials, Sustainability.

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1. INTRODUCTION

Foamed concrete FC is a lightweight concrete by virtue of its unique porous structure which lowers concrete density, improves thermal, and acoustic insulation. It is easy to place and does not need compaction or surface leveling. Compared to normal concrete, Khan [1] remarks that FC weighs only 1.5 to 4 times less. While conventional concrete compressive strength is more than 28 MPa, FC only compressively ranges 7-30 MPa. Thus, FC is lightweight favorable to traditional concrete. Flexural capacity is a strong point of FC as noted by Sun et al.[2, 3] even after being exposed to high temperatures, while other works [4-6] remain skeptical stating concrete can spall from fires. Depending on the percentages of the concrete constituents, the dry density of FC ranges from 400 to 1600 kg/m³. It is suggestible that mixtures less than 800 kg/m³ density are sand-free and their compressive strength is very low, which makes them structurally non-applicable [7]. On the other hand, the compressive strength of FC zoned between 800 - 1400 kg/m³ can be sanded and range between 17MPa and 1400 kg/m³, with the compressive strength surpassing 17MPa, sanded and unsanded FC can be used structurally for housing, slabs, and load bearing frames. Additionally, with a controlled cement dosage, strength can be valorized but at a high cost. The use of low-density FC on structural applications reduces the dead weight of the building, resulting in lower reinforcement and material costs in handling and transportation. Moreover, the superior insulating properties lower the dead load and enhance the performance of building elements, thereby improving energy efficiency and reducing heating and cooling costs. In addition, enhanced acoustic insulation and improved workability optimized the performance of foamed concrete mixtures, allowing them to be used more effectively in functional applications. At present, the construction industry places significant emphasis on sustainability[8] [9, 10]. As a result, mechanical performance and cement-based construction materials must also have impact on the ecological and economic performance [11, 12]. The last few years have seen attention towards the research and development of Lightweight Foamed Concrete LWFC to be budget friendly and environmentally friendly. Alireza and Sina [13] studied FC with nano-silica and made a comparison to FC with micro-silica and the reference concrete. According to Alireza, micro-silica was less effective than nano-silica in enhancing the young age compressive strength of the concrete with the exception of in the sand-free mixes. On the other hand, the compressive

strength of concrete with increased pore size reduces [14]. Other factors such as (w/c) ratio of water to cement, ratio of cement to aggregate, nature of aggregate, and the duration of curing have all been seen to have an impact on the FC's mechanical performance. Mixes rich in fine sand tend to be stronger as compared to other mixtures. There is a lack of substantial proof regarding the ever-increasing value of fly ash or low-density fillers. It is observed that mixtures with expanded shale aggregates outperform sand-based mixtures achieving similar strength at similar wet densities [21, 22].

While prior research has examined various factors, some aspects remain underexplored, particularly the characteristics of sustainable foamed concrete containing waste glass powder and leaf stem ash. Using these materials as supplementary cementitious materials (SCMs) not only helps address waste management by reducing landfill usage, but also conserves energy and lowers carbon emissions. In this context, the focus of this study is a thorough evaluation of five pozzolanic materials that have not been widely investigated, each replacing 15% of the cement by weight. This replacement ratio is relatively less studied compared to the more common 10%, 20%, 30%, and 40% replacement levels that dominate the literature [16, 23-31].

The study aims to assess the density, compressive strength, and thermal conductivity of foamed concrete to identify the best pozzolanic material for producing sustainable foamed concrete. By focusing on this specific replacement ratio across multiple industrial by-products, the study offers novel insights into material efficiency, environmental benefits, and performance optimization. In doing so, it contributes to a broader understanding of sustainable mix design strategies for foamed concrete applications.

2. EXPERIMENTAL WORK

2.1 Materials

In this experimental study, 42.5 N Portland cement with a specific gravity of 3.15 was used. The test results confirmed the cement's compliance with Iraqi Standard No. 5/2019. Five different pozzolanic materials were used as partial replacements for cement, each at a constant substitution rate of 15% by weight. A uniform replacement level was applied to all materials to ensure a fair comparison across different curing ages. The materials used were: silica fume (SF), glass powder (GP), fly ash Class F (FA)—which meets the requirement of a combined SiO_2 , Al_2O_3 , and Fe_2O_3 content of less than 70%—leaf stem ash

(LA), and ground granulated blast-furnace slag (GGBFS). The chemical and physical properties of the cement and the supplementary cementitious materials (SCMs) are provided in Table-1. For the fine lightweight aggregate (LWA) in the control mixture (CIt), a saturated surface-dry Porcelanite was used. Table-2 presents the physical and chemical properties of Porcelanite rock. The aggregate gradation met the grading criteria of Zone 2 as per Iraqi Specification No. 45/1984, and the fine aggregate's particle size distribution is shown in Table-3. To achieve the desired flowability, a high-range water-reducing superplasticizer (SP) designed for self-compacting concrete was used. Workability was evaluated using the table flow test, targeting a diameter of 200 ± 2 mm, as per ASTM C230. Flowed concrete was produced using a protein-based foaming agent, which incorporated controlled levels of air into the mixture. A high-speed mixer was employed to prepare the foaming solution, with a water-to-agent ratio of 3:1. This resulted in a foam density of 42 kg/m^3 . The reference mixture consisted of cement and natural sand in a 2:1 weight ratio. Table-4 provides the proportions and descriptions of all concrete mixtures used in the study.

Table 1: Chemical composition and physical properties of cement and SCMs.

Properties	Oxide compounds	Abbreviation	Compound composition					
			OPC	SF	GP	LA	GGBFS	FA
Chemical	CaO	Lime	62.8	-	11	10.19	43.2	10.19
	SiO ₂	Silica	19.63	93.47	68	52.36	29.2	61.38
	Al ₂ O ₃	Alumina	4.29	2.15	7	12.34	13.8	9.72
	Fe ₂ O ₃	Iron oxide	5.41	0.65	1	2.64	5.5	0.63
	MgO	Magnesia	2.38	-	1	5.77	6.7	1.98
	SO ₃	Sulfate	2.31	Nil	0.4	0.39	Nil	3.72
	L.O.I	Loss on ignition	1.85	2.14	-	16.3	-	9.10
	I.R	Insoluble residue	0.54	-	-	-	-	-
	L.S.F	Lime saturation factor	0.96	-	-	-	-	-
		Free lime	0.9	-	-	-	-	-
Physical	Fineness cm ² /g		3998	200,000	30000	3200	4000	3800
	Specific gravity		3.15	2.37	2.58.	2.2	2.9	2.59

Table 2: Physical and chemical properties of Porcelanite rocks.

Property	Standards test	Results
Sulfate content as (SO ₃), %	BS3797: Part 2:1981	0.38
Aggregate crushing value, %	BS812: Part 110:1990	16
Dry-rodded density, Kg/m ³	ASTM C29-15	625
Dry-loose density, Kg/m ³		734
Absorption, %	ASTM C127-15	29.6
Specific Gravity		1.65

Table 3: Grading of Porcelanite.

Sieve opening, mm	Cumulative passing, %	IQS Limit NO.45\1984 zone 1
4.75	99.3	90-100
2.36	70	60-95
1.18	40	30-70
0.600	19	15-34
0.300	9	5-20
0.150	2.5	0-10

Table 4: Mix proportions of foam concretes mixtures, kg/m³.

Mixture ID	Cement	SCMs					Fine aggregate*			SP	Water	Foam details	
		SF	GP	FA	LA	Slag	Sand	Porcelanite	Foaming agent			Water	
Ctl.	1000	-	-	-	-	-	500	-	15	228	21.4	7.1	
RP	1000	-	-	-	-	-	-	260	20	261.7	21.4	7.1	
MS	850	150	-	-	-	-	-	260	20	305	21.4	7.1	
MG	850	-	150	-	-	-	-	260	20	276	21.4	7.1	
MF	850	-	-	150	-	-	-	260	20	301.7	21.4	7.1	
ML	850	-	-	-	150	-	-	260	20	272	21.4	7.1	
M-slag	850	-	-	-	-	150	-	260	20	314	21.4	7.1	

2.2 Methodology

This experimental investigation focused on using supplementary cementitious materials (SCMs) to evaluate changes in the density, compressive strength, and thermal conductivity of foamed concrete. The foaming agent-to-water ratio was set at 1:3 by weight for all mixtures. To account for water absorption, the fine aggregate was soaked for 48 hours and then air-dried for about one hour to reach its optimal moisture content before mixing. The foam was prepared by combining the foaming agent and water in a high-speed mechanical mixer. The fresh density was measured using a pre-weighed container of known volume. The foam generated had a density of 42 kg/m³.

The foam was then mixed with either ordinary or blended cementitious materials in controlled amounts to achieve the desired volume of foamed concrete in both its fresh and hardened states [32]. Each batch was mixed for approximately three minutes until the paste was visually homogeneous. It should be noted that the blends were not designed to achieve a specific density. Foamed concrete (FC) was tested for density, compressive strength, and thermal conductivity in compliance with ASTM C642, ASTM C109, and BS 874:1973, respectively. For mechanical tests, six 50 mm cube specimens were cast for each mixture and cured under water at 20 ± 2 °C for 7, 28, and 90 days according to ASTM C192. For thermal conductivity testing, two prismatic specimens measuring 200 × 100 × 50 mm were prepared per mix and tested after 28 days of wet curing, following BS 874:1973 [4]. Fig. 1 shows part of the experimental setup.

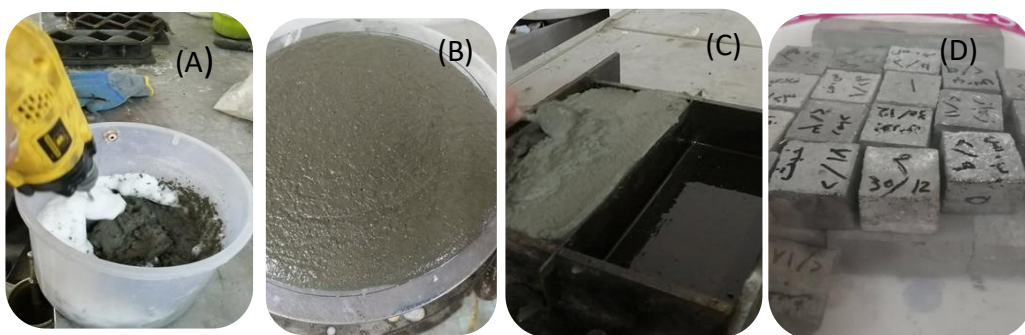


Figure 1: Part of experimental work (a) mixing foam concrete, (b) flow table test, (c) casting, (d) curing.



3.RESULTS AND DISCUSSION

3.1 Unit weight

Fig. 2 shows the density results for all mixtures compared to the control mix at 28 days. The density of foamed concrete decreases by about 22% when using Porcelanite as the fine aggregate (RP) compared to mixes using normal sand (Ctl). Three factors, as reported in the aforementioned literature review [33-35], explain this decrease: first, the increase in Porcelanite content leads to a higher proportion of voids in the structure of the FC matrix; second, fine Porcelanite has a lower specific gravity compared to natural fine aggregates; and third, the introduction of fine Porcelanite results in more voids in the FC structure instead of water when dry, which leads to excess water content.

The densities of Porcelanite-foam concrete indicate that for the same percentage of replacement using different pozzolanic materials, the values ranged from 1100 to 1290 kg/m³. The results show that the density of the MS, MG, MF, and M-slag mixes decreased by 14%, 8.6%, 8.2%, and 6%, respectively, while a slight increase was observed for the LM mix compared to the RP mix. These findings are consistent with previous studies [26, 36], which demonstrated that pozzolanic materials, such as fly ash or fine sand, can act as fillers and influence the mixture's density.

Due to its finer particles, fly ash promotes a more uniform distribution of air voids, providing a consistent coating on all air bubbles and preventing their merging [37]. Kearsley and Wainwright [16] investigated FC mixtures with densities ranging from 773 to 1751 kg/m³ and concluded that the fineness of the filler material significantly affects the density of FC. However, the influence of extremely fine silica fume (SF) in combination with fly ash (FA) on the density of FC remains controversial. This is because the air-void system, which arises from both foam and SF content, is quite complex [23].

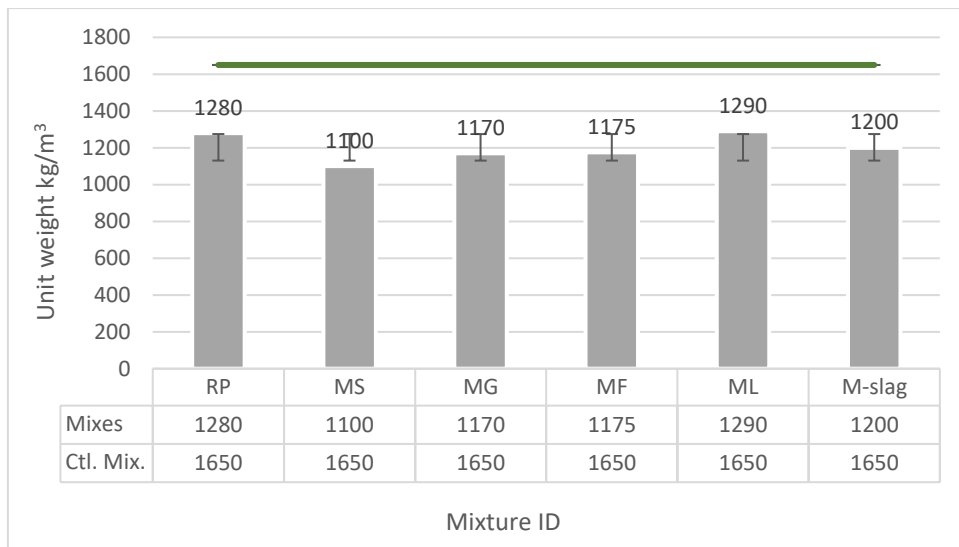


Figure 2: Effect of SCMs materials on unit weight of FC at 28 days.

3.2 Compressive strength

Fig. 3 shows the compressive strengths of foamed concrete (FC) with different pozzolanic components. The use of Porcelanite as a fine aggregate resulted in a decrease in early compressive strength compared to mixtures with natural sand. However, the strength differences appeared to converge by about 28 days, likely due to the cement hydration process, supported by the gradual release of absorbed water from the Porcelanite. Essentially, Porcelanite acted as an internal curing agent, enhancing long-term strength development.

Generally, the compressive strength of FC with pozzolanic additions decreased by 28 days, with the exception of the ML mix, which saw an increase of about 5%. This increase is likely attributed to the slow pozzolanic reaction, which leads to a delayed release of heat and a subsequent increase in strength. Over time, the compressive strength followed a pattern typical of conventional concrete.

For pozzolanic mixtures, FC achieved 62.5% to 85% of its 28-day strength by 7 days, with the RP mix containing Porcelanite reaching 86%. The early strength development is likely due to better integration of foam with binder constituents that have low specific gravity, fine particle size, and a porous structure—all of which improve the uniformity of the matrix and strengthen the mixture [23]. Additionally, pozzolanic materials contribute to the formation of calcium silicate hydrate (C–S–H) with a lower Ca/Si ratio, which is stronger than typical C–S–H [38].

Fig. 4 shows the strength development over time, with a focus on the RP mix at 28 and 90 days. The replacement of cement with 15% slag and fly ash resulted in continuous strength gains with sustained curing. Increased capillary absorption and porosity from fly ash, along with a slower rate of pozzolanic reaction that gradually consumes calcium hydroxide, explains this effect. This behavior is especially evident with extended curing periods, such as the 90-day mark [23].

The hydration mechanism of slag in combination with Portland cement is more complex than that of Portland cement alone. The presence of alkalis and sulfates triggers slag hydration, leading to the formation of additional components, including extra C–S–H phases, which help refine the pore structure. This results in a more compact cementitious matrix with lower capillary porosity. However, the rate of strength development in such mixtures is often slower compared to ordinary Portland cement systems.

On the other hand, foamed concrete (FC) mixtures containing ML, MS, and MG exhibited a slower rate of strength development, particularly the MS mixture. This observation is consistent with the findings of De Gutiérrez et al. Furthermore, Ugwu and Ugwuanyi reported significant long-term strength gains when cement was partially replaced with leaf stem ash. The pozzolanic effect of glass powder (GP) becomes more pronounced over time, especially by 28 days, though the rate of strength improvement eventually levels off. Du and Tan [42] observed that ultra-fine GP enhances early-age cement hydration and strength development, which aligns with the results of this study. At later ages, GP continues to react with calcium hydroxide from Portland cement hydration, contributing to a denser and more refined microstructure [25, 30, 39].

To assess the impact of pozzolanic materials, a statistical analysis of the relationship between FC density and compressive strength was performed. Fig. 5 shows a strong correlation ($R^2 = 0.924$), indicating that porosity is a critical factor influencing compressive strength, particularly at later ages. The results demonstrate that the addition of pozzolanic materials significantly alters the density of FC. This change is attributed to physical modifications in the cement paste, such as pore refinement and changes in the pore structure and distribution. Additionally, the high pozzolanic activity of these materials promotes the formation of secondary C–S–H gels in the interfacial transition zone, enhancing the compactness of the matrix, reducing permeability, and generating a denser microstructure [45].

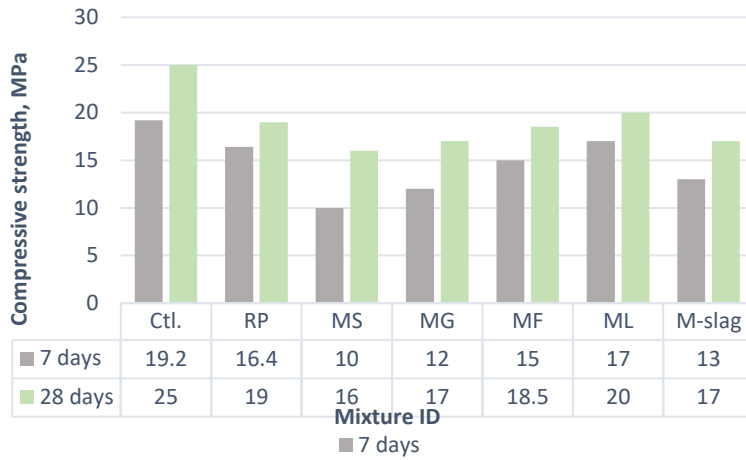


Figure 3: Effect SCMs materials on development strength with time comparing with RP mixture.



Figure 4: Development compressive strength with time compared with RP mixture.

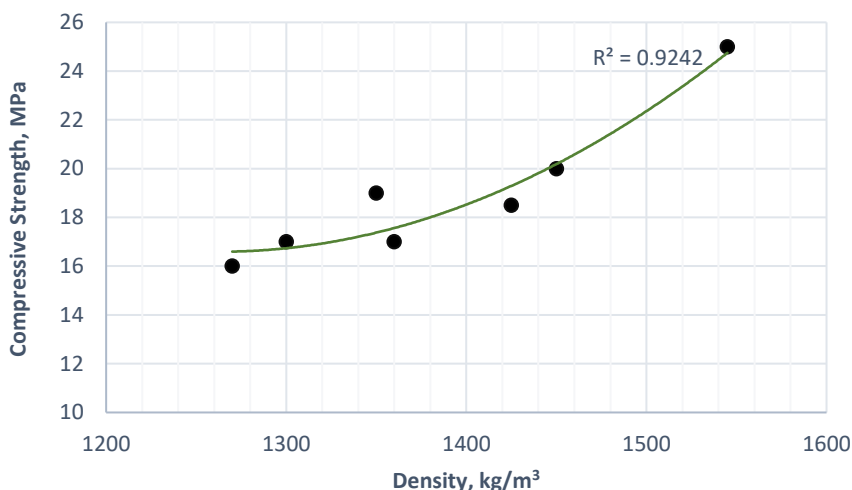


Figure 5: Correlation between compressive strength and density for Pozzolanic FC at 28 days.

3.3 Thermal Conductivity TC

This test was conducted according to B.S. 874:1973 [4], using the Kyoto Electronics QTM 500, as shown in Fig. 6, to measure thermal conductivity (K) and thermal conductivity factor (U). The thermal characteristics of composite materials, such as concrete, are influenced by the thermal properties of the individual components, including the void space within the composite. Factors that influence the thermal conductivity of concrete include age, aggregate volume fraction, amount of cement, types of admixtures, fine aggregate fraction, temperature, and moisture content [46].

The thermal conductivity (TC) results for pozzolan-based FC mixtures tested at 60 days are presented in Table-5. Since concrete typically consists of 60% to 70% (or more) aggregate by volume, its thermal properties are heavily influenced by the thermal properties of the aggregates. As shown in Fig. 7, Series I represent the reduction in TC compared to the control FC mix, while Series II represents the reduction in TC compared to the RP FC mix. The results clearly show that using Porcelanite as a fine aggregate, compared to normal sand, has a positive effect on reducing the amount of heat transmitted through the thickness of the FC specimen. The reduction in thermal conductivity reached approximately 14.5%. This decrease can be attributed to the lighter weight of Porcelanite compared to natural sand.

Moreover, a reduction in thermal conductivity (TC) was observed due to the use of pozzolanic materials. The reduction ranged from 8% to 35% compared

to Porcelanite-foam concrete without pozzolanic materials (RP). This reduction may be partly due to the amorphous silica content in the pozzolanic materials [47, 48].

In general, foamed concrete (FC) is a type of lightweight concrete (LWC) with a porous, closed-cell structure, which results in a low TC of up to 0.66 W/m·K at a density of 1600 kg/m³. In comparison, conventional concrete has a TC of 1.6 W/m·K at a density of 2200 kg/m³, which is 59% higher than the thermal resistance of FC. In a previous study by Jones and McCarthy, TC ranged between 0.23 and 0.42 W/m·K at dry densities of 1000 and 1200 kg/m³ [38] [49-51].



Figure 6: Thermal conductivity device

Table 5: Thermal conductivity of pozzolan foam concrete mixes.

Mixture ID	Thermal conductivity, W/mK
Ctl	0.3207
RP	0.2740
MS	0.1776
MG	0.1945
MF	0.2156
ML	0.2521
M-slag	0.2289

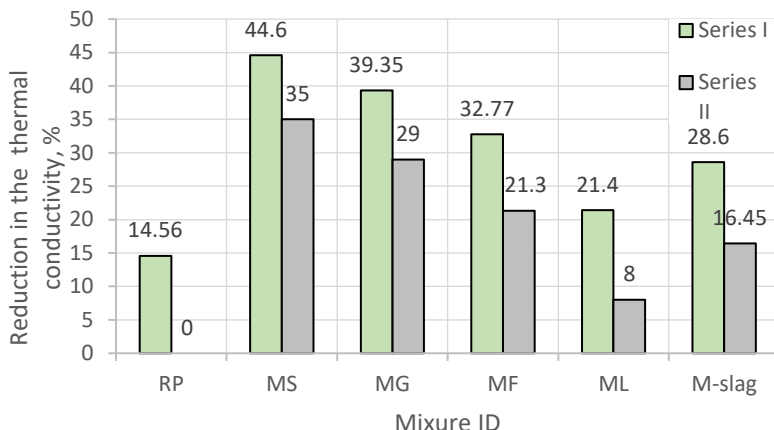


Figure 7: Reduction in TC of Pozzolan FC as compared to control and RP mixes at 60 days age.

4. STATISTICAL ANALYSIS

Pearson’s correlation coefficient (r) was used to quantify the linear relationships among density, compressive strength, and thermal conductivity, allowing for an evaluation of both the magnitude and direction of these associations. Simple linear regression was then applied to illustrate the parametric trends among the variables under investigation. Figs. 8-10 illustrate the interdependencies between density, compressive strength, and thermal conductivity for the various concrete formulations, with the corresponding Pearson correlation coefficients presented in Table-6.

Density shows a strong positive correlation with compressive strength, as shown in Fig. 8 ($r = 0.82$; $R^2 \approx 0.68$), suggesting that increases in density reduce porosity and improve particle packing, both of which enhance strength. The moderate-to-strong positive correlation between density and thermal conductivity, as seen in Fig. 9 ($r = 0.75$; $R^2 \approx 0.56$), indicates that as density increases, the volume fraction of air voids—acting as thermal insulators—decreases, thereby facilitating enhanced thermal conduction. Fig. 10 reveals a moderate correlation between compressive strength and thermal conductivity ($r = 0.69$; $R^2 \approx 0.48$), which suggests an important design consideration: higher strength mixes are likely to exhibit increased thermal conductivity, indicating a trade-off between mechanical and thermal properties.

These findings highlight the coupling between mechanical and thermal behavior in both lightweight and chemically modified concrete formulations. While an increase in specific mass improves compressive strength, it simultaneously reduces effective thermal resistivity.

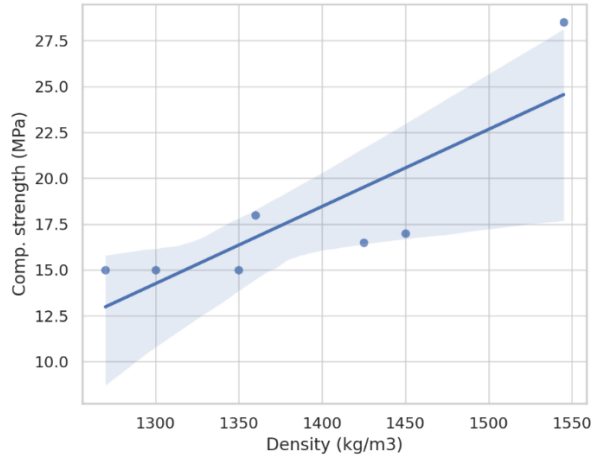


Figure 8: Relationship between Density and Compressive Strength of FC.

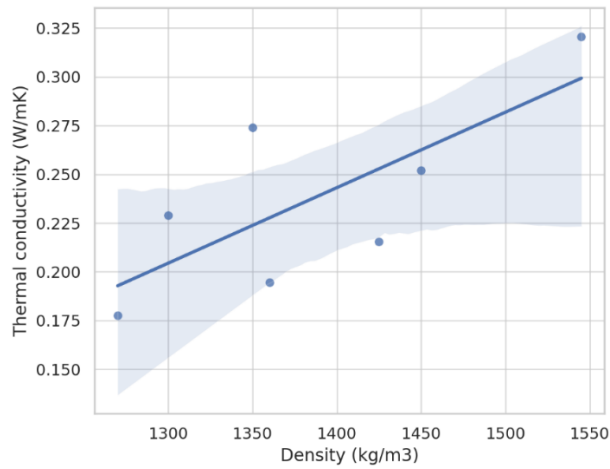


Figure 9: Relationship between Density and Thermal Conductivity.

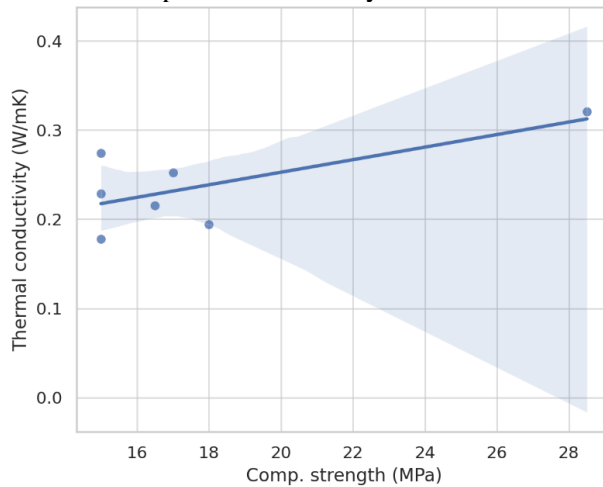


Figure 10: Relationship between Compressive Strength and Thermal Conductivity.



Table 6: Pearson correlation coefficients between density, compressive strength, and thermal conductivity of the studied FC mixes.

Relationship	Pearson correlation coefficient (r)	Relationship type
Density ↔ Compressive strength	0.82	Strong positive
Density ↔ Thermal conductivity	0.75	Moderate to strong positive
Compressive strength ↔ Thermal conductivity	0.69	Moderate positive

5. CONCLUSIONS

This investigation highlights the innovative aspect of the study, focusing on the effectiveness of lightweight aggregates (LWA) and various pozzolanic materials in enhancing the thermal and mechanical properties of foamed concrete (FC). The study demonstrates the practicality of creating sustainable structural materials that offer both energy efficiency and reduced density.

- Based on the reported study, conclusions drawn from the introduction of LWA to replace natural sand reduced density by approximately 22% and due to using a 15% cement replacement of either (SF) or slag, unit weight was lowered as well. This shows this type of material has potential for use in lightweight structural applications.
- (FC) was created with structural grade of unit densities from 1100 kg/m³ to 1290 kg/m³ with compressive strengths of 16-25 MPa with the dedicated use of pozzolanic materials which showed feasibility of use and usefulness in real construction designs.
- As was anticipated with testing, the use of pozzolanic materials showed that the use of LA at a 15% partial binder replacement produced the overall highest 28-day compressive strength of ~20MPa, showing LSA as a viable sustainable alternative binder.
- The study also showed that strength development of FC at 90 days varied significantly for each pozzolanic material previously described as a function of hydration activity, meaning long term performance benefits as well as differences in hydration activity.
- Across the study, it was found that the total porosity of the samples showed a high correlation ($R^2=0.924$) to compressive strength meaning that pozzolanic materials create internal microstructure changes within FC.

- Regarding thermal properties, as previously mentioned, the thermal conductivity had approximately a 15% reduction compared with the control. The lowest thermal conductivity recorded was 0.1776 W/m·K.
- Additional research should focus on the durability aspects of foamed concrete, including its performance in aggressive environments, freeze-thaw resistance, shrinkage, and acid resistance. Furthermore, investigating the optimal replacement levels for each pozzolanic material could lead to further improvements in both strength and durability.

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تعزير استدامة الخرسانة الرغوية باستخدام المنتجات الثانوية الصناعية والمواد البوزولانية المضافة

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الملخص

تتناول هذه الدراسة تأثير المواد البوزولانية المختلفة على الخصائص الفيزيائية والميكانيكية والحرارية للخرسانة الرغوية. ولهذا الغرض، تم وضع خطة تجريبية مكثفة تتكون من خلطات خرسانية رغوية متضمنة خمس إضافات بوزولانية (دخان السيليكا، ومسحوق الزجاج، والرماد المتطاير، ورماد سيقان الأوراق، والخبث)، والتي تم استخدامها جميعاً كبديل بنسبة ١٥٪ للإسمنت. تم استخدام مادة البورسيلانيت كركام خفيف وناعم لجميع الخلطات باستثناء الخلطة المرجعية. كما تم استخدام نسبة ٣:١ من عامل الرغوة إلى الماء لجميع الخلطات، مما أدى إلى كثافة رغوية بلغت ٤٢ كجم/م³. أكدت نتائج الاختبار أن الخرسانة الرغوية التي تتراوح كثافتها بين ١١٠٠ إلى ١٢٩٠ كجم/م³ ستحقق قوة ضغط تبلغ حوالي ١٦ إلى ٢٠ ميجا باسكال عند ٢٨ يوماً عند استخدام الإضافات البوزولانية. كما أدى استخدام هذه المواد كمضافات إلى تقليل التوصيل الحراري بشكل كبير. على وجه الخصوص، كان أداء الخلطة التي تحتوي على ١٥٪ من رماد سيقان الأوراق أفضل من بدائل البوزولانا الأخرى، حيث أظهرت أفضل الخصائص الحرارية والميكانيكية والفيزيائية.

الكلمات الرئيسية: خرسانة رغوية، مسحوق الزجاج، خرسانة خفيفة الوزن، مواد بوزولانية، الاستدامة.

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