Proceedings of the 10th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2025)
July, 2025 | Imperial College London Conference Center, London, United Kingdom
Paper No. 209
DOI: 10.11159/iccste25.209

Evaluation of a Sustainable Concrete Design with Fly Ash Type C and Expanded Clay to Improve Workability and Ensure Efficient Performance

Valery López[1], Ivan Neyra[2], Karla López[2]
[1]Universidad Peruana de Ciencias Aplicadas
Av. La Marina 2810, Lima, Peru
u20201b802@upc.edu.pe; u20201b649@upc.edu.pe
[2]Universidad Peruana de Ciencias Aplicadas
Av. La Marina 2810, Lima, Peru
pcciklop@upc.edu.pe

Abstract - The construction industry is key to economic development, with cement as an essential material, despite its high environmental impact due to CO_2 emissions. Despite the relevance of concrete, it faces challenges such as the loss of workability that leads to inadequate practices affecting its strength and durability. This research proposes a modified concrete mix design with 20%, 40% and 50% of fly ash type C as a replacement of Portland cement and 5% of expanded clay as a substitute for coarse aggregate to improve the workability of fresh concrete and guarantee the rest of its properties for its reliable use in construction. The characterization of materials, the design and preparation of concrete mixes and the evaluation of the physical and mechanical properties of concrete are contemplated. The results showed that with replacements of up to 20% fly ash and 5% expanded clay, the slump of fresh concrete can be increased by 50% compared to a conventional mix. Also, with this replacement rate, the concrete achieved a 28-day compressive strength at only 4.02% of its design value.

***Keywords*:** fly ash, expanded clay, sustainable concrete, workability, physical properties, mechanical properties

1. Introduction

The construction industry plays a vital role in global economic and social development, with cement standing out as one of the most important materials due to its contribution to the stability and durability of key structures. In 2021, global cement consumption reached approximately 4.4 billion tons [1]. In the Peruvian context, the construction sector accounts for 5.10% of the country's Gross Domestic Product (GDP) [2], with a growth of 13.16% in January 2024, driven by a 9.25% increase in domestic cement consumption. This positions Peru as the third country with the highest per capita cement consumption in Latin America, at 416 kg per inhabitant in 2021 [1].

Despite its importance, cement has a high environmental impact due to carbon dioxide (CO_2) emissions during its production. This issue has prompted numerous studies on the use of alternative materials such as fly ash and expanded clay, which improve the sustainability and performance of concrete. However, concrete still faces operational challenges, such as the loss of workability—a crucial factor for efficient placement and compaction of the mix. According to [3], surveys conducted among civil engineers in Lima revealed that 21.31% of workability and quality issues in concrete are attributed to the water-cement ratio and environmental conditions, while another 19.67% are related to the quality of materials used. Additionally, [4] found that construction foremen in Lima often add extra water to concrete to improve workability and facilitate pouring, disregarding the original mix design. This practice increases slump but decreases the strength and durability of the concrete.

Recent studies have proposed alternatives to improve workability and reduce the environmental impact of concrete using supplementary cementitious materials. In [5], it was shown that replacing 20% of cement with fly ash yielded workabilities of 25, 15, and 10 centimeters with water-cement ratios of 0.39, 0.36, and 0.34, respectively. However, when replaced at 40%, workability improved, though compressive strength decreased by 15%. On the other hand, [6] used lightweight expanded clay aggregate (LECA) combined with fly ash to improve workability by 25% and increase compressive strength by 15% at

28 days. In [7], mixtures achieving up to 49% greater workability were explored using lightweight aggregates, demonstrating that fly ash can significantly reduce compressive strength at certain percentages.

In additional studies, [8] observed that mixes with expanded clay achieved flow workabilities of up to 90 cm and strengths of up to 40 MPa when cement replacement was 25%. Similarly, [9] found that self-compacting concrete (SCC) mixes with LECA and 15% fly ash met the criteria for workability and cohesiveness, achieving densities above 1700 kg/m^3. Finally, the results in [10] showed that the 7-day compressive strength of concrete with expanded clay was higher at 22.20 MPa compared to 14 MPa for standard concrete. Additionally, the improved workability translated into more homogeneous and easier-to-place concrete, maintaining adequate mechanical properties for structural applications.

In this context, this research proposes a mix design that improves the workability of fresh concrete by increasing its slump through the incorporation of fly ash as a supplementary cementitious material and expanded clay as a partial replacement for coarse aggregate. This design optimizes the physical characteristics of concrete while ensuring its mechanical properties for reliable use in structural engineering elements.

The proposed mix design with fly ash and expanded clay introduces an innovative approach to the construction industry by leveraging new techniques that represent a significant advancement in optimizing construction materials, overcoming the limitations of conventional mixes. From a sustainability perspective, the use of fly ash, an industrial by-product, promotes responsible waste management and reduces environmental harm. On the other hand, the inclusion of expanded clay decreases the extraction of natural aggregates, fostering resource conservation. Thus, the proposed mix minimizes the carbon footprint of concrete production.

2. Materials

The concrete mix design to be developed in this research considers the use of the following materials:

Fly ash will be used as the supplementary cementing material in the proposed concrete mix. This material was obtained from the boilers of the TRUPAL plant, located in the district of Santiago de Cao, Ascope province, in the La Libertad department.

Expanded clay will be used as a partial substitute for coarse aggregate in the modified concrete mix. This material was sourced from Agriplant S.R.L., located in the district of Surco, Lima province, in the Lima department.

Coarse sand and crushed stone are the aggregates used in the production of both standard and modified concrete mixes. Finally, Portland cement is the cementing material used for the preparation of concrete mixes.

3. Methodology

This research was conducted in four stages.

In the first stage, the characterization of the materials to be used in the concrete mixes was carried out, considering the physical properties and chemical composition of fly ash and Portland cement, as well as the physical properties of expanded clay, crushed stone, and coarse sand.

The second stage involved designing the control mix and the modified concrete mix following the guidelines of the American Concrete Institute (ACI) Committee 211 and preparing the concrete mixes.

The third stage covered the analysis of the physical properties of fresh concrete in terms of temperature, slump, unit weight, and air content. Additionally, this penultimate stage included molding the specimens for subsequent testing.

Finally, the fourth stage included the curing and testing of cylindrical and rectangular specimens to evaluate the mechanical properties of hardened concrete, specifically compression strength and flexural strength, respectively.

One control mix (standard) and three modified concrete mixes were prepared with 20%, 40%, and 50% type C fly ash as a replacement for Portland cement, and 5% expanded clay as a partial substitute for coarse aggregate. These mixes are identified as M20C5A, M40C5A, and M50C5A, respectively, in this study.

A total of 48 concrete specimens were prepared, of which 36 were cylindrical specimens for measuring compressive strength at 7, 14, and 28 days, and 12 were rectangular specimens for evaluating flexural strength at 28 days.

3.1. Material characterization

This stage began with the procurement and selection of the materials to be used. These were stored and protected from the elements until the start of the characterization tests.

The granulometric analysis was performed manually through sieving for all aggregates and binding materials. The material samples were selected according to NTP 400.010. Additionally, the sieve sizes were chosen following NTP 400.011. Tables 1 and 2 show the granulometric analysis of the expanded clay and fly ash, respectively, conducted in accordance with NTP 400.012 (ASTM C136).

Table 1: Granulometric analysis of expanded clay.

Sieve Size	**Opening**	**Retained Material**		**% Cumulative**		**ASTM C33 Limits**	
	(mm)	***(g)***	***(%)***	***Retained***	***Passing***		
2"	50.00	0.0	0.0	0.0	100.0		
1 1/2"	37.50	0.0	0.0	0.0	100.0	100	100
1"	24.50	0.0	0.0	0.0	100.0	95	100
3/4"	19.05	0.0	0.0	0.0	100.0		
1/2"	12.50	830.0	76.1	76.1	23.9	25	60
3/8"	9.53	180.0	16.5	92.6	7.4		
Nº 04	4.76	80.3	7.4	100.0	0.0	0	10
N° 08	2.38	0.0	0.0	100.0	0.0	0	5
N° 16	1.18	0.0	0.0	100.0	0.0		
Pan		0.0	0.0	100.0	0.0		

Table 2: Granulometric analysis of type C fly ash.

Sieve Size	**Opening**	**Retained Material**		**% Cumulative**	
	(mm)	***(g)***	***(%)***	***Retained***	***Passing***
20	0.850	0.00	0.00	0.00	100.00
50	0.300	52.99	44.16	44.16	55.84
70	0.212	55.49	46.24	90.41	9.59
100	0.150	6.58	5.48	95.89	4.11
140	0.106	1.10	0.91	96.80	3.20
200	0.075	0.79	0.66	97.46	2.54
Pan		0.0	0.0	100.0	0.0

The aggregates were characterized in terms of moisture content, specific gravity, absorption percentage, unit weight, among others. Table 3 shows the physical characterization of crushed stone, coarse sand, and expanded clay, providing a clear view of their main properties. The moisture content test was conducted according to the guidelines in NTP 339.185. Similarly, the loose and compacted unit weight was determined using NTP 400.017. The specific gravity and water absorption test followed NTP 400.021.

Table 3: Physical properties of aggregates.

Physical properties	**Unit**	**Crushed stone**	**Coarse sand**	**Expanded clay**
Moisture content	%	1.51	1.70	0
Nominal máximum size	in	1/2	N°4	1/2
Fineness modulus		6.42	2.93	6.93
Specific gravity of mass S.S.S.	g/cm^3	2.66	2.65	
Specific gravity of dry oven mass	g/cm^3	2.64	2.66	0.29
Apparent specific gravity of mass	g/cm^3	2.71	2.63	
Loose unit weight	kg/m^3	1538	1590	180
Compacted unit weight	kg/m^3	1692	1648	224
Water absorption	%	1.10	3.30	22.70

The binding materials were characterized in terms of density, loss on ignition (LOI), among others. Table 4 presents the main physical characteristics of the fly ash and Portland cement.

Table 4: Physical properties of binder materials.

Physical properties	**Unit**	**Fly ash**	**Hydraulic cement**
Water absorption	%	35.61	
Specific gravity		0.85	
Moisture content	%	0.8	
Density	g/cm^3		3.12
LOI	%	5.11	1.92

Table 5 details the chemical composition of the binding materials in terms of oxides after performing an elemental scan from sodium (Na) to uranium (U) using X-ray fluorescence spectrometry on the SHIMADZU EDX equipment, so that the oxides with the greatest presence within their composition are identified.

Table 5: Chemical properties of binding materials.

Components	**Symbol**	**Fly ash (%)**	**Hydraulic cement (%)**
Silicon Oxide	SiO_2	34.669	9.062
Sulfur Oxide	SO_3	4.806	3.295
Aluminum Oxide	Al_2O_3	18.868	1.293
Iron Oxide	Fe_2O_3	10.994	5.872
Potassium Oxide	K_2O	4.297	0.995
Titanium Oxide	TiO_2	3.124	0.462
Calcium Oxide	CaO	16.812	76.651
Others		1.265	0.420

3.2. Mix design and concrete manufacturing

The designed mixes are detailed in Table 6, which summarizes the materials and dosages used in the different variations of the concrete mixes. Each mix was prepared following the ACI method established by Committee 211.

All concrete mixes were designed for a compressive strength ($f'c$) of 280 kg/cm^2 at 28 days with a water-cement (w/c) ratio for strength of 0.46.

Table 6: Natural weight batching for 1 m^3 of concrete.

Concrete mixes	**Materials**					
	Water (L)	***Hydraulic cement (kg)***	***Crushed Stone (kg)***	***Coarse sand (kg)***	***Fly ash (kg)***	***Expanded clay (kg)***
Control mix	235	495	922	660	0	0
M20C5A	235	396	876	660	27	5
M40C5A	235	297	876	660	54	5
M50C5A	235	248	876	660	67	5

A careful process of weighing and mixing the materials was carried out, ensuring the cleanliness of the drum-type mixer to avoid contamination. The sequence of material incorporation began with the aggregates (crushed stone, expanded clay, and coarse sand) along with half of the mixing water. Next, the cement and fly ash were added. Finally, the remaining water was included and mixing continued for an additional 3 minutes to achieve the homogeneity of the concrete.

3.3. Physical properties of fresh concrete

The slump test of fresh concrete was performed using the Abrams cone, in accordance with NTP 339.035, to assess the workability of fresh concrete.

The temperature measurement follows the guidelines of NTP 339.184, where the thermometer had to be immersed at least 3 inches into the fresh concrete, maintaining the same minimum distance in all directions to avoid contact with the buggy.

To determine the unit weight of fresh concrete, a cylindrical container is used, into which the concrete is placed in three properly compacted layers. This test was carried out following the guidelines established in NTP 339.046.

The air content in the fresh mix is evaluated using the pressure method, according to NTP 339.080, which quantifies the trapped air in the mix. A type B air meter, in this case, the Washington pot, is used for the test.

The results are shown in Table 7.

Table 7: Physical properties of concrete in fresh state.

Tests	**Unit**	**Concrete mix**			
		Control mix	***M20C5A***	***M40C5A***	***M50C5A***
Unit weight	kg/m^3	2285	2135	2115	2050
Slump	in	4	6	4	3
Air content	%	2.30	2.30	2.35	2.60
Temperature	°C	20.90	20.30	20.50	20.80

3.4. Mechanical properties of hardened concrete

The compression resistance test was conducted at 7, 14, and 28 days using cylindrical molds and evaluated according to NTP 339.034. Similarly, the flexural strength at 28 days was measured on concrete prismatic beams following NTP 339.063.

4. Analysis of results

4.1. Slump

In Fig. 1, the M20C5A mix achieved a 50% higher slump than the control mix, effectively doubling its value. This significant increase in workability of the M20C5A mix is due to the physical and chemical properties of the fly ash and expanded clay.

On one hand, fly ash is characterized by its spherical, glassy-surfaced particles that act as a plasticizer, helping to reduce friction between cement paste particles and improving its flowability. Moreover, the high amounts of SiO_2 and Al_2O_3 in the fly ash give it slow pozzolanic activity, which releases heat during hydration, causing the setting time to be delayed and allowing the concrete mix to retain its workability longer compared to a conventional mix.

On the other hand, the particles of expanded clay, physically characterized by their irregular rounded shape, have less resistance to sliding against each other, meaning less friction compared to the angular particles of conventional crushed stone, which positively influences the workability of the concrete.

To enhance the flowability of fresh concrete, the fly ash replacement should be less than 40%, with significant increases observed up to 20%.

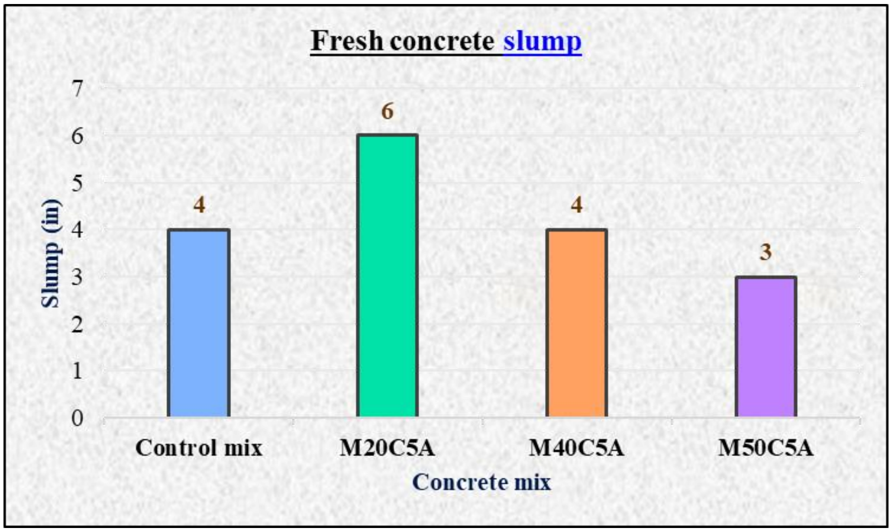

Fig. 1: Slump of fresh concrete.

4.2. Compressive strength

After 7 days, in Fig. 2, the control mix achieved a compressive strength of 17.19 MPa, developing 62.60% of its 28-day design strength (27.46 MPa); on the other hand, the M20C5A, M40C5A, and M50C5A mixes developed 55.95%, 58.79%, and 56.02%, respectively. Furthermore, the M20C5A, M40C5A, and M50C5A mixes achieved 10.61%, 6.08%, and 10.51% lower strength compared to the control mix. The trend shows that the compressive strength at 7 days improves with increases from 20% to 40% of type C fly ash while keeping the 5% expanded clay constant.

At 14 days, in Fig. 2, the control mix achieved 82.51% of the planned compressive strength. In contrast, the M20C5A, M40C5A, and M50C5A mixes achieved strengths equivalent to 57.86%, 63.18%, and 56.92% of the design, representing a reduction of 29.87%, 23.42%, and 31.01%, respectively, compared to the control mix.

The results demonstrate the slow pozzolanic activity of fly ash. This material becomes a reactive component in concrete when it chemically interacts with water and the $Ca(OH)_2$ generated during cement hydration. This gives it pozzolanic properties, which slow down the hydration process, emitting less heat. In contrast, the control mix develops strength quickly since the cement has hydraulic activity, and the alite phase (C_3S) in its composition rapidly reaches initial strength, producing high exothermic heat at early stages.

At 28 days, in Fig. 2, the control mix achieved 105.80% of the design compressive strength. The M20C5A, M40C5A, and M50C5A mixes reached strengths of 95.98%, 85.96%, and 81.84% of the design strength, respectively. The M20C5A mix showed only 4.02% less strength than the design value, being the closest and most optimal in compressive strength among the modified mixes.

While the compressive strength of the control mix at 28 days increased by only 28.23% compared to that at 14 days, the M20C5A, M40C5A, and M50C5A mixes increased by 65.90%, 36.05%, and 43.78%, respectively. This confirms the pozzolanic capability of fly ash to develop better strengths at later ages compared to conventional mixes.

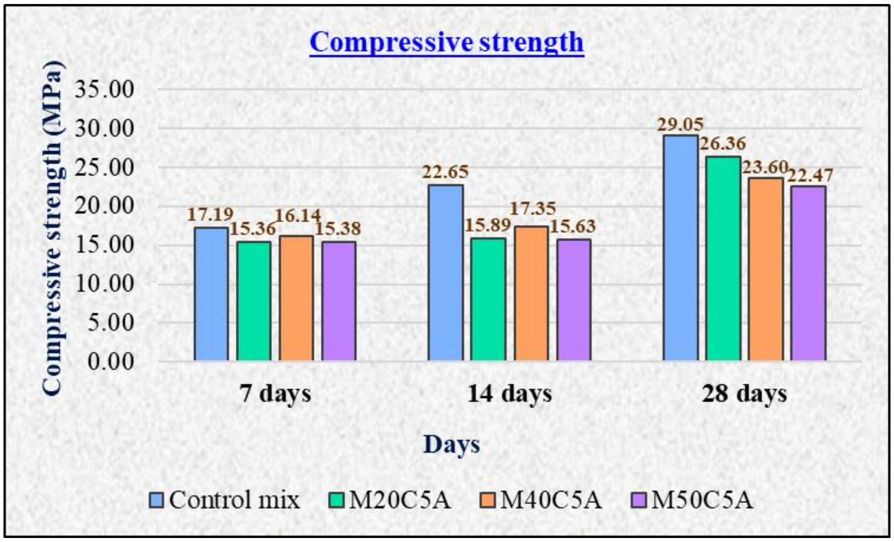

Fig. 2: Compressive strength hardened concrete at 7, 14 and 28 days.

4.3. Flexural strength

At 28 days, in Fig. 3, the flexural strengths of the M20C5A, M40C5A, and M50C5A mixes are 14.72%, 23.71%, and 28.11% lower than the reference mix, respectively, showing a reduction in the modulus of rupture as the fly ash content increases. However, considering ACI 363, the ratio between compressive strength and modulus of rupture should range between 33.30 kg/cm² and 53.21 kg/cm^2 for a $f'c = 280$ kg/cm^2, so all modified mixes develop adequate flexural strength.

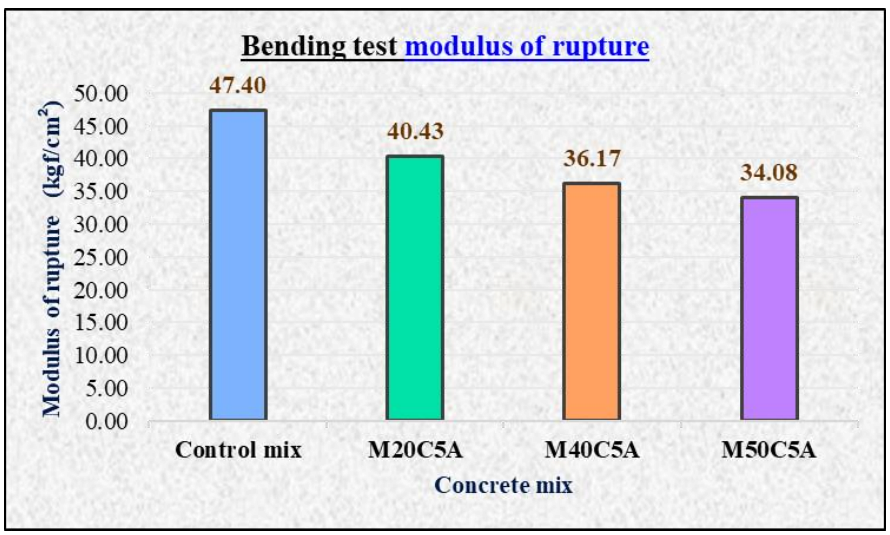

Fig. 3: Flexural strength hardened concrete at 28 days.

5. Conclusion

The high incidence of silicon oxide and aluminum in the chemical composition of fly ash provides it with pozzolanic capacity, allowing it to create hydration products within the concrete for the development of its strength, which is why it is effective as a partial substitute for Portland cement.

Expanded clay and type C fly ash, due to their lightness and the spherical shape of their particles, give concrete adequate workability, making it easier to handle without the risk of segregation in the fresh state. Thus, with replacements of up to

20% fly ash and 5% expanded clay, fresh concrete achieves more than 50% superior workability compared to a conventional mix.

The pozzolanic activity characteristic of fly ash causes it to react chemically with water more slowly than hydraulic cement, releasing lower heat of hydration. Therefore, the development of mechanical strength is slow at early ages and gains more strength at later ages. Thus, incorporating 20% fly ash and 5% expanded clay allows the compressive strength to remain within 4.02% of the design value. For higher replacement rates, each additional 10% fly ash reduces compressive strength by approximately 5.01%.

References

[1] Inter-American Cement Federation (FICEM), "Statistical Report 2021," 2021. [Online]. Available: https://ficem.org/wp-content/uploads/2023/08/Informe-estadistico-2021.pdf.

[2] National Institute of Statistics and Informatics (INEI), "National production increased by 1.37% in January 2024," Jan. 2024. [Online]. Available: https://m.inei.gob.pe/prensa/noticias/produccion-nacional-aumento-137-en-enero-de-2024-15074/.

[3] E. N. Ruiz, "Factors influencing the quality of ready-mixed concrete and its high performance in construction," Bachelor's thesis, Faculty of Engineering, Universidad Peruana Unión, Lima, Peru, 2020.

[4] P. L. Garay and C. C. Quispe, "Study of concrete used in residential roof slab pours in Lima and evaluation of an improvement alternative using high-range water-reducing superplasticizer additive," Bachelor's thesis, Faculty of Science and Engineering, Pontificia Universidad Católica del Perú, Lima, Peru, 2017.

[5] M. Egemen, F. Ali, and E. Aydin, "An Approach to Mixture Design and Cost Analysis for Cement Pastes Composed of Class C Fly Ashes for Better Sustainable Construction," *Buildings*, vol. 14, no. 2, article 373, 2024. https://doi.org/10.3390/buildings14020373.

[6] L. Mahmmod, A. Dulaimi, L. Bernardo, and J. Andrade, "Characteristics of Lightweight Concrete Fabricated with Different Types of Strengthened Lightweight Aggregates," *Journal of Composites Science*, vol. 8, article 144, 2024. https://doi.org/10.3390/jcs8040144.

[7] T. Mohammed, F. Aguayo, M. Nodehi, and T. Ozbakkaloglu, "Engineering properties of structural lightweight concrete containing expanded shale and clay with high volume class F and class C fly ash," *Structural Concrete*, vol. 24, no. 3, pp. 4029–4046, 2023. https://doi.org/10.1002/suco.202200562.

[8] B. Kanagaraj, N. Anand, B. Praveen, S. Kandasami, E. Lubloy, and M. Naser, "Physical characteristics and mechanical properties of a sustainable lightweight geopolymer-based self-compacting concrete with expanded clay aggregates," *Developments in the Built Environment*, vol. 13, article 100115, 2023. https://doi.org/10.1016/j.dibe.2022.100115.

[9] S. Bozorgmehr and M. Nemati, "Applied development of sustainable-durable high performance lightweight concrete: Toward low carbon footprint, durability, and energy saving," *Results in Materials*, vol. 20, article 100482, 2023. https://doi.org/10.1016/j.rinma.2023.100482.

[10] S. Ahmadi, M. Reisi, and S. Sajadi, "Comparing properties of foamed concrete and lightweight expanded clay aggregate concrete at the same densities," *Case Studies in Construction Materials*, vol. 19, no. 1, article e02539, 2023. https://doi.org/10.1016/j.cscm.2023.e02539.