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. 176
DOI: 10.11159/iccste25.176

Effect of the Replacement of Cement by Fly Ash and Calcined Clay on the Mechanical-Physical Properties of Conventional Mortar

Aracelly Saravia[1], Gladys Vela[2], Karla Lopez[3]
[1]Universidad Peruana de Ciencias Aplicadas
Lima, Peru.
u20201a904@upc.edu.pe; u20201c236@upc.edu.pe
[2]Universidad Peruana de Ciencias Aplicadas
Lima, Peru.
pcciklop@upc.edu.pe – Universidad Peruana de Ciencias Aplicadas

Abstract **-** This article explored the effects of replacing Portland cement with fly ash and calcined clay on the strength and durability of conventional mortar, focusing on improving its mechanical properties and reducing the carbon footprint generated by the construction industry. Tests were conducted on samples with 20% and 55% cement replacements ratios, evaluating parameters such as compressive strength, flexural strength, and porosity. The results indicated that mortars with cement replacements outperformed the control mortar in terms of strength and compaction. At 28 days, the mortar with a 20% replacement achieved a compressive strength of 24.67 MPa, surpassing the standard design. Lower porosity was also observed in mortars with replacements, contributing to greater durability and resistance to water absorption. This study concluded that using fly ash and calcined clay as a partial replacement for cement was viable for structural applications, particularly in seismic zones, due to improved cohesion and reduced formation of voids in the mix, enhancing its mechanical performance and reducing its environmental impact.
Keywords**:** Compressive Strength, Flexural Strength, Porosity, Durability, Fly Ash, Calcined Clay.

1. Introduction

The mechanical properties of conventional mortar depend on factors such as the selection and composition of materials, mix design, and a correct construction process. These factors determined the behavior of the hardened mortar. Occasionally, when the materials were not properly selected [1], the water/cement ratio was incorrect [2], and the construction process was improperly followed [3], it led to issues of inadequate adhesion [2], compromising the structural integrity and durability of the structure [3]. The VI International Congress on Pathology and Structural Recovery [4] reported cases in Argentina of improper use of air-entrained cement mortar, resulting in hydraulic shrinkage and cracks in masonry structures. Similarly, 51.52% of construction process errors in confined masonry housing in Cajamarca occurred in walls and foundations [5]. This situation was also reflected in Metropolitan Lima, where [6] indicated that 83.5% of the houses were built with masonry walls, highlighting the seismic vulnerability and the need to ensure good interaction between mortar and brick to prevent cracks [7]. For this reason, materials that enhance the mechanical properties of the mortar and guarantee the structure's durability should be selected. Currently, many studies focus on finding alternatives to improve the behavior of mortar while reducing the CO2 emissions produced during cement manufacturing. Geopolymer mortars with fly ash have been not only improved compressive strength, reaching values up to 54.5 MPa at 80°C but also showed a significant reduction in porosity, minimizing water absorption to 3.47%, thereby increasing the durability of structures [8]. Additionally, the importance of optimal curing for alkali-activated mortars was highlighted, establishing those temperatures between 30°C and 85°C and curing times of 24 to 48 hours maximized strength up to 46.5 MPa, crucial factors in the construction of load-bearing walls [9]. Moreover, the combined use of fly ash and clay was evaluated, achieving improvements in both compressive and flexural strength, reaching 65.6 MPa and 14.30 MPa, respectively. It was demonstrated that clay, due to its pozzolanic activity, contributed to the strengthening of mortar properties [10]. Similarly, it was emphasized that replacing fly ash with Portland cement not only improved properties but also reduced carbon emissions. Microscopic analysis of the materials showed that the particles had irregular shapes, which generated greater adhesion [11]. It was concluded that the incorporation of these materials reduced the heat of hydration by 37%, preventing crack formation and increasing durability. This approach not only enhanced structural strength but also reduced maintenance costs [12]. Calcined clay in alkali-activated mortars was also studied, finding that this material significantly increased compressive strength by up to 20% and improved mechanical and adhesion properties

[13]. Furthermore, the classification of fly ash particles was investigated, finding that 70% ranged in size from 40 to 100 µm, indicating that smaller particles could improve strength, fluidity, and adhesion in the mortar [14].

This article aimed to analyze the use of fly ash and calcined clay as replacement materials in 20% and 55% of Portland cement in the manufacture of mortar for confined masonry walls, with the goal of improving mechanical and physical properties: compressive strength, flexural strength, and porosity.

The main contribution of this research was to evaluate the behavior of conventional mortar and mortar modified with Fly Ash and Calcined Clay replacements, considering the influence of material characterization on mechanical and physical properties. These materials not only aim to improve the mechanical performance of mortar but are also part of a global effort to reduce cement-related CO2 emissions.

2. Materials and equipment

2.1. Materials

The materials used in the present study included ordinary Portland cement produced by Cemento Sol. This cement is classified as Type 1 according to the standard specifications for Portland cement outlined in ASTM C150-22. Its chemical composition is summarized in Table I. The particles were generally angular in shape, with a specific surface area of 323 m²/kg and a loss on ignition of 1.92%. As a pozzolanic material, it exhibited a compressive strength of 449 kg/cm² at 28 days.

TABLE I. CHEMICAL COMPOSITION OF PORTLAND CEMENT

Materials	Chemical Composition (%)			
	Calcium Oxide (CaO)	**Iron Oxide (Fe_2O_3)**	**Sulfur Oxide (SO_3)**	**Loss on Ignition**
Cement	76.65	5.87	3.3	1.92

Fine aggregate used in this study consisted of sand sourced from the Trapiche quarry located in Lima, Peru. It was determined that the loose bulk density was 1592 kg/m³, and the compacted bulk density was 1651 kg/m³. Following the experimental process, the specific gravity was identified as 2.63 g/cm³, with an absorption rate of 1.7%.

Additionally, fly ash and calcined clay were used as replacement materials for Portland cement. The fly ash was obtained from **Trupal**, a paper production company based in Lima, Peru. The fly ash exhibited a loss on ignition of 12.11%, a specific gravity of 0.85 g/cm³, and an absorption rate of 35.61%. The calcined clay was sourced from **CONSTRUCSERVIS VARA RAMOS SAC**, a company located in Lima, Peru. Its water absorption rate was determined to be 42.71%, with a loss on ignition of 6.730% and a specific gravity of 1.08 g/cm³. Table II shows the chemical composition of the fly ash and calcined clay.

TABLE II. CHEMICAL COMPOSITION OF FLY ASH AND CALCINED CLAY

Pozzolanic Materials	Chemical Composition (%)			
	Silicon Dioxide (SiO_2)	**Iron Oxide (Fe_2O_3)**	**Aluminum Oxide (Al_2O_3)**	**Loss on Ignition**
Calcined Clay	46.61	24.02	13.84	6.73
Fly Ash	34.67	9.99	15.86	12.11

2.2. Equipment

For the characterization of the materials and laboratory tests, various equipment was used to ensure accuracy in the measurements and analysis of the mortar's properties. A muffle furnace was utilized for drying the materials and conducting the loss on ignition test, where the sample reached temperatures up to 1100°C, eliminating moisture. Additionally, the EDX-7200 energy dispersive *X-ray fluorescence spectrometer* was employed to identify the chemical composition expressed in oxides.

To corroborate the mix design, a 254 mm *flow table* was used along with a cast bronze conical mold based on ASTM C230, with a base diameter of 100 mm, a height of 50 mm, and a top diameter of 70 mm. The table performed controlled drops of 12.6 mm from a specific height to measure the expansion of fresh mortar. Also, to verify the setting time, a *Vicat Apparatus* was used in accordance with ASTM C187, which defines the procedure for determining the initial and final setting time. Finally, a high-quality 2000 KN *automatic compression machine* was used to measure the compressive and flexural strength of hardened mortars at 7, 14, and 28 days. According to ASTM C109, the machine applied a load with an accuracy of ±1%. The display also presented values with 1% precision. The compression plates had a diameter of 150 mm to ensure uniformity of the applied force. For the flexural tests, the machine was adapted with flexural accessories to apply the load precisely at the top of the specimens.

3. Methodology

3.1. Material Characterization

For the characterization of the cement, density tests were conducted based on ASTM C188, and X-ray fluorescence testing was performed according to ISO 29581-2:2010, which allowed determining its chemical composition. For sand, fly ash, and calcined clay, ASTM C136 was used for sieve analysis, ASTM C29 for unit weight testing, ASTM C127 for specific gravity testing, and ASTM C128 for absorption percentage. Additionally, for fly ash and calcined clay, ASTM D7348 was employed for the loss on ignition test, as shown in Fig. 1a.

3.2. Mix Design

Similarly, for the mix design, the basic proportions specified in NTP E.070 "Masonry," equal to 1:4, were considered for mortar in confined masonry bearing walls. Based on this, the proportions were modified to partially replace cement by mass with 20% fly ash and 55% calcined clay, resulting in proportions of 1:4.4 and 1:9.4 for cement and sand, respectively. The specific proportions for each mix are shown in Table III.

TABLE III. MIX DESIGN PROPORTIONS

Mortars	**Mix Design Proportions**			
	Cement	**Sand**	**Fly Ash**	**Calcined clay**
Standard Mortar	1	4.23	-	-
20% Replacement	1	4.44	0.033	0.0424
55% Replacement	1	9.4	0.1355	0.1721

3.3. Hardened State Testing

All specimens were cured for 28 days at a controlled temperature following the specifications of ASTM C511, which sets the criteria and conditions for the storage of mortar and concrete samples, as shown in Fig. 1b.

3.3.1. Compression Strength Test

Cubic specimens measuring 50 mm x 50 mm x 50 mm were considered, according to ASTM C109. Three specimens per sample type were prepared, for a total of 27 specimens to be cured at 7, 14, and 28 days.

3.3.2. Flexural Strength Test

For this test, the specifications of ASTM C348 were followed. The specimens measured 40 mm x 40 mm x 160 mm. Three specimens per sample type were considered, for a total of 9 specimens. The flexural strength was evaluated at 28 days, considering the influence of fly ash and calcined clay on the sample.

3.3.3. Absorption, Porosity, and Void Percentage Test

The specifications of ASTM C642-06 were followed. The specimens were dried in an oven at 100-110°C, cooled to room temperature, and submerged for 48 hours. A total of 9 specimens were prepared, with 3 from each mix design.

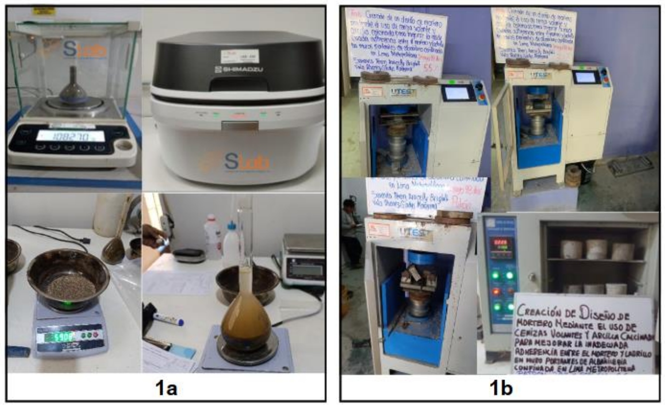


Fig. 1.*Figure 1a shows the characterization tests, and 1b shows the hardened state tests.*

4. Results and analysis

4.1. Characterization of Materials

4.1.1.Sand

The granulometric distribution was analyzed for the proportion of particles retained on each sieve. The specific results of this distribution are detailed in Fig. 2.

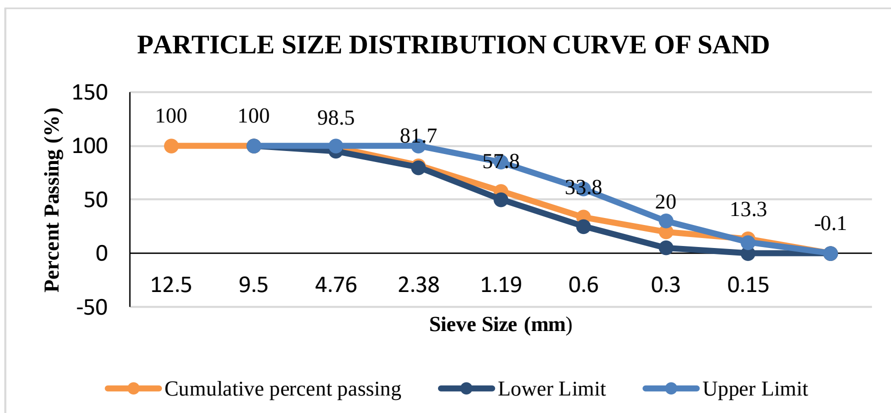


Fig. 2.Particle Size Distribution Curve of Fine Aggregate.

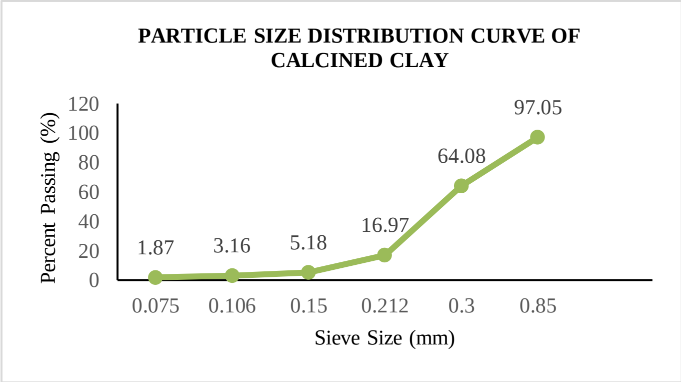
In Fig. 2, it can be observed that most of the particles are retained in sieves No. 16 and No. 30, with 24% and 24.1%, respectively. This suggests that the sand has an appropriate particle distribution to provide good compaction to the mortar. However, the material passing through sieve No. 100 slightly exceeds the expected range, which is attributed to the presence of impurities in the sand, a factor considered when designing the mix.

4.1.2.Calcined Clay

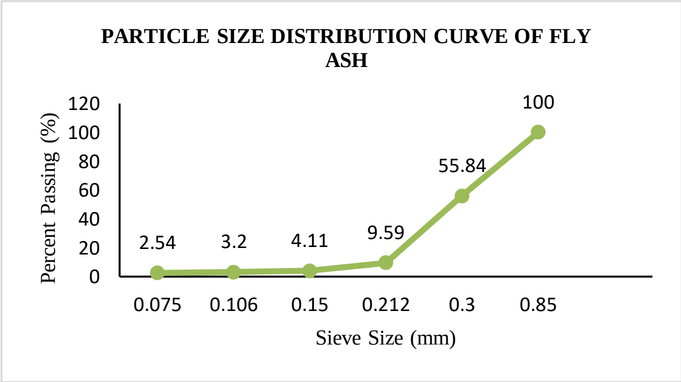
The granulometry was evaluated to determine its fineness and suitability for the mix, using a series of sieves. The granulometric distribution, as seen in Fig. 3a, shows that most of the particles pass through sieve No. 50, while around 5.18% pass through sieve No. 100. This profile indicates a fine particle distribution, which is beneficial for improving the cohesion of the mortar mix. The fineness of the calcined clay allows for greater contact between particles, promoting compaction and reducing voids in the hardened mortar.

4.1.3.Fly Ash

The granulometric distribution was evaluated to ensure particle uniformity and integration in the mortar. The granulometry indicates high retention between sieves No. 50 and No. 70, demonstrating its fine distribution, as shown in Fig. 3b. This particle size is suitable for use in the mortar, as it facilitates interaction with the cement and the creation of a dense and well-compacted matrix.



3a



3b

Fig. 3. Figure 3a represents the particle size distribution of calcined clay and 3b of fly ash.

4.2. Hardened State Test

4.2.1. Compressive Strength Test

The compressive strength test was conducted at 7, 14, and 28 days. The design strength considered was 17.16 MPa. At each date, the maximum load of the specimens was recorded.

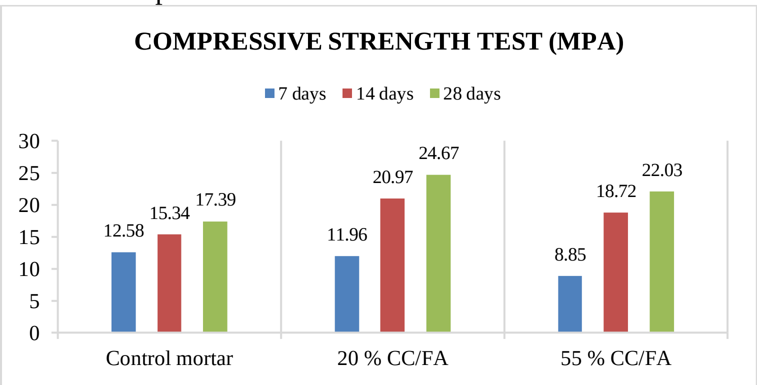


Fig. 4. Compressive Strength Test results.

The results reveal an increase in strength with curing time in the three types of mortar, although with significant differences in the mortars with 20% and 55% replacement of cement with fly ash and calcined clay. At 7 days, the control mortar shows a higher initial strength of 12.58 MPa compared to the mortars with replacements. This difference in strength occurs because these materials have a slower rate of strength gain in the early stages due to their lower initial reactivity compared to Portland cement. However, at 14 days, the mortar with 20% replacement already surpasses the control mortar. This is attributed to the pozzolanic activity of the fly ash and calcined clay, which reacts with the lime released during the cement hydration process and contributes to the formation of additional hydration products. Furthermore, the mortar with 55% replacement increases its strength to 18.72 MPa, also surpassing the control mortar. At 28 days, the mortar with 20% replacement reaches its maximum strength of 24.67 MPa, followed by the mortar with 55% replacement at 22.03 MPa, while the control mortar reaches 17.39 MPa, as shown in Fig. 4. These values indicate that, with a longer curing period, the mortars with replacements exceed the strength of the control mortar, surpassing the design strength. This increase in long-term strength reinforces the mortar's capacity for masonry applications.

4.2.2. Flexural Strength Test

The flexural strength test was conducted at 28 days, considering the heat development from the hydration of the fly ash and calcined clay.

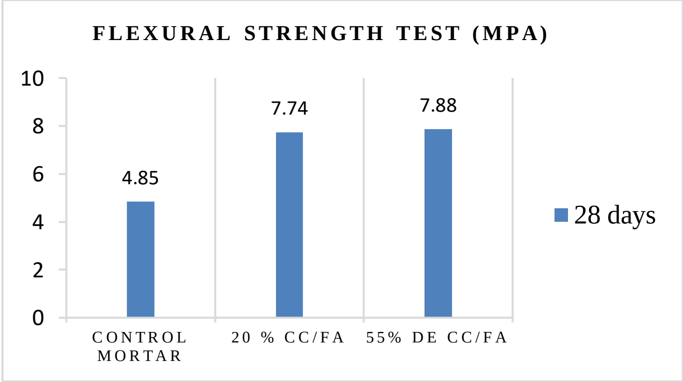


Fig. 5. Flexural Strength Test results at 28 Days.

The strength measured at 28 days shows that the mortars with 20% and 55% replacement of Portland cement with fly ash and calcined clay significantly outperform the control mortar, with strengths of 7.74 MPa and 7.78 MPa, respectively, as shown in Fig. 5. This increase in flexural strength indicates that the use of fly ash and calcined clay improves the mortar's ability to resist lateral forces, which is particularly important in seismic-prone areas. The higher strength in the mortars with replacements is the result of the internal compaction provided by the particles of these materials, strengthening the cohesion of the internal structure of the mortar and reducing the voids that are susceptible to failure due to bending stress.

4.2.3. Absorption, Porosity, and Void Content Test

The absorption, porosity, and void content test in the mortar revealed the results shown in Fig. 6.

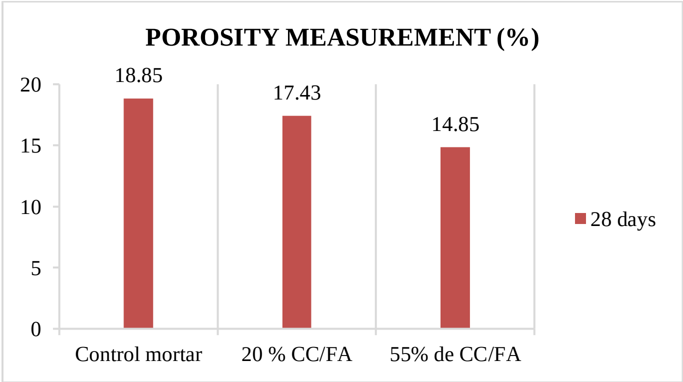


Fig. 6. Porosity measurement results at 28 Days.

The strength measured at 28 days of curing shows the values obtained in the density, porosity, and void content test for the three types of mortar. The control mortar exhibits the highest porosity value at 18.85%, while the mortars with 20% and 55% cement replacement using fly ash and calcined clay reach values of 17.43% and 14.85%, respectively, as shown in Fig. 6. This reduction in porosity of the mortars with replacement can be attributed to the finer and well-graded particle size distribution of these pozzolanic materials. In the designs with replacements, the fine particles of the materials achieve better compaction of the mix, filling the voids and resulting in a denser internal structure. In the case of the mortar with 55% replacement, the higher proportion of fine particles allows for more efficient filling of the voids, thereby reducing the overall porosity of the material. These materials improve the physical properties of the mortar by making it denser and less permeable, increasing its resistance to water penetration and its durability in various environments.

5. Conclusion

5.1. Material Characterization Test

It was concluded that both fly ash and calcined clay are viable replacements for cement in mortars, due to their chemical and physical properties. Fly ash, with a silica (SiO_2) content of 34.67%, showed adequate pozzolanic activity and a spherical particle size distribution, which facilitates cohesion and workability in the mix. Calcined clay, which contains 13.84% aluminum oxide (Al_2O_3) and 24.02% iron oxide (Fe_2O_3), proved to be a reactive component that enhances the density of the mortar. The granulometry and specific weight tests performed on sand and Portland cement confirmed that these materials provide the necessary cohesion and density to maintain the mechanical properties in designs with 20% and 55% replacement.

5.2. Hardened State Test

It was concluded that the mortar with cement replacements shows significant improvements in strength and durability. In the compression test, at 28 days, the mortar with 20% replacement sustained a maximum load of 24.67 MPa, and the 55% replacement reached 22.03 MPa, both exceeding the control mortar, which sustained a maximum load of 17.39 MPa. In the flexural test, the mixes with 20% and 55% replacement recorded increases of 59.6% and 62.47%, respectively, over the conventional mortar, indicating an improvement in cohesion and stress distribution. Regarding porosity, the mortar with 55% replacement reduced its pore volume from 18.85% (control mortar) to 14.85%, which increases the mix's compaction and its resistance to water absorption. These results suggest that these replacement materials enhance the mechanical and physical properties of the mortar, making it suitable for structural applications and in environments with high durability demands.

6. References

[1] R. Fernandez, V. Ramirez, “Propuesta de diseño de un mortero adicionando fibras de polipropileno para mejorar la adherencia del mortero-ladrillo en muros de albañilería simple en la ciudad de Lima Metropolitana”, Tesis de titulación, Universidad Peruana de Ciencias Aplicadas, Facultad de Ingeniería. Lima, Perú, 2023. [https://repositorioacademico.upc.edu.pe/bitstream/handle/10757/667876/Fern%C3%A1ndez_BR.pdf?sequence=17&isAllowed=y]

[2] R. Garcia, “Evaluación y reparación de fisuras en estructuras de concreto armado mediante el comité ACI 224 en el distrito de Vicco – Pasco 2018”, Tesis para optar titulo profesional, Universidad Nacional Daniel Alcides Carrión, 2009. [http://repositorio.undac.edu.pe/handle/undac/1532]

W. Goñi, N. Maquin, “Análisis de errores constructivos en viviendas de albañileria confinada en países altamente sísmicos y reforzamiento de muros con malla galvanizada”, Trabajo de investigación, Universidad Peruana de Ciencias Aplicadas, 2019. [http://hdl.handle.net/10757/648598]

[3] P. Yugovich, “Tópico 1(Patología en las construcciones),” en VI Congreso Internacional sobre Patología y Recuperación de Estructuras: Estudio de dos casos paradigmáticos de fallas en construcciones con la utilización de morteros de cemento con aire incorporado y sin cal, Córdoba, Argentina, 2021. [https://www.edutecne.utn.edu.ar/cinpar_2010/Topico%201/CINPAR%20061.pdf]

[4] M. Calderon, “Evaluación de errores más comunes en el proceso constructivo en cimentación y muros en las viviendas de albañilería confinada de los sectores 14, 19 y 21 Cajamarca 2019”, Tesis de titulación, Universidad Privada del Norte, Facultad de Ingeniería Civil. Cajamarca, Perú, 2021. [https://hdl.handle.net/11537/27776]

[5] Instituto Nacional de Estadística e Informática (INEI). "*Estadística de seguridad ciudadana*, Lima, 2023." [https://m.inei.gob.pe/media/MenuRecursivo/boletines/estadisticas-de-seguridad-ciudadana-enero-2023-junio-2023.pdf]
[6] Instituto Nacional de Defensa Civil (INDECI), "Escenario sísmico para Lima Metropolitana y Callao: Sismo 8.8Mw, Lima, 2017." https://portal.indeci.gob.pe/wp-content/uploads/2019/01/201711231521471-1.pdf]
[7] A. Yılmaz, F. Degirmenci, Y. Aygörmez, "Effect of initial curing conditions on the durability performance of low-calcium fly ash-based geopolymer mortars," *Boletín de La Sociedad Española de Cerámica y Vidrio*, 2023, 15(18). [https://doi.org/10.1016/j.bsecv.2023.10.006]
[8] S. Sargon, E. Gomaa, A. Gheni y M. ElGawady, Optimization of curing parameters of class C fly-ash-based alkali-activated mortar. *ACI materials journal*, 2022, 119(3). [https://doi.org/10.14359/51734608]
[9] W. Chen, H. Zhu, Y. Li, L. Yang, S. Cheng, y H. Yu, Engineered cementitious composites using blended limestone calcined clay and fly ash: Mechanical properties and drying shrinkage modeling. Case Studies in Construction Materials, 2024, 20(1), 1–23. [https://doi.org/10.1016/j.cscm.2024.e02960]
[10] P. Kumar, G. Nakkeeran, K. Onyelowe y L. Krishnaraj, Comparative study on net-zero masonry walls made of clay and fly ash bricks and grouts/mortars/stuccos with the effect of super fine fly ash blended cement—low carbon cement. International Journal of Low-Carbon Technologies, 2023, 18, 1008–1014. [https://doi.org/10.1093/ijlct/ctad087]
[11] S. De Carvalho, Q. Dieu, y W. Arnaud, Carbonation resistance of calcined clay-ground granulated blast furnace slag alkali-activated mortar. Construction and Building Materials, 2023, 393(1), 1–11. [https://doi.org/10.1016/j.conbuildmat.2023.131811]
[12] Z. Liu, J. Han, y L. Hu, Mechanical properties and microstructure of cement-fly ash-dacite powder composite cementitious system. Developments in the Built Environment, 2024, 17, 100305. [https://doi.org/10.1016/j.dibe.2023.100305]
[13] S. Feng, X. Zhang, L. Xu, W. Tao y G. Duan, Correlation analysis of various characteristics of fly ash based on particle separation. Case Studies in Construction Materials, 2024, 20(1), 1–15. [https://doi.org/10.1016/j.cscm.2023.e02785]