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Original Article

Influence of Metakaolin Incorporation on the Physical-Mechanical Performance of Structural Repair Mortar

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Abstract *- The deterioration of buildings and infrastructure creates a need for repair materials with adequate mechanical performance and practical applicability. The study focused on evaluate the effect of replacing part of the cement with metakaolin on the fresh-state and mechanical behavior of structural repair mortar. Under this premise, an experimental study was designed with a mix targeting 250 kg/cm², prepared following the ACI method, where the reference mortar was compared with three mixtures in which part of the cement was replaced by 5%, 10%, and 15% metakaolin. The fresh mortar was evaluated through flow, air content, and setting time tests, as well as hardened mortar was also tested for compressive and flexural strength after 7, 14, and 28 days of curing. In general, adding metakaolin reduced flow from 101.48% to 96.37% and increased air content from 3.53% to 5.09% as the dosage increased. Likewise, initial setting time decreased from 344.60 min to 334.70 min and final setting time from 495.40 min to 455.10 min. Regarding mechanical performance, the most favorable response was obtained with 10% metakaolin, reaching a compressive strength of 284.38 kg/cm² and a flexural strength of 41.03 kg/cm² at 28 days. Among the tested mixtures, the 10% metakaolin dosage gave the best overall response, since it kept a good balance between workability and mechanical strength, which may be considered a technically viable alternative for structural repair mortars.*

Keywords *- Metakaolin, Strength, Performance, Mortar, Structural repair, Testing.*

1. Introduction and Background

In Peru, the need to intervene in existing housing and infrastructure represents a relevant technical need. According to INEI, in 2024, 8.0% of households in the country had a qualitative housing deficit, which includes dwellings with inadequate materials, overcrowding, or lack of basic services [1]. In addition, there is a long-known structural vulnerability: CENEPRED warns that around 50% of Peruvian homes are made of rammed earth or adobe, which are particularly vulnerable under seismic action [2], but the situation is not limited to housing. According to a report from the Comptroller's Office, more than 50% of public schools sampled nationwide had deficiencies in their infrastructure, with many displaying deteriorations in their roofs, walls, floors, and other major components [3]. While not all deficiencies directly relate to structural pathology, they indicate that an evaluation of the built environment is required, along with its maintenance and, in most cases, require repairs that are technically correct.

In these applications, structural repair mortar is expected to perform to very high standards on site. The material needs to achieve a high compressive strength, as well as be able to withstand the conditions it is exposed to, in addition to the expected behaviours of the repaired system (based on ACI) [4]. Several sources indicate that many of the reasons for the failure of repairs relate not to the nominal strength being too low but rather to the new material not being compatible with the existing substrate or to the new material shrinking, resulting in cracking or bond failure [5].

According to a study conducted by Hassan et al., the durability of the repaired concrete matrix is closely related to both the stability of the repair material over time and the level of compatibility with the existing concrete surrounding the repaired area [6]. This observation highlights the compelling technical issues associated with determining what constitutes a successful repair. In this regard, the use of metakaolin as an alternative to cement is a viable option with trade-offs. When part of the cement is replaced with metakaolin, the mortar or concrete matrix tends to become denser, which can improve strength and durability [7]. Furthermore, it has been shown to produce lower levels of permeability and increased performance under conditions of aggressive exposure [8].

However, the extremely high fineness of metakaolin increases the water demand associated with creating mortar, and thus may negatively impact workability, especially when the metakaolin/cement replacement ratio is not adequately adjusted to meet performance requirements [7]. The primary question concerning the performance of mortar containing metakaolin is not whether it will enhance the performance of mortar, but rather the maximum amount of metakaolin that can be incorporated into a mortar without compromising the fresh-state performance properties of the mortar. This issue is particularly critical in countries such as Peru, where repair quality can significantly affect the structural integrity of existing elements compared to that of new construction.

Dakwale et al. [9] investigated how metakaolin could be used with concrete and polymer-modified mortar to repair damaged structures. They studied the influence of substituting part of the cement for metakaolin on the performance of polymer-modified concrete and mortar when used for repairs and refurbishment. Of the mixes tested, it was found that adding 10% metakaolin produced a very acceptable mix with high compressive strength and relatively low water absorption compared to other mixes. In addition, when 0.5% of polymer latex was added to the mix, both durability and mechanical performance improved. One important finding was that the same mix design was subsequently used on a structure that was degraded, where the results were consistent with the laboratory experiments.

In China, Wang et al. [10] evaluated hydraulic lime mortar containing metakaolin for possible use as a repair material. The researchers focused on how progressively higher metakaolin content influenced the mortar's microstructure, physical attributes and mechanical attributes for repair purposes. They found that increasing the amount of metakaolin resulted in lower flowability, decreasing setting times; however, as the amount of metakaolin increased, also compressive strengths, flexural strengths and bond strengths increased. Therefore, the matrix became denser, with reduced porosity. The study concluded that metakaolin improves the performance of the mortar when used at appropriate quantities.

In their work in 2025, Sulca et al. [11] investigated the performance of structural concrete which had been exposed to the marine environment of Callao, Peru. They evaluated the effect of replacing 10% or 15% of the cement in the concrete mix with metakaolin on the fresh and hardened properties of each mix design with a specified compressive strength of f'c = 300 kg/cm², and with water-to-cement ratios of 0.45 and 0.50. Results indicated that metakaolin reduced the slump and altered the air content of the mixtures, while also improving indicators for strength and durability. The mixed design with 15% metakaolin exhibited very low chloride permeability; nevertheless, the authors indicated that the 10% replacement had produced the best overall balance of strength and durability.

Finally, Loureiro et al. [12] conducted a study in Brazil on lime-metakaolin restoration mortars created using industrial by-products from the Amazon. They mainly wanted to see if lime–metakaolin mortars could match well with historical mortars in mineralogical, physical, and mechanical terms, for possible use in restoration and conservation. The study found that mortars created using metakaolin were actually compatible with the original materials on a mineralogical as well as a physical and mechanical basis. Therefore, the results suggested that these metakaolin mortars were suitable for use in restoration projects, as metakaolin is produced from industrial waste. Furthermore, they mentioned that metakaolin has a great deal of practical applicability as a component of repair mortars.

Contrary to other research performed recently regarding the effect of replacing 5%, 10%, and 15% of the cement in structural repair mortars with metakaolin, this project evaluated the effect of different percentages of metakaolin on the fresh state properties and mechanical properties of the mortar at different curing times; it also sought to establish what dosage of metakaolin provided an optimal balance between physical/mechanical characteristics and material efficiency. Another important finding of this study was that metakaolin was evaluated using consistent replacement ratios and with no chemical admixture, thus allowing more precise evaluation of its direct pozzolanic activity on the repair mortar.

2. Materials and Methods

The study was developed under an experimental design with a quantitative approach and an explanatory level since the independent variable was the percentage of cement replaced with metakaolin, which was adjusted to examine its effect on the mechanical and physical behavior of the structural repair mortar. The study was carried out in a laboratory environment, where mortar mixes were designed and prepared using materials that had been previously selected and characterized.

2.1. Constituent Materials

2.1.1. Fine Aggregate

The fine aggregate selected in this research plays a decisive role in mortar behavior, since it influences adhesion to the cementitious paste, workability of the mortar, and its fresh and hardened behavior. In accordance with ASTM C-33 [13], fine aggregate corresponds to particles passing the 4.75 mm sieve and retained above 75 µm.

The fine aggregate was obtained from the Umuto quarry, located approximately 20 minutes from Huancayo, and was transferred to the laboratory for physical characterization, as shown in Table 1, which served as the basis for the mortar mix design for structural repair, no significant presence of silt or clay was observed; therefore, the aggregate was considered suitable for preparing the mixes tested in the study.

Table 1. Physical properties of fine aggregate

Umuto Quarry	
Fineness Modulus	2.42
Natural Moisture Content (%)	0.38
Bulk Density (kg/m³)	1410
SUCS Soil Class	Poorly-graded sand - SP
Density (kg/m³)	2479.93
Specific Gravity (g/cm3)	2.37
Water Absorption (%)	2.75

2.1.2. Metakaolin

Metakaolin utilized for the purposes of this research was metamorphosized from kaolin clay by firing it into a pozzolanic material made up of an aluminosilicate composition. As a pozzolan supplier, the produced metakaolin appears to be a fine whitish powder with a specific gravity of 2.60 g/cm³ and has a laminar morphology, which contributes to its ability to react within the cementitious matrix. Based on the technical specification provided for metakaolin, the properties that will assist in determining its usefulness as a pozzolan include: 1) pozzolanic reactivity of 120%; 2) 9% passing through a #325 mesh; 3) specific surface area of 3m²/g; and 4) absorption of 1.5% (Table 2). The above-mentioned properties demonstrate that metakaolin has adequate fineness and reactivity for utilization as an SCM. The chemical composition of metakaolin consists of 98% $SiO_2+Al_2O_3+Fe_2O_3$; 0.6% SO_3; 0.3% Na_2O+K_2O; 0.2% moisture; and 0.5% loss on ignition. The results of this study provided insight into the effects of using metakaolin to replace part of the cement at 5%, 10%, and 15%, and examining the resulting changes in the fresh and hardened behavior of the structural mortar.

Table 2. Properties of metakaolin

Property	Value
Specific Gravity	2.60 g/cm³
Pozzolanic Activity	120%
Fineness (passing No. 325)	9%
Specific Surface Area	3 m²/g
Absorption	1.50%
$SiO_2 + Al_2O_3 + Fe_2O_3$	98%
SO_3	0.60%
$Na_2O + K_2O$	0.30%
Moisture Content	0.20%
Loss on Ignition	0.50%

2.1.3. Water

The water utilized during this study had a vital role to play in both mixing and curing the structural repair mortar, as it participates in cement hydration and, as a result, affects the fresh and hardened characteristics of the mixture. Only water that was free from harmful materials, which include acids, bases, salts, organic materials, contaminants, or any other undesirable substances that could negatively impact the behavior of the mortar, were considered for this study. Therefore, the amount of water used in each blend was calculated based on the water-cement ratio defined by the mix design, as this ratio has a direct effect on the consistency, workability, and final performance of the product. Water was also used throughout the curing process of the test specimens to ensure the adequate strength and stability of the evaluated mortars; therefore; water was an important part of the experimental procedures from start to finish.

2.1.4. Cement

The foremost binding agent for the production of mortar is cement, which produces the paste that provides bonding between fine aggregates, as well as providing strength gain. This research study utilizes Andino Type I Portland Cement as a base material in both the reference mix and the partial cement replacement mixes incorporated with metakaolin. Andino Type I Portland Cement complies with ASTM C-150 [14] (the standard for Type I Portland cement), and its properties are compatible with the designed mixes. The general properties of the Andino Type I Portland Cement, as specified by the manufacturer, are presented in Table 3.

Table 3. Technical characteristics of the cement

Property	Description
Type of Cement	Type I Portland Cement
Commercial Name	Andino Type I
Material	Cement
Presentation	42.5 kg bag
Density	3150 kg/m³
Characteristics	Obtained from the joint grinding of clinker and gypsum
Standard	ASTM C150

2.2. Mix Design Method

According to UNE-EN 1504-3 [15], which divides repair mortars into non-structural and structural classes, the mortar mix design had to meet minimum compressive strengths of 25 MPa for Class R3 and 45 MPa for Class R4. This reference was useful for the study because it did not focus on a conventional masonry mortar, but on a mixture that could be used for the repair of concrete elements. A nominal design strength of 250 kg/cm² was selected based on this standard. This value allowed the effect of metakaolin to be examined within repair mortars for moderate-demand uses. ASTM C270 [16] is valuable in other situations, but it was not the most suitable reference for this one because it mostly focuses on masonry mortars.

Using the ACI approach [17], the reference mix was designed based on that design strength. It used the physical parameters of the cement, fine aggregate, and water that were previously determined and are presented in Table 4. The first step in designing the mix was the selection of a water-to-cement ratio compatible with the desired strength. Then, the required quantities of cement, water, and sand for 1 m³ of mortar were obtained, with the water dosage adjusted according to the fine aggregate absorption. This correction was relevant because small variations in the available water can impact fresh-state behavior and consistency of the mortar.

Table 4. Input parameters used for the mortar mix design

Material parameter	
Cement unit weight (kg/m³)	1310
Cement specific gravity	3.15
Sand unit weight (kg/m³)	1410
Sand specific gravity	2.37
Water specific gravity	1
Water unit weight (kg/m³)	1000
Water-to-cement ratio	0.47

Three additional dosages were made based on the reference mix. In these, metakaolin was incorporated as partial cement replacement at weights of 5%, 10%, and 15% of the cementitious material; the remaining mixture conditions were kept constant, and only the cement replacement percentage was modified. This criterion allowed any changes in performance to the presence of metakaolin. Table 5 shows the final proportions of the reference mortar, while Table 6 includes the mixes prepared with metakaolin replacing part of the cement. For the experimental program, 12 specimens were assigned to the air content test, 12 to the flow test, and 12 to the setting time test. Also, 36 specimens were prepared for compression and another 36 for flexural testing. These tests were carried out after 7, 14, and 28 days of curing. No superplasticizer was used, so the effect of metakaolin on the fresh and hardened mortar could be seen more directly. This decision also made it possible to evaluate the loss of workability associated with higher replacement levels under a base mixture without chemical admixtures.

Table 5. Proportions of the reference mortar mixture

Component	Mass	Density (kg/m³)	Volume (m³/m³)
Fine Aggregate (kg)	1378.68	2479.93	0.549
Cement (kg)	507.94	3150	0.159
Water (L)	296.45	1000	0.292

Table 6. Mix design incorporating metakaolin

Materials	5%	10%	15%
Cement (kg)	482.54	457.14	431.75
Fine Aggregate (kg)	1378.68	1378.68	1378.68
Water (L)	296.45	296.45	296.45
Metakaolin (kg)	25.39	50.79	76.19

2.2.1. Flow Test

The flow of fluid (fresh) mortar was tested using ASTM C1437 [18] as an evaluation method for determining mortar workable and consistency. Workable and consistency have a direct impact on the placement and compaction of repair mortars; thus, it was imperative that an evaluation of the fluidity of the mortars was conducted prior to the completion of placement and compaction for the mortar repair project. The experimental set-up consisted of a flow table, a metal-tapered cone mold, and mortar that has been divided into two equal layers of approximately 25 mm thick. Each layer of mortar was compacted with 20 strokes of the tamper prior to taking a measurement of flow. The mold was raised vertically, and 25 drops with an approximate drop height of 12.70 mm were performed in 15 seconds; at the end of the drying process, each spread of fresh mortar was measured in all of the samples, and the average of three measurements was determined for each sample. For this portion of the experiment, the reference mix and samples containing 5%, 10%, or 15% partial replacement of OPC by metakaolin were included in the total amount of four groups of samples tested (12 total samples). The tools required for this phase of the experiment included a flow table, tapered cone mold, tamper, caliper, scale, containers, spatulas, and basic PPE.

2.2.2. Air Content Test

The determination of the amount of air contained in the mortar was made in accordance with ASTM C185 [19] to quantify the volume of air trapped in the fresh mortar mix - because this characteristic can directly affect the density, workability, and mechanical properties of hardened mortar. A steel cylinder (inside diameter 76 mm ±2 mm, depth about 88 mm), which will hold approximately 400 ml ±1 ml of water, was used to conduct this test. The test involved filling the cylinder in three layers of equal thickness; compacting each layer with 20 tamper strokes, followed by gentle tapping around the mold to release trapped air; removing any excess material to provide a flat top; and weighing both the mold and material together at the end of the test. Three specimens of each mix, including the control mix and the mixes with 5%, 10%, and 15% metakaolin as a partial replacement for cement, produced a total of 12 samples for this test. The tools and equipment used for this procedure included a mortar mixer, cylinder, tamper, balance, graduated cylinder, container, spatula, and gloves.

2.2.3. Setting Time Test

Setting time was evaluated according to ASTM C403 [20], with the room temperature kept between 20 and 25 °C throughout the test. The procedure consisted of applying the penetration apparatus needle to a depth of 25 ± 2 mm within an interval of 10 ± 2 seconds, recording the force required for each measurement to determine the mortar's penetration resistance. From those values, the initial and final setting times were established based on the resistance reached at each stage. For each sample, six penetrations were carried out at regular intervals in order to obtain a satisfactory curve of penetration resistance as a function of elapsed time; the test was applied to the reference mix and to the mixes with 5%, 10%, and 15%

partial cement replacement by metakaolin, with three samples per dosage – for a total of 12 samples. Fresh mortar was placed in specimen molds for the setting time test, and the procedure required a penetration needle, tamping rod, pipettes, thermometer, and compression device.

2.2.4. Compressive Strength Test

Compressive strength of the mortar was obtained according to ASTM C109/C109M [21], using 50 mm cube specimens prepared and cured under the conditions specified in that procedure. After obtaining the reference mix and the mixes with 5%, 10%, and 15% partial cement replacement by metakaolin, the mortar was placed into pre-lubricated metal molds. Filling occurred in two layers, each layer compacted through four distinct stages (eight strokes at ten seconds for each compaction stage) before removing any air pockets, creating a uniform fill and decreasing internal voids; specimens received a damp cloth cover for 24 hours following molding to reduce early moisture loss; specimens were subjected to the curing process up until the time tests were conducted. Compressive strength evaluation was carried out at 7, 14, and 28 days, using three samples per dosage at each age – which represented a total of 36 specimens. For this test, mortar specimens were tested in a compression machine, using metal molds, a tamper, a scale, containers, a spatula, lubricant, gloves, and graduated cylinders.

2.2.5. Flexural Strength Test

The flexural strength was evaluated using the procedure described in ASTM C348 [22], which establishes the procedure for testing prismatic specimens subjected to center-point loading. For this purpose, the reference mix and the mixes with 5%, 10%, and 15% partial cement replacement by metakaolin were placed into pre-lubricated metal molds measuring 40 × 40 × 160 mm. Filling was done in two layers, compacting each layer with 60 strokes over 60 seconds; the final layer was struck off flush with the surface using the edge of a metal straightedge. Once demolded, preparation was completed, the specimens were kept under a moist cloth for the first 24 hours before being transferred to curing until the testing age. Flexural strength evaluation was carried out at 7, 14, and 28 days, using three specimens per dosage at each age – which represented a total of 36 samples. Mortar specimens were prepared using metal molds, a tamper, containers, a scale, lubricant, gloves, graduated cylinders, a spatula, and a compression testing machine.

3. Results and Discussion

First, this section presents the fresh mortar results, such as flow, air content, and setting time. Then, it shows the compressive and flexural strength results of the hardened mortar after 7, 14, and 28 days of curing. The reference mix was compared with mixtures containing 5%, 10%, and 15% metakaolin as cement replacement, in order to observe how this material affected the behavior of the structural repair mortar.

3.1. Flow Test Results

Table 7 presents the flow test results for mortar with metakaolin dosages of 0%, 5%, 10%, and 15% as partial cement replacement. Three samples were evaluated for each dosage, following the procedure established in ASTM C1437 [18].

Table 7. Flow test results

Specimen	0%	5%	10%	15%
M-01	104.34	98.25	99.68	97.12
M-02	101.36	103.41	97.65	98.23
M-03	103.25	101.55	99.84	102.81
Average	102.98	101.07	99.06	99.39
Standard Deviation	1.51	2.61	1.22	3.02
Mean - SD	101.48	98.46	97.84	96.37

Based on the consistency ranges reported in [23], mortar flow is classified as dry when it is below 90%, plastic between 90% and 110%, and fluid when it ranges from 110% to 130%, so respect to this classification and the values shown in Table 7, all tested mixes – the reference sample as well as those with 5%, 10%, and 15% metakaolin – fell into the plastic consistency range.

In addition, ASTM C1437 [18] establishes that the optimal mortar flow should be within 100 ± 5%, that is, between 95% and 105%. Considering the final values for each dosage – 101.48% for 0%, 98.46% for 5%, 97.84% for 10%, and 96.37% for 15% – all remained within that optimal interval. A slight decrease in flow can be observed, however, as the metakaolin percentage increases relative to the reference mix. This suggests that incorporating metakaolin moderately reduces mortar workability, though without compromising its proper behavior in the fresh state.

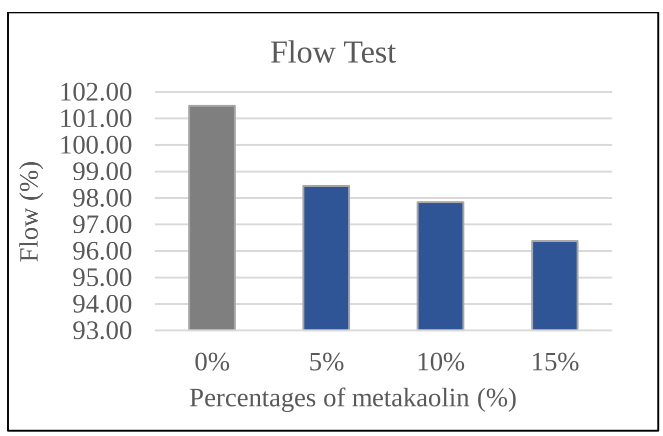

Fig. 1 Bar chart of the flow test

Figure 1 shows that mortar flow decreased as the metakaolin percentage increased; thus, the reference mix (0%) had the highest flow and the mix with 15% metakaolin presented the lowest, with reductions of 2.98%, 3.59%, and

5.04% for the 5%, 10%, and 15% mixes compared to the reference mortar, indicating that metakaolin incorporation reduced the workability of fresh state.

3.2. Air Content Results

In Table 8 presents the air content test results for mortar with 0%, 5%, 10%, and 15% metakaolin as partial cement replacement; three samples were evaluated for each dosage, following the procedure established in ASTM C185 [19].

Table 8. Air content for each mix proportion

Specimen	0%	5%	10%	15%
M 1	3.75	3.98	4.33	5.10
M 2	3.51	4.46	5.00	5.41
M 3	3.83	4.11	4.72	5.22
Mean	3.70	4.18	4.68	5.24
Std. dev.	0.17	0.25	0.34	0.16
Mean - Sd	3.53	3.94	4.35	5.09

In Peru, there is currently no specific standard that defines allowable air content values for structural repair mortars; NTP 399.610 is more oriented toward mortars used in masonry work. For reference, ASTM C270 [16] indicates a maximum air content of 12% relative to mortar volume. Based on Table 8, all the mixes (0%, 5%, 10%, and 15% metakaolin) remained within the limit set by that standard, and as the metakaolin dosage increased, the air content also increased, from 3.53% in the reference mix to 3.94%, 4.35%, and 5.09% in the mixes with 5%, 10%, and 15% metakaolin, indicating that metakaolin slightly increased entrained air without exceeding the adopted reference limit.

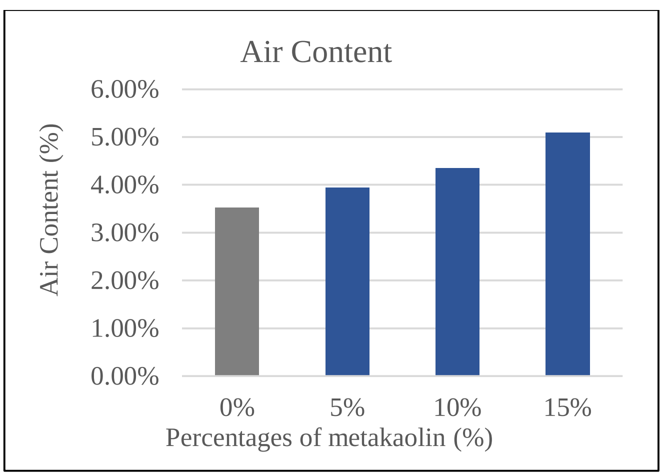

Fig. 2 Bar chart of the air content test

Figure 2 shows an increasing trend in air content with higher metakaolin replacement; therefore, the reference mix (0%) presented the lowest value and the mix with 15% metakaolin had the highest, with increases of 11.61%, 23.23%, and 44.19% for the 5%, 10%, and 15% mixes compared to the reference mortar, indicating that metakaolin incorporation increased entrained air in the fresh mortar but all values remained within the limit set by ASTM C270 [16].

3.3. Setting Time Test Results

Table 9 shows the average setting times for mortars with 0%, 5%, 10%, and 15% metakaolin as partial cement replacement. Six penetrations were performed for each dosage according to ASTM C403 [20]. Measurements were initially taken every 30 minutes and then adjusted to 15-minute intervals as the mixture became stiffer. For each measurement, the force needed for penetration was noted, and these values were used to define the penetration resistance and the related setting times.

Table 9. Initial and final set values for each mortar mixture

Mixture	Initial set		Final Set	
	min	h	min	h
0%	344.60	5.74	495.40	8.26
5%	341.90	5.70	484.70	8.08
10%	340.20	5.67	471.20	7.85
15%	334.70	5.58	455.10	7.59

Following ASTM C403 [20], the setting process was interpreted from the increase in penetration resistance. In this study, values close to 3.5 MPa and 27.6 MPa were taken as references for the initial and final set, respectively. In that regard, Table 9 shows that as the metakaolin percentage increases, both initial and final setting times tend to decrease; the reference mix recorded an initial setting time of 344.60 min and a final time of 495.40 min, while the mix with 15% metakaolin gave the lowest values – 334.70 min and 455.10 min, respectively; it can be said that adding metakaolin accelerates the setting process of the mortar, a behavior that is consistent with what Rashad [24] reported for cementitious materials containing metakaolin.

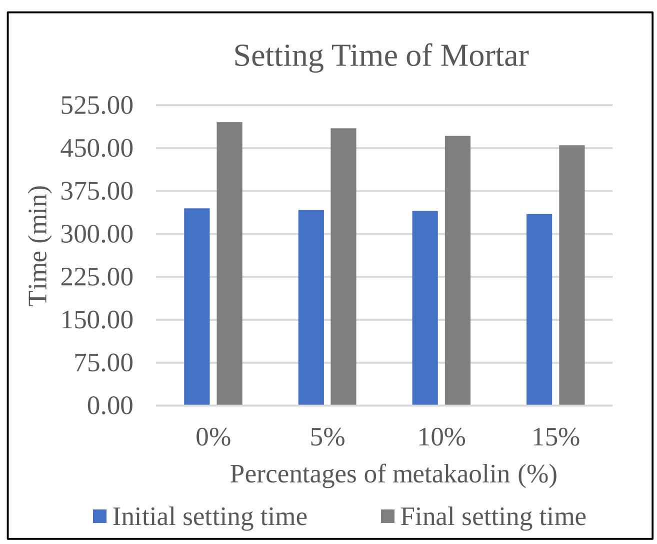

Fig. 3 Bar chart of the setting time test

As can be seen in Figure 3, adding more metakaolin led to shorter initial and final setting times. Compared with the control mortar, the reductions in final setting time were 2.16%, 4.88%, and 8.13% for the 5%, 10%, and 15% mixtures, respectively. For the initial setting time, the reductions were smaller, reaching 0.78%, 1.28%, and 2.87%; indicating that metakaolin accelerated setting, with a more evident effect on the final setting time.

3.4. Compressive Strength Test Results

The 7-day results are shown in Table 10, and the control mix was compared with the 5%, 10%, and 15% metakaolin mixes. The highest strength at this age was obtained with 10% metakaolin, reaching 107.33 kg/cm². It can also be seen that when the dosage goes above 10%, compressive strength tends to drop. Three samples were tested for each dosage, following the procedure established in ASTM C109/C109M [21].

Table 10. Compressive resistance of mortar mixtures at 7 days

Sample	0 %	5 %	10 %	15 %
C 1 (kg/cm2)	94.53	99.02	108.76	106.80
C 2 (kg/cm2)	98.26	107.42	122.56	108.36
C 3 (kg/cm2)	90.65	105.27	112.21	101.45
Average	94.48	103.90	114.51	105.54
Standard Deviation	3.81	4.36	7.18	3.62
Av - SD	90.67	99.54	107.33	101.91

The results after 14 days are shown in Table 11, the comparison included the control mortar and the mixes with 5%, 10%, and 15% metakaolin replacing part of the cement. The best result was obtained with 10% metakaolin, reaching 258.62 kg/cm². It can also be seen that when the dosage goes above 10%, compressive strength tends to drop. Three samples were tested for each dosage, following the procedure established in ASTM C109/C109M [21].

Table 11. Compressive resistance of mortar mixtures at 14 days

Sample	0 %	5 %	10 %	15 %
C 1 (kg/cm2)	247.25	250.26	260.86	261.54
C 2 (kg/cm2)	243.21	253.74	261.46	257.38
C 3 (kg/cm2)	248.28	260.38	258.40	256.6
Average	246.25	254.79	260.24	258.51
Standard Deviation	2.68	5.14	1.62	2.66
Av - SD	243.57	249.65	258.62	255.85

The results at 28 days are shown in Table 12. The control mortar was compared with the mixtures containing 5%, 10%, and 15% metakaolin as cement replacement. The strength increased up to the 10% mixture, which reached the highest compressive strength value, 284.38 kg/cm². It can also be seen that when the dosage goes above 10%, compressive strength tends to drop. Three samples were tested for each dosage, following the procedure established in ASTM C109/C109M [21].

Table 12. Compressive resistance of mortar mixtures at 28 days

Sample	0 %	5 %	10 %	15 %
C 1 (kg/cm2)	270.04	276.30	284.42	280.17
C 2 (kg/cm2)	274.31	278.61	287.65	279.58
C 3 (kg/cm2)	261.17	288.70	291.09	275.95
Average	268.51	281.2	287.72	278.57
Standard Deviation	6.7	6.59	3.34	2.29
Av - SD	261.8	274.61	284.38	276.28

Besides, Table 12 shows that all of the dosages tested (0%, 5%, 10%, and 15% metakaolin) exceeded the design strength of 250 kg/cm² after 28 days of curing. The 10% metakaolin mix presented the highest compressive strength at 284.38 kg/cm², followed by the 15% mix at 276.28 kg/cm², the 5% mix at 274.61 kg/cm², and the reference mix (0%) at 261.80 kg/cm². The results of these studies also showed that the metakaolin's contribution to the compressive strength increased with increasing amounts of metakaolin, until a 10% replacement rate, followed by a slight decrease in compressive strength beyond that. Nonetheless, all the mixtures tested were greater than the specified minimum of 25MPa, which is required for class R3 mortars according to UNE-EN 1504-3, thus justifying their classification as structural repairs within the constraints of this research.

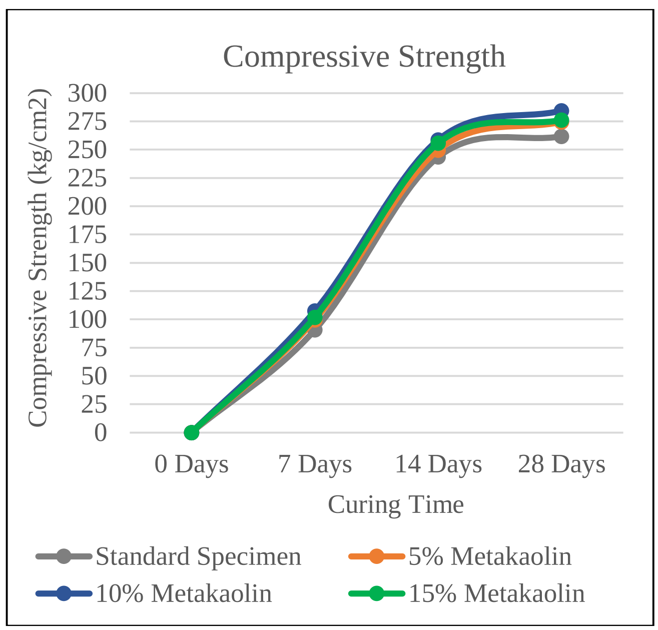

Fig. 4 Compressive strength vs. Curing time curve

The strength curve of all the various blends is depicted in Figure 4. Nevertheless, the metakaolin behaved differently, showing a nonlinear response. The reference mix achieved a final compressive strength of 261.80 kg/cm² at 28 days. The blends of 5%, 10%, and 15% blend ratios attained compressive strengths of 274.61 kg/cm², 284.38 kg/cm² and 276.28 kg/cm², respectively. This is equivalent to an increase over the reference material of 4.89%, 8.63% and 5.53%, respectively. The 10% blend exhibited the most favourable response, meaning that metakaolin assisted in the development of compressive strength at moderate levels of replacement. However, after reaching the optimum metakaolin replacement ratio (10%), there is no longer an improvement in the compressive strength of the blends tested, as evidenced by the results of the 15% replacement blend. Thus, indicating that the contribution of metakaolin to further enhancing compressive strength reaches a maximum amount, where the addition of further replacement ratios to the concrete composite tested will not continue to yield mechanical benefits.

3.5. Flexural Strength Results

The flexural strength results at 7 days are given in Table 13. For this test, the control mortar was compared with the 5%, 10%, and 15% metakaolin mixes. The values did not increase in a completely uniform way, but the 15% mixture gave the highest result at this age, reaching 20.92 kg/cm². Three specimens were tested for each dosage, using the ASTM C348 [22] procedure.

Table 13. Flexural strength of mortar mixtures at 7 days

Sample	0 %	5 %	10 %	15 %
F 1 (kg/cm2)	15.74	16.88	19.25	21.48
F 2 (kg/cm2)	16.96	15.98	18.47	20.86
F 3 (kg/cm2)	17.41	18.86	17.96	21.55
Average	16.7	17.24	18.56	21.3
Standard Deviation	0.86	1.47	0.65	0.38
Av - SD	15.84	15.77	17.91	20.92

Table 14 reports the flexural strength results after 14 days of curing. At this age, the control mortar was compared with the mixes where part of the cement was replaced by metakaolin at 5%, 10%, and 15%. Flexural strength increases up to a metakaolin content of 10%, reaching a value of 37.64 kg/cm². It can also be seen that when the dosage goes above 10%, flexural strength tends to drop. Three specimens were tested for each dosage, following the procedure established in ASTM C348 [22].

Table 14. Flexural strength of mortar mixtures at 14 days

Sample	0 %	5 %	10 %	15 %
F 1 (kg/cm2)	33.62	36.46	40.33	37.25
F 2 (kg/cm2)	31.13	35.21	37.83	35.11
F 3 (kg/cm2)	34.24	38.83	43.87	39.69
Average	33	36.83	40.68	37.35
Standard Deviation	1.65	1.84	3.03	2.29
Av - SD	31.35	34.99	37.64	35.06

The 28-day results are shown in Table 15. The control mortar was compared with the mixtures containing 5%, 10%, and 15% metakaolin as a replacement for part of the cement. Flexural strength increases up to a metakaolin content of 10%, reaching a value of 41.03 kg/cm². It can also be seen that when the dosage goes above 10%, flexural strength tends to drop. Three specimens were tested for each dosage, following the procedure established in ASTM C-348 [22].

Table 15. Flexural strength of mortar mixtures at 28 days

Sample	0 %	5 %	10 %	15 %
F 1 (kg/cm2)	40.71	38.21	46.65	44.10
F 2 (kg/cm2)	38.18	42.36	43.15	40.13
F 3 (kg/cm2)	37.19	39.22	41.37	42.16
Average	38.69	39.93	43.72	42.13
Standard Deviation	1.82	2.16	2.69	1.99
Av - SD	36.88	37.77	41.03	40.14

Also, Table 15 shows that, at 28 days of curing, the reference mortar reached a flexural strength of 36.88 kg/cm² - a value that falls within an expected range, considering that this type of strength typically represents about 10% to 15% of compressive strength, as noted by Gianfranco [25]. Based on this relationship, partially replacing cement with metakaolin improved the flexural behavior of the mortar, though not in a strictly increasing manner. The highest final result corresponded to the 10% dosage, which reached 41.03 kg/cm²; followed by the 15% mix at 40.14 kg/cm², followed by the 5% mix at 37.77 kg/cm². Compared to the reference mortar, all mixes with partial cement replacement by metakaolin showed an increase in flexural strength, suggesting a favorable effect from this addition. However, the best performance was recorded with 10%, so it can be inferred that, under the conditions of this study, that dosage offered the most suitable response, while with 15% the strength remained above the reference, though without surpassing the value obtained with 10%.

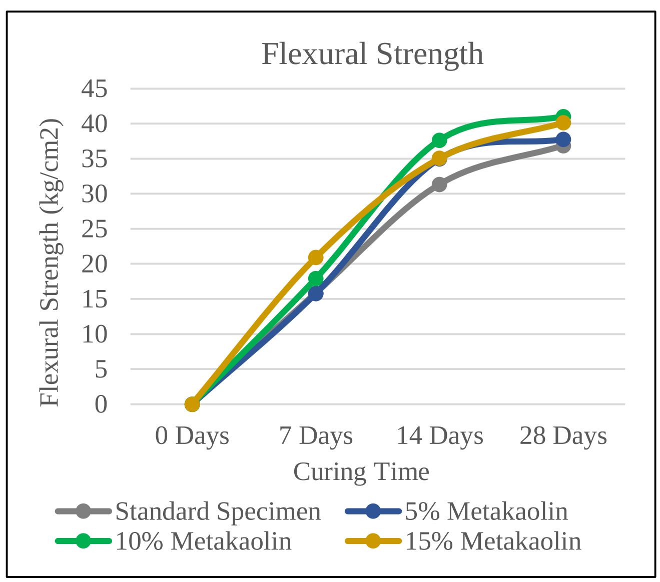

Fig. 5 Flexural strength vs. Curing time curve

Figure 5 shows that flexural strength increased with curing time for all mixes, though the curves did not follow exactly the same path; during the first 7 days, the mix with

15% metakaolin showed faster strength development, reaching the highest initial value among the dosages tested. However, between 7 and 14 days, the steepest slope was observed for the 10% mix, which then showed the highest mechanical response and maintained that position up to 28 days. The reference mortar and the 5% mix followed a more moderate evolution and remained below the higher replacement dosages. At 28 days, the reference mortar reached 36.88 kg/cm², while the mixes with 5%, 10%, and 15% metakaolin recorded 37.77 kg/cm², 41.03 kg/cm², and 40.14 kg/cm² – representing increases of 2.41%, 11.25%, and 8.84%, respectively; the shape of the curves indicates that partial cement replacement by metakaolin affected not only the final strength but also the rate of strength development, since the 10% mix showed the most consistent increase and the highest final value, and the 15% mix showed higher early strength but finished slightly below the 10% mix.

Table 16. Flexural-to-compressive strength ratio at 28 days

Metakaolin content (%)	Flexural strength (kg/cm²)	Compressive strength (kg/cm²)	(f'f / f'c)
0	36.88	261.80	14.09%
5	37.77	274.61	13.75%
10	41.03	284.38	14.43%
15	40.14	276.28	14.53%

Table 16 shows the flexural-to-compressive strength ratio after 28 days for all mortar mixes. This comparison helps to observe how each metakaolin percentage changed the relation between both mechanical properties. The reference mix had a ratio of 14.09%, the 5% metakaolin mix had a ratio of 13.75%, the 10% metakaolin mix had a ratio of 14.43%, and the 15% metakaolin mix had a ratio of 14.53%, all of which fall within the commonly accepted range of 10% to 15%. Thus, by incorporating metakaolin in these partial substitutions for cement, it did not change negatively relative to the flexural versus compressive relationship. Additionally, it should be noted that while the 10% mix exhibited the highest amount of flexural strength, the 15% mix exhibited the highest f'f / f'c ratio. This indicates that greater relative proportions do not always equal higher absolute values. These items combined indicate that the mechanical behavior of all of the trial mixes was consistent with a structural repair mortar.

3.6. Statistical Analysis

A one-way ANOVA was conducted on the tests conducted with three independent samples per dose size to support interpretations of experimental results. A significance level of 0.05 was adopted. The analysis was performed as a complementary tool to the descriptive statistics already reported in the tables; therefore, the results should be viewed in conjunction with mean values and standard deviations. The ANOVA p-values were as follows: flow, $p = 0.195$; air content, $p = 0.00026$; compressive strength at 7, 14, and 28 days, $p = 0.0079$, $p = 0.0035$, and $p = 0.0112$, respectively; and flexural strength at 7, 14, and 28 days, $p = 0.0013$, $p = 0.0211$, and $p = 0.0860$, respectively. The results indicate significant differences for air content and most mechanical properties, while flow and 28-day flexural strength did not show statistically significant differences at the 5% level. This finding supports a cautious interpretation of the flexural response at 28 days, where the 10% mixture presented the highest numerical value, but the statistical evidence was limited by the sample size.

3.7. Study Limitations

The experimental program was limited to three specimens per dosage and testing age, which is consistent with the adopted laboratory procedures but restricts the statistical generalization of the results. In addition, durability-related tests, such as absorption, chloride penetration, sulfate resistance, or freeze-thaw cycles, were not included. For that reason, the conclusions of this study were limited to the physical and mechanical properties measured experimentally, while durability was discussed only as background from previous research.

4. Conclusion

The use of metakaolin as cement replacement affected the mortar in both fresh and hardened conditions. In the fresh state, flowability decreased little by little, from 101.48% in the control mix to 98.46%, 97.84%, and 96.37% for the 5%, 10%, and 15% metakaolin mixes, respectively, while air content increased from 3.53% to 3.94%, 4.35%, and 5.09%, and initial setting time decreased from 344.60 min to 341.90, 340.20, and 334.70 min, and final setting time decreased from 495.40 min to 484.70, 471.20, and 455.10 min, indicating that metakaolin reduced workability, increased air content, and accelerated setting in a moderate manner.

The mechanical test data yielded positive results; however, they were not all linear in behaviour. After 28 days of curing, the control mortar reached 261.80 kg/cm² in compressive strength, increasing to 274.61 kg/cm² at 5% metakaolin, 284.38 kg/cm² at 10% metakaolin and finally decreasing slightly to 276.28 kg/cm² with 15% metakaolin addition. Flexural strength showed a similar trend, from 36.88 kg/cm² in the control mix to 37.77, 41.03, and 40.14 kg/cm² for replacement levels of 5%, 10%, and 15%. All of the mixes with metakaolin exceeded the design strength of 250 kg/cm², but the 10% mixture presented the best response, with improvements of 8.63% in compression and 11.25% in flexural strength compared to the mortar without replacement. The 15% mixture remained above the reference, but did not exceed the intermediate dosage. This indicates that the benefits of metakaolin were not proportional to the increase in replacement percentage. Under the conditions of this study, the 10% metakaolin dosage was the most suitable, since it offered the best balance between fresh-state behavior and mechanical performance; although increasing the replacement level reduced flowability and shortened setting time, the 10%

mix achieved the most favorable structural response without excessively compromising physical properties. From that perspective, metakaolin can be considered a viable alternative for structural repair mortars, as long as the replacement level is kept within a range that maintains an appropriate balance between performance and workability.

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References

[1] National Survey of Budget Programs, 2024, National Institute of Statistics and Informatics, 2024. [Online]. Available: https://www.gob.pe/institucion/inei/informes-publicaciones/6918505-encuesta-nacional-de-programas-presupuestales-2024

[2] Manual for the Reduction of Seismic Risk in Housing in Peru, Ministry of Housing, Construction and Sanitation (MVCS) and National Center for Disaster Risk Estimation, Prevention and Reduction (CENEPRED), pp. 1-112, 2016. [Online]. Available: https://sigrid.cenepred.gob.pe/docs/PARA%20PUBLICAR/MINISTERIOS/Manual%20para%20la%20Reduccion%20del%20Riesgo%20Sismico%20de%20Viviendas%20en%20el%20Peru.pdf

[3] More than 50% of Public Schools in the Country Have Infrastructure Deficiencies and Lack Basic Services, Office of the Comptroller General of the Republic, 2022. [Online]. Available: https://www.gob.pe/institucion/contraloria/noticias/589947-mas-del-50-de-iiee-publicas-del-pais-tienen-deficiencias-de-infraestructura-y-carencia-de-servicios-basicos

[4] Concrete Repair-Guide, ACI Committee 546, ACI PRC-546-23. Farmington Hills, MI, USA: American Concrete Institute, 2023. [Online]. Available: https://www.concrete.org/Portals/0/Files/PDF/Previews/546-23_preview.pdf

[5] M.H. Decter, "Durable Concrete Repair-Importance of Compatibility and Low Shrinkage," *Construction and Building Materials*, vol. 11, no. 5-6, pp. 267-273, 1997. [CrossRef] [Google Scholar] [Publisher Link]

[6] K.E. Hassan, J.J. Brooks, and L. Al-Alawi, "Compatibility of Repair Mortars with Concrete in a Hot-Dry Environment," *Cement and Concrete Composites*, vol. 23, no. 1, pp. 93-101, 2001. [CrossRef] [Google Scholar] [Publisher Link]

[7] Soner Guler, and Zehra Funda Akbulut, "Workability, Physical and Mechanical Properties of the Cement Mortars Strengthened with Metakaolin and Steel/Basalt Fibers Exposed to Freezing-Thawing Periods," *Construction and Building Materials*, vol. 394, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] Deveshan L. Pillay et al., "Engineering Performance of Metakaolin Based Concrete," *Cleaner Engineering and Technology*, vol. 6, pp. 1-12, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Vaidehi Aniket Dakwale et al., "Use of Metakaolin with Polymer Modified Concrete in Repairing of Structures," *Materials Today: Proceedings*, vol. 72, no. 1, pp. 9-18, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[10] Xiaolong Wang et al., "Enhancing Hydraulic Lime Mortar with Metakaolin: A Study on Improving Restoration Materials for Historic Buildings," *Materials*, vol. 17, no. 14, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] Sulca Gonzales et al., "*Influence of Metakaolin on the Fresh and Hardened State Properties of a Structural Concrete f'c 300 kg/cm2 for Buildings Exposed to Marine Environments, Av. Costanera- Callao*," U.G thesis, Peruvian University of Applied Sciences, pp. 1-62, 2025. [Publisher Link]

[12] Alexandre Máximo S. Loureiro et al., "Assessment of Compatibility Between Historic Mortars and Lime-Metakaolin Restoration Mortars Made from Amazon Industrial Waste," *Applied Clay Science*, vol. 198, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] *ASTM C33/C33M-18, Standard Specification for Concrete Aggregates*, Advancing Standards Transforming Markets, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[14] ASTM C150/C150M-24, Standard Specification for Portland Cement, Advancing Standards Transforming Markets, 2024. [CrossRef] [Publisher Link]

[15] Spanish Association for Standardization (AENOR), "*Products and Systems for the Protection and Repair of Concrete Structures*," Part 3: Structural and Non-Structural Repair, UNE-EN 1504-3:2006. Madrid, Spain: AENOR, 2006. [Google Scholar] [Publisher Link]

[16] *ASTM C270-19, Standard Specification for Mortar for Unit Masonry*, Advancing Standards Transforming Markets, pp. 1-14, 2019. [CrossRef] [Publisher Link]

[17] *ACI PRC-211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*, American Concrete Institute, 1991. [Google Scholar] [Publisher Link]

[18] *Standard Test Method for Flow of Hydraulic Cement Mortar*, Advancing Standards Transforming Markets, 2020. [Publisher Link]

[19] *ASTM C185-20, Standard Test Method for Air Content of Hydraulic Cement Mortar*, Advancing Standards Transforming Markets, 2020. [Google Scholar] [Publisher Link]

[20] *ASTM C403/C403M-23, Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, Advancing Standards Transforming Markets, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] *ASTM C109/C109M-21, ASTM International, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*, Advancing Standards Transforming Markets, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] *ASTM C348-21, Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars*, Advancing Standards Transforming Markets, pp. 1-6, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[23] Virtual Materials Testing Laboratory: Mortar Consistency in the Laboratory – Flow Table Method According to NCh 2257/1, Pontifical Catholic University of Chile, [Online]. Available: https://www7.uc.cl/sw_educ/construccion/materiales/html/lab_h/mortero2.html
[24] Alaa M. Rashad, "Metakaolin: Fresh Properties and Optimum Content for Mechanical Strength in Traditional Cementitious Materials—A Comprehensive Overview," *Reviews on Advanced Materials Science*, vol. 40, no. 1, pp. 15-44, 2015. [Google Scholar] [Publisher Link]
[25] Gianfranco Ottazzi Pasino, "*Notes from the Reinforced Concrete I*," Pontifical Catholic University of Peru, pp. 1-530, 2015. [Publisher Link]