Egyptian Journal of Archaeological and Restoration Studies (EJARS)
An international peer-reviewed journal published bi-annually
www.ejars.sohag-univ.edu.eg

Original article

ENHANCING THE SUSTAINABILITY OF LIME MORTAR USING FLY ASH AND NANO-FLY ASH FOR CULTURAL HERITAGE APPLICATIONS

Nail, S.[1], Rehan, F.[2(*)], Alabiad, I.[3], Tahaa, A.[3] & El Gemaiey, Gh.[4]

[1]*Inorganic Materials Conservation dept., Faculty of Archaeology, Cairo Univ., Giza, Egypt*
[2]*Environment & Restoration dept., Faculty of Nanotechnology for Postgraduate Studies, Cairo Univ., El Sheikh Zayed, Egypt.*
[3]*Construction & Building Engineering dept., Tanta Higher Institute for Engineering & Technology (THIET), Tanta, Egypt.*
[4]*Islamic Archaeology dept., Faculty of Archaeology, Cairo Univ., Giza, Egypt*
**E-mail address: Fayrouzyasser12@gmail.com*

Article info.
EJARS – Vol. 15 (2) – Dec. 2025: 189-195

Article history:
Received: 18-5-2024
Accepted: 14-4-2025
Doi: 10.21608/ejars.2025.471783

Keywords:
Lime mortar
Fly ash
Nano-Fly-ash
Cultural heritage
Sustainability

Abstract:
Emphasizing the influence of thermal aging on lime mortar, lime mortar enhanced by fly ash, and lime mortar enhanced by a percentage of nano fly ash, a comparative study is held to deduce the probability of using pozzolanic additives (fly ash) and high-tech (nanotechnology) to lessen the drawbacks of lime mortar for cultural heritage applications. This was achieved by analyzing their mechanical properties and investigating their crystalline structure before and after subjecting them to thermal aging. The optimal lime mortar achieved was the mixture enhanced by a percentage of nano fly ash, which showed a 15.8% increase in its compressive strength, and a 9.288% decrease in the mortar's porosity compared to that of the reference mortar, in addition to enhancing the overall packing density of the mortar. These findings suggest that nano fly ash can significantly enhance the durability of lime mortar, offering a promising solution for preserving cultural heritage structures.

1. Introduction

Many scientists have recently focused on the use of advanced green materials across various fields of study aiming to approach sustainable development [1]. It is critical to address the replacement of damaged materials with those with similar characteristics when considering cultural heritage sustainability in a conservation project [2]. As a result, examining the usage of lime mortar is important since it has traditionally been used in various parts of traditional building, including concrete foundations, flooring, mortar for wall construction, pointing mortar, renders, plasters, and lime washes and paints. The disadvantages of lime mortars, such as poor durability, low compressive strength, and inconsistent hardening rates could be overcome by inventing alternative additives and strengthening the binding material to stay up with current architectural improvements and climate change [3,4]. The changes in our planet's climate are leading to significant degradation of environmental stability, profoundly impacting archaeological structures and materials with serious consequences. The increase in rainfall, more frequent extreme weather events, higher temperatures, and rising sea levels create new risks while worsening existing vulnerabilities and threats to these valuable cultural artifacts [5]. Limestone is a naturally occurring rock formed through chemical sedimentary processes, such as the precipitation of calcium carbonate from lake or ocean water and the sedimentation of organic detritus like shells, coral, algae, and fecal material [6]. Lime is produced by burning limestone and then slaking it with water. To create lime mortar, lime is mixed with aggregate and water in specific ratios. It served as a binding agent in producing traditional mortars for ancient buildings until the early 20th century when Portland cement was introduced, which has been shown to negatively affect historic buildings [3]. Lime mortar has experienced a comeback in the restoration and conservation field due to its significant characteristic compatibility with heritage buildings and its resistance to the masonry movement. Its' highly stable properties are due to the carbonation process that reinforces the mortar and increases its longevity, a chemical reaction where calcium hydroxide ($Ca(OH)_2$) inside the mortar, reacts with carbon dioxide (CO_2) from the atmosphere producing calcium carbonate ($CaCO_3$). The key factors controlling this reaction are the mortar's exposure to air, its' moisture content in which the

CO_2 dissolves, the CO_2 concentration, and the time required for the reaction to take place [7]. Any reactive substance that imparts qualities of lime is now referred to as "pozzolans", this includes brick dust, ground tile or pottery, fly ash, granulated blast furnace slag (GBFS), some processed clays (metakaolin), and other related materials. Pozzolans are substances comprising reactive silica and alumina. When they are finely ground and combined with lime, they give the binder a hydraulic quality. Therefore, they could be used to replace a portion of lime to utilize the more finely powdered alternatives, in which up to 40% of the volume of the mortars' binder can be replaced by pozzolan. Some requirements still list pozzolan additions as a volumetric percentage of the mortar mix, which could make up to 10% of the total mix [3]. Focusing on fly ash (FA) as an admixture for lime mortar, it should be able to compensate for lime's shortcomings and significantly boost the mortar's early strength, making the mixture more appealing to use [4]. FA is the surplus ash produced when coal is burned in thermal power plants to produce energy and is considered one of the four byproducts of coal combustion [8]. It's classified into two types: Class F type, which is naturally siliceous, and Class C type, which is calcareous [9]. The use of fly ash in mortars has an impact on the qualities of material both in the hardened and fresh phases; it enhances workability, increases strength, decreases drying shrinkage, and temperature rise, and boosts abrasion resistance [10]. To further enhance the durability of lime mortar, advanced technologies must be anticipated and set into application, thus, the use of nanomaterials in this experimental study was put into consideration as the properties of materials tend to completely alternate when conveyed to nanoscale. Since Feynman first stated the importance of nanotechnology in 1959, there has been a massive development in the science of nanotechnology, especially throughout the last decade [11]. Nanotechnology is the science that manages matters and structures ranging in size from 1-100 nanometers at least in one dimension, while nano-modification is the manipulation of structures at the nanoscale [12]. There are various types of nanomaterials, such as carbon-based nanoparticles, inorganic nanoparticles, organic nanoparticles, Nano-clays, and Nano-emulsion [13]. In this paper we are going to focus on the use of nano-clay "Nano-Fly-ash", and its' effect on enhancing the durability of lime mortar, as it was proven effective by R. Mohana and S.M. Leela Bharathi in 2022, as a low-cost Nano-Fly ash powder was created and added to a geopolymer mortar as a filler. Their results demonstrated that pre-treated fly ash-based geopolymer mortars demonstrated a very workable mixture with a 130% increased flow rate without adding any superplasticizer. Furthermore, the greatest compressive strength of 71.22 MPa was demonstrated with the addition of 1% nano fly ash [12]. According to recently developed literature in this field of study, the effectiveness of a green binder made of lime, FA, ceramic waste powder, and anhydrous gypsum was examined by some experts in 2020, a blend of 30% lime, 50% FA, 20% ceramic waste powder, and 10% anhydrous gypsum produced a strength of more than 25 MPa after 28 days of curing [9]. Another PG-based binder composite made of PG, lime, FA, and basic oxygen furnace slag was examined by the expert Mashifana in 2019, in which at an elevated temperature of 80 °C for 4 days, a mixture of 20% raw PG, 70% lime-FA in a 1:2 ratio, and 10% BOF acquired a strength of 7.4 MPa [9]. While the discovered use of Pozzolanic materials and gypsum for historical mortars in the Roman Odeion of the archaeological site of Dion, the ingredients of the original lime were based on lime, clay, pozzolan, gypsum, brick dust, and different types of aggregates [14]. As for Md. Moniual Islam & Md. Saiful Islam in 2010, established a comparison between fly ash mortar and Portland cement (OPC) mortar, aiming to replace the use of Portland cement in cultural heritage conservation. The results revealed that after 90 days of curing, fly ash mortars with a 40% cement replacement exhibit a compressive strength that is approximately 14% higher than OPC mortar, and the tensile strength corresponded to an 8% rise [15]. Vaishali Sahu and V. Gayathri in 2014, they have concluded that lime sludge and fly ash are compatible with one another and can replace cement due to the huge amounts of silica and alumina present in both materials and included that due to the increased pozzolanic reaction, the inclusion of gypsum improved the strength of the mortar [16]. Furthermore, to obtain the ideal percentage of lime and fly ash as a complete replacement for cement in mortar, D.L. Naktode, Dr. S.R. Chaudhari, and Dr. U.P. Waghe selected several mortar combinations in 2016, in which the results concluded that the ratio of 1:1:3 (Fly Ash: Lime: Sand) was ideal for the mortar mix and would provide the mix with the necessary compressive strength [16]. While Ash Ahmed, Laila Mahmood, and other scientists also claim that non-hydraulic lime (putty) mortar with as low as 2.5% Pulverized Fly ash (PFA) addition (by weight) substantially accelerates the setting time with strengths comparable to other mortar mixes they have evaluated in 2020 [17]. All have positively proven the use of fly ash with lime to produce a repair mortar, both in literature and history, showing satisfying conclusions and good mechanical properties. Furthermore, although lime has several extremely valuable features, it could be concluded that it's better not to use it on its own but must be combined as a binding material with another binder or additive to be a viable alternative to current cement mortar mixes when addressing cultural heritage buildings and artifacts. Over the past few decades, it has become increasingly clear that cement mortar shouldn't be used to restore traditional buildings, as due to the materials' intrinsic incompatibility, particularly in terms of flexibility and vapor permeability, traditional buildings with cement mortar applications have started to exhibit indicators of accelerated masonry degradation, regardless of their higher mechanical properties in stabilizing masonry structures than traditional lime mortar [3]. Consequently, the objective of this study is to compare three different mixtures of lime mortar in which the first is enhanced with fly ash and the second is enhanced using nano fly ash with the standard lime mortar, aiming to approach a durable mix of lime mortar applicable for use in the conservation of cultural heritage buildings. This will be achieved by discussing the main processing steps of standard lime mortar (L.M.), lime mortar enhanced by fly ash (F. L.M.), and lime mortar enhanced using a percentage of Nano-Fly-ash (N.L.M.) [18]. Adequate investigations and analysis were conducted on the mortar specimens to measure their physical properties before and after subjecting them to thermal aging and their mechanical properties [10]. Then compare the resulting values to deduce the probability of using advanced green materials (fly ash) and high-tech (nanotechnology) for more sustainable repair mortars, in terms of the conservation of historic buildings.

2. Materials and Methods

The research employs an experimental comparative design, which combines experimental research with quantitative characterization and analysis techniques to achieve methodological triangulation and ensure comprehensive data collection. Three mixtures of different lime mortar were prepared and tested under controlled conditions, then their performance was tested before and after the experiment. All procedures were aligned with ASTM and EN standards to ensure accuracy and reproducibility.

2.1. *Materials*

The primary variables include compressive strength, water absorption, porosity, and microstructural characteristics. Three types of lime mortar mixtures were tested: standard lime mortar (L.M.), lime mortar enhanced with fly ash (F. L.M.), and lime mortar enhanced by nano fly ash (N.L.M.). Hydraulic lime of high calcium content from CMB, limestone powder, gypsum, clay-free fine sand, and tap water, were the key raw materials used to prepare the mixtures with variations in the class F fly ash imported from India and the nano fly ash content [19]. The fine sand was sieved to a maximum particle size of 1.18 mm according to HTC 1: 2020 and acted as an aggregate for the three mixtures. Three specimens per mixture were made in 2.5×2.5×2.5 cm molds, making a total of 9 mortar cubes using ASTM C102/ C1012M-09 standards [20]. Specimens underwent a controlled process of thermal aging and curing before analysis.

2.1.1. Preparation of nano fly ash

The nano-sized fly ash (N.F.A.) was achieved using mechanical ball milling in a Planetary Ball Mill at a rotational speed of 735-870 rev/min, fig. (1-a). 100 g of sieved FA was brought with the appropriate weight percentage of stainless-steel balls of hardness ≥ 6.0 Mohs and sizes ranging from 1 mm to 30 mm with a ball-to-powder ratio of 7:1, fig. (1-b). All were later placed in 304 stainless-steel mill jars, fig. (1-c) [21]. The milling process was made of three cycles, 4 hours each, with a 20-minute cooling interval between each cycle and under a vacuumed atmosphere. The resulting N.F.A. was sieved after the milling process only to separate the powder from the milling balls, and not to control the particle size, then it was transferred into a tight glass-air container. To analyze the average particle size of the N.F.A. they were analyzed using a dynamic light scattering (D.L.S.) technique with the Nicomp Nano Z3000 system, fig. (1-d). The Gaussian distribution results indicated a mean particle diameter of 86.26 nm, fig. (1-e), as detailed in tab. (1).

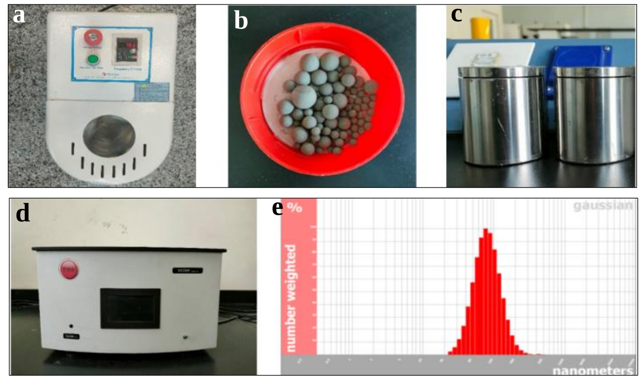

Figure (1) **a.** planetary ball mill operated at a rotational speed of 735-870 rpm, used for the milling process, **b.** stainless-steel balls of hardness ≥6.0 Mohs and various sizes stainless-steel milling balls with hardness > 6.0 Mohs and diameters ranging from 1 to 30 mm, **c.** 304 stainless-steel milling jars containing the fly ash powder and stainless-steel balls during milling, **d.** Nicomp Nano Z3000 particle size analyzer used for particle size analysis, **e.** particle size distribution obtained using the NICOMP system based on Dynamic Light Scattering (DLS).

Table (1) DLS particle size distribution parameters. (Analysis conducted at the Faculty of Nanotechnology, Cairo University).

Properties	Intensity (nm)	Volume (nm)	Number (nm)
Mean diameter	242.26	205.99	86.26
St D.	104.66	88.99	37.26
CV %	43.20%	43.20%	43.20%
PI	0.19	0.19	0.19

2.1.2. Preparation of mixtures

In the L.M. mixture, the raw materials were mixed in a 3:2:1 ratio of lime, sand, and aggregate, respectively. The aggregate was composed of a percentage of natural gypsum ($CaSO_4 \cdot 2H_2O$) and fine-ground limestone powder. This mixture served as the reference mortar mixture, in which no pozzolanic materials were added. For the F.L.M. a partial replacement of the aggregate was made using raw fly ash, in which the aggregate was made of raw fly ash, limestone powder, and gypsum. As for N.L.M., the aggregate mixture was made of nano fly ash, gypsum, and limestone powder. The three mixtures were poured in 2.5×2.5×2.5 cm molds - according to the ASTM C102/C1012M -09-, fig. (2-a) and compacted using a flat trowel, fig. (2-b) [20]. The precise mass measurements of the raw materials are mentioned in tab. (2). The preparation procedures were identical for the three mixtures. First, the raw materials were weighed using a Mettler PE 6000, fig. (2-c), before mixing. The dry components were hand mixed in a circular motion for 2 minutes to ensure high distribution between particles. Then, 288 ml of tap water was gradually added according to "The Heritage Technical

Code" (HTC 1:2020). The total dry weight of binders (lime, fly ash, and nano fly ash) was 350 g for L.M., 408.3 g for F.L.M., and 353 g for N.L.M., which results in a water-to-binder ration (W/B) of 0.823, 0.705, and 0.816, respectively. The mortar mixtures were placed on a vibrating table for 20 seconds to release unnecessary air bubbles. After molding, the mortar cubes were left to air cure for 7 days under an average temperature of approximately 15.4°C and a relative humidity of 61% before tests were conducted. The samples were left exposed to air during the curing process.

Figure (2) **a.** the metal mortar molds (2.5×2.5×2.5 cm) used for molding the LM, FLM, & NLM mortars, **b.** placement and leveling of the fresh mortar paste inside the molds using a flat trowel on a vibrating table, **c.** Mettler PE 6000 balance used for weighing raw materials prior to mixing.

Table (2) mix proportions (by weight) of LM, FLM, and NLM mortars.

Mortar types	Lime	Sand	Gypsum	Limestone powder	Fly ash	Nano Fly ash	Water
				(gm)			(ml)
L.M.	350	233	5.8	110.2	-	-	288
F.L.M.	350	233	2.7	55	58.3	-	288
N.L.M.	350	233	5.65	107.35	-	3.0	288

2.2. Methodology

The particle size of Nano-Fly ash was analyzed using Dynamic Light Scattering (D.L.S.) technology, while the mortars' surface morphology and texture were scanned using a Scanning Electron Microscope (SEM), their water absorption and porosity were studied by calculating the weight of the mortar samples pre and post being immersed in water. Additionally, their mechanical properties were analyzed through compressive strength tests. These studies were performed before and after their exposure to thermal aging, to study their behavior after a specific period. Thermal aging was conducted according to the European standard 14066:2003 EN, in which the samples were exposed to a temperature of 105 °C in the oven for 24 hours to reach the constant weight, then they were immersed in water for 4 hours, followed by placing in the oven for a further 18 hours at temperature 60 ºC [21]. The weights of the L.M., F.L.M., and N.L.M. mortar specimens were monitored after each cycle, tab. (3). The final weight was subtracted from the initial weight to calculate the absorption percentage. S.E.M. analysis was conducted using a Scanning electron microscope Quanta 3D 200i, fig. (3-a & b), to examine and analyze the micro- and nanoparticles imaging characterization of the solid objections [22]. One small fragment (5-10 mm) from each mortar cube -L.M., F.L.M., and N.L.M- to expose a fresh fracture surface for imaging, then were sputtered with a conductive material. The sample was mounted onto aluminum SEM stubs and then were subjected to (L.F.D.) a large field of crystals detection and (B.S.D.) backscattered for the detection of salt crystals, at 500x, 1000x, 2000x, 4000x, 5000x, and 10000x magnifications at 20 kV acceleration potential. The compressive strengths of the mortar cubes were tested using a compression testing machine located at the National Research Center (NRC) in Egypt to analyze the mortars' ability to withstand axial loads and then compare the results to have an overview of the degree of sustainability of each mortar. The test was conducted at a constant loading rate, 0.25 MPa/s according to ASTM C109, gradually increasing pressure was applied until the sample cracked and failed, recording the maximum load at failure [23].

Table (3) physical properties of L.M., F.L.M., and N.L.M. mortars.

Specimens	Dimensions (cm)			Weight (gm)	Weight after immersion (gm)	Water absorption (%)	Porosity (%)	Density (g/cm²)
	L.	*W.*	*H.*					
L.M.1	2.5	2.4	2.5	29.2	37.2	27.40	53.33	1.95
L.M.2	2.5	2.4	2.5	29.3	37.6	28.33	55.33	1.95
L.M.3	2.5	2.5	2.4	29.7	38.1	28.28	56.00	1.98
Average	**2.5**	**2.43**	**2.47**	**29.40**	**37.63**	**28.00**	**54.89**	**1.96**

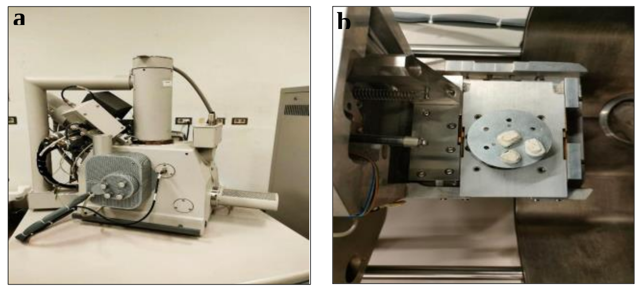

Figure (3) **a.** SEM Quanta 3D 200i in the Grand Egyptian Museum (GEM), where the three mortar mixtures were analyzed, **b.** the three samples were taken from the LM, FLM, & NLM mortars for SEM imaging.

3. Results

3.1. *Dynamic light scattering (D.L.S.) technology*

The Gaussian distribution results indicated a mean particle diameter of 86.26 nm (by number), 205.99 nm (by volume), and 242.26 nm (by intensity). The standard deviation was 37.26 nm (by number) and 88.99 nm (by volume), with a coefficient of variation (CV) of 43.20%. The polydispersity index (PI) was recorded as 0.19, indicating a relatively narrow size distribution, as mentioned in tab. (1).

3.2. *Water absorption*

The results of water absorption tests for the three mortars are summarized in tab (3). L.M. mortar recorded an average water absorption percentage of 28 %, F.L.M. 25.7%, and N.L.M. 23.42%. Correspondingly, the average porosity values were 54.89%, 50.21%, and 45.6% for L.M., F.L.M., and N.L.M. mortars, respectively. An average of 1.95 g/cm^3 volumetric weight (density) remained relatively constant across all 9 tested specimens.

3.3. *Scanning electron microscope (SEM) micrographs*

Figure 4 presents all the L.M., F.L.M., and N.L.M. mortars before and after being subjected to thermal aging, fig. (4). L.M. mortar is more heterogeneous and porous than the other mixtures, with a discernible interparticle distance between aggregates and lime, indicating poor adhesion between components. After subjecting L.M. to thermal aging it showed further deterioration and declination in the interparticle distances, tab. (4). At 4,000x magnification, the F.L.M. mortar's microstructure appears homogenous, dense, and salt-free, as strong adhesion between sand and cementitious paste is observed. N.L.M. mortar's microstructure appears to be the most uniform, fig. (5). It contains huge quartz crystals and rod-like structures, consistent with the presence of gypsum ($CaSO_4.2H_2O$). However, the interparticle distance between the lime and aggregates used in N.L.M. mortar is not distinguishable.

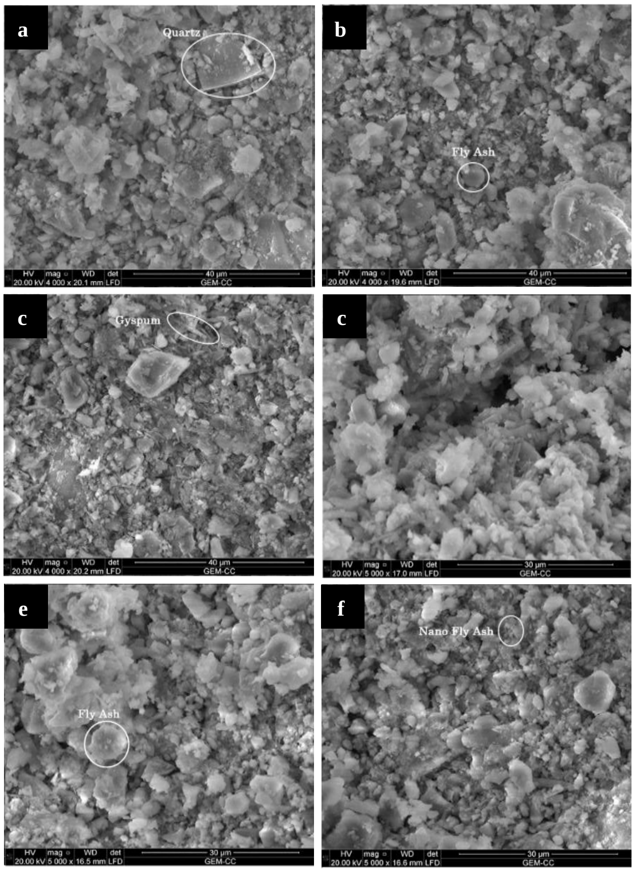

Figure (4) SEM photomicrographs of the investigated three mortar samples ***before*** subjecting to thermal aging **a.** lime mortar, **b.** lime mortar enhanced by fly ash, **c.** lime mortar enhanced by Nano-Fly ash, **d.** lime mortar ***after*** being subjected to thermal aging, **e.** F.L.M. after being subjected to thermal aging, **f.** N.L.M. after being subjected to thermal aging.

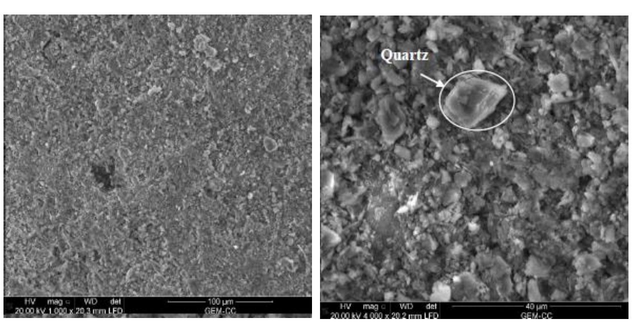

Figure (5) SEM photomicrograph showing nano fly ash–lime mortar (NLM) showing a dense and compact microstructure with uniformly distributed crystalline phases.

Table (4) physical properties of L.M., F.L.M., and N.L.M. mortar specimens.

Specimens	Dimensions (cm)			Weight	Immersed weight	Water abs.	Porosity	Density
	L.	W.	H.	(gm)		(%)		(g/cm²)
L.M.1	2.5	2.4	2.5	29.2	37.2	27.40	53.33	1.95
L.M.2	2.5	2.4	2.5	29.3	37.6	28.33	55.33	1.95
L.M.3	2.5	2.5	2.4	29.7	38.1	28.28	56.00	1.98
Average	**2.5**	**2.43**	**2.47**	**29.40**	**37.63**	**28.00**	**54.89**	**1.96**
F.L.M.1	2.5	2.4	2.5	30.1	37.9	25.91	52.00	2.01
F.L.M.2	2.5	2.5	2.5	29.3	36.9	25.94	48.64	1.88
F.L.M.3	2.5	2.5	2.4	29.7	37.2	25.25	50.00	1.98
Average	**2.5**	**2.47**	**2.47**	**29.70**	**37.33**	**25.70**	**50.21**	**1.95**
N.L.M.1	2.5	2.4	2.5	29.6	36.5	23.31	46.00	1.97
N.L.M.2	2.5	2.5	2.5	29.5	36.5	23.73	44.80	1.89
N.L.M.3	2.5	2.5	2.4	29.7	36.6	23.23	46.00	1.98
Average	**2.5**	**2.47**	**2.47**	**29.60**	**36.53**	**23.42**	**45.60**	**1.95**

3.4. *Compressive strength results*

The compressive strength values for L.M., F.L.M., and N.L.M. are presented in tab. (5). The reference mortar (L.M.) exhibits an average compressive strength of 18.69 kg/cm², while the F.L.M. specimens show a higher average compressive strength of 9.94 kg/cm², representing a 6.7% increase than that of the reference mortar. The N.L.M. recorded the highest compressive strength, averaging 21.64 kg/cm², which is 15.8% higher than the L.M. mortar. The force measurements are of the same trend, with an average force of 1.11 N, 1.21 N, and 1.31 N, for the L.M., F.L.M, and N.L.M. respectively.

Figure (6) compressive test machine present at NRC, Egypt.

Table (5) A comparison between the different compressive strengths of mortars L.M., F.L.M., and N.L.M.

Specimens	Compressive strength *(kg/cm²)*	Force *(Newton)*
L.M.1	18.97	1.116
L.M.2	18.92	1.113
L.M.3	18.18	1.114
Average	**18.69**	**1.11**
F.L.M.1	20.60	1.212
F.L.M.2	19.60	1.201
F.L.M.3	19.62	1.202
Average	**19.94**	**1.21**
N.L.M.1	22.29	1.311
N.L.M.2	21.25	1.302
N.L.M.3	21.40	1.311
Average	**21.64**	**1.31**

4. Discussion

The use of fly ash as an additive in lime mortar has been a topic of interest for many researchers in recent years. Ahmed, A. et al. in 2020, and D.L. Naktode, Dr. S.R. Chaudhari, and Dr. U.P. have previously mentioned that the use of fly ash can enhance the properties of lime mortar. Our research has taken this a step further by exploring the use of nano fly ash in lime mortar [17, 24]. As the average values of the water absorption decreased as fly ash was added to the lime mortar, and further decreased when in the nano size, this could be due to the high pozzolanic reaction of fly ash that decreased the porosity of mortar when in normal size, and further when in nanoscale, indicating a directly proportional relation between the porosity of lime mortar and the size of fly ash particles used in the mixtures. For the mortars' compressive strengths and durability over time, the addition of fly ash has increased the compressive strength of lime mortar by 6.7% and the substitution of 2.5% of the aggregate with nano fly ash has further increased the strength and durability by 15.8%, this is due to the hydration reaction that occurred between the lime and fly ash, which further indicates an increase in the mortar's tensile and shear strength, all of which appears as major lateral stresses. Further studies should investigate the mechanical properties of L.M., F.L.M., and N.L.M. after 28 days and 91 days [25]. These observations align with Osman et al. 's findings (2016), who analyzed lime mortars used in historical buildings and identified that the porosity of the mortar plays a crucial role in their durability, whereas reducing their porosity through binder-aggregate interactions significantly improves the mechanical stability, reinforcing the impact of nano fly ash in decreasing the interparticle distance of the mortar [26]. The SEM analysis revealed that the interparticle distance between the lime and aggregates is distinguishable in the L.M., less distinguishable in the F.L.M., and not clear in the N.L.M. indicating the strong adhesion between the aggregates and the binder past, caused by the aggregates' potential pozzolanic reactivity with the binding material $CaCO_3$. This explains the high mechanical properties observed by N.L.M. and the filling of the micro-nano pores in the lime paste structure, increasing the mortars' durability. Osman et al. (2016) also found that lime C plays a crucial role in improving mortar cohesiveness and stability, while Abdelmegeed and Hassan (2019) found that the mineralogical composition of mortar affects its resistance to environmental degradation, further supporting that nano fly ash can improve its durability [26,27]. Finally, the use of nano fly ash reduces the carbon footprint associated with cement production, making it a more environmentally friendly option [28]. Our research suggests that the use of nano fly ash in lime mortar has the potential to revolutionize the conservation of heritage buildings by providing a more sustainable alternative to the conventional use of cement-based mortars.

5. Conclusion

The study demonstrated that incorporating fly ash and nano fly ash into lime mortar significantly enhances its mechanical and durability properties, making it a suitable viable solution for cultural heritage buildings conservation. An increase of 15.8% in the compressive strength and a 9.288% reduction in porosity occurred when the nano fly ash was added to standard lime mortar, attributed to improved pozzolanic reactions and denser microstructure. SEM analysis confirmed the stronger adhesion between aggregates and the binder in the lime mortar enhanced by nano fly ash, contributing to an increase in the mortar's durability. Water absorption analysis revealed decreased permeability, supporting its appropriateness for cultural heritage applications. These findings indicate that nano fly ash can alleviate the disadvantages of regular lime mortar, offering a long-lasting, high-performance repair solution. Future studies should focus on long-term natural aging studies to establish its efficacy in real-world environments.

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