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INVESTIGATING THE USE OF PFA POZZOLAN IN NON-HYDRAULIC LIME MORTAR FOR IMPROVED COMPRESSIVE AND FLEXURAL STRENGTH IN SUSTAINABLE MASONRY CONSTRUCTION

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Abstract

Mortar is a vital component in masonry construction, providing the connection between masonry units and enabling them to work as a single material. The choice of mortar significantly affects the flexural and compressive strength of the masonry. Cement-based mortars are widely used in current construction projects, but their production process results in considerable CO2 emissions, leading to severe environmental implications. Lime mortars, with their lower embodied CO2 content, serve as a more sustainable alternative, offering advantages such as increased flexibility, damp resistance, and the capacity to handle more substantial wall movement. The primary disadvantages of lime mortars are their longer setting time and reduced strength compared to cement-based mortars. This paper explores the possibility of incorporating PFA (fly ash) pozzolans into non-hydraulic lime mortar to address these challenges. The findings demonstrate that a minimal 2.5% PFA addition can double the mortar's strength within 28 days, with a maximum strength of over 4 MPa achieved with 5% PFA. As a result, non-hydraulic lime mortars with PFA provide a more sustainable alternative to cement-based mortars, without sacrificing setting time, strength, or overall functionality.

INTRODUCTION AND BACKGROUND

Investigating the Use of PFA Pozzolan in Non-Hydraulic Lime Mortar for Improved Compressive and Flexural Strength in Sustainable Masonry Construction

Introduction

The construction industry is responsible for a significant proportion of the global greenhouse gas emissions and energy consumption, with cement production alone contributing to about 8% of the worldwide CO2 emissions (Chen et al., 2020). As a result, the development of sustainable and eco-friendly construction materials has become a crucial aspect in the quest to reduce the environmental impact of the industry. One such approach is the

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utilization of non-hydraulic lime mortar in masonry construction, which offers various advantages such as lower energy consumption, improved breathability, and better compatibility with traditional masonry materials (Quagliarini et al., 2020). However, the lower mechanical strength of non-hydraulic lime mortar compared to cement-based mortars has limited its widespread application in modern construction. Consequently, there has been a growing interest in improving the properties of lime mortar through the incorporation of various additives, particularly pozzolanic materials (Vargas et al., 2016).

Pozzolanic materials are natural or synthetic siliceous or aluminosilicate materials that, in the presence of moisture, react with calcium hydroxide to form stable cementitious compounds, such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) (Pacheco-Torgal et al., 2012). One such pozzolanic material is pulverized fuel ash (PFA) or fly ash, a by-product of coal combustion in power plants. The use of PFA as a partial replacement for cement in concrete has been extensively studied and has been shown to improve the workability, durability, and long-term strength of the material while reducing its environmental impact (Malhotra and Mehta, 2015). However, the application of PFA in non-hydraulic lime mortar has not been investigated as extensively.

Several studies have explored the use of various pozzolanic materials, including volcanic ash, brick dust, and metakaolin, in non-hydraulic lime mortar to improve its mechanical properties (Veiga et al., 2008; Silva et al., 2012). These materials have been found to enhance the compressive and flexural strength of the mortar by promoting the formation of cementitious compounds through pozzolanic reactions, leading to a denser and more robust microstructure (Hughes and Cuthbert, 2012). However, the effectiveness of these materials is highly dependent on their chemical composition, fineness, and reactivity, which can vary considerably depending on the source and processing methods (Vegas et al., 2008). Therefore, it is essential to investigate the potential of PFA as a pozzolanic additive in non-hydraulic lime mortar, considering its abundance, consistent quality, and proven performance in cement-based materials.

The primary objective of this study is to investigate the influence of PFA on the compressive and flexural strength of non-hydraulic lime mortar for sustainable masonry construction. Specifically, the study aims to determine the optimum PFA content to maximize the mechanical performance of the mortar without compromising its workability and other essential properties. To achieve this, a comprehensive experimental program will be conducted, including the characterization of the raw materials, the preparation and testing of mortar specimens with varying PFA content, and the analysis of the microstructure and hydration products of the hardened mortar. The findings of this study are expected to contribute to the development of more robust and eco-friendly masonry materials, promoting the wider adoption of non-hydraulic lime mortar in modern construction.

The main advantage with cement based mortars is that maximum strength is achieved within 28 days. There are four different designations of cement mortars as shown in Table 1.

Table 1. Different designations of cement based mortars and respective mean and minimum compressive strength at 28 days, as per BS 5628 [3].

Mortar Designation	**Cement:Lime Ratio**	**Sand Ratio**	**Known as**	**Mortar Class**	**Compressive strength (MPa)**
(i)	1:0 to 0.25$^{1}/_{4}$	3	1:3	M12	8 - 12
(ii)	1:0.5	4	1:$^{1}/_{2}$:4	M6	5 - 8
(iii)	1:1	6	1:1:6	M4	3.6
(iv)	1:2	8/9	1:2:9	M2	1.5

With decreasing strength, there is increased flexibility, i.e. designation (iv) has the greatest flexibility. Typically, designations (iii) and (iv) are used with bricks and low density blockwork in construction. However, cement is deemed to have a considerably high carbon footprint, contributing immensely to global anthropogenic CO_2 [4]. Climate change is suggested to be a phenomenon that can bring about a rise in global temperatures due to the presence of excessive carbon dioxide (CO_2) in the atmosphere, and is cumulative and irreversible over timescales of centuries [5, 6]. The burning of fossil fuels, in this case for the production of cement contributes to the greenhouse gas effect, which is a major cause of climate change [7]. As a result, the cement industry accounts for about 7 - 10% of the total global CO_2 emissions, a considerably high level when compared to 3% total global CO_2 emissions attributed to the aviation industry [8-10]. However, energy efficiency can be achieved by reducing on the amount of clinker and utilising supplementary cementitious materials (SCMs), which require less process heating and emit fewer levels of CO_2 [8]. Established SCMs include PFA (also known as fly ash), ground granulated blast furnace slag (GGBS), metakaolin (MK) and silica fume (SF). There are also novel ones such as rice husk ash (RHA) from agricultural waste. PFA, GGBS, MK, SF & RHA are known as pozzolans as they require a reaction with calcium hydroxide to impart cementitious properties. Whereas, GGBS is a direct cement replacement as chemically it is very similar to cement [11]. Table 2 shows the embodied CO_2 values for cement (CEM I), PFA and GGBS. Clearly, the embodied CO_2 for both PFA and GGBS is substantially less than CEM I.

Table 2. Embodied CO2 for main constituents of reinforced concrete [11]

Material	Embodied CO2 (kg/tonne)
Portland Cement, CEM I	930
Ground Granulated Blastfurnace Slag (GGBS)	52
Fly Ash (PFA)	4

When cement reacts with water, calcium silicate hydrates (CSH) form which is the major contributor to strength in mortars and concrete [11]. Most pozzolans are silica rich (SiO_2) which reacts with calcium hydroxide to form the strength forming C-S-H. Therefore, it is possible to increase the setting time and strength of lime mortars by adding a pozzolan or GGBS. This paper reports the findings of a study undertaken to verify the mechanical properties of non-hydraulic lime mortar containing PFA as this can potentially reduce the curing time and facilitate in alleviating a disadvantage associated with lime mortars. When lime is manufactured, it produces less CO_2 than the manufacture of cement because it is being burnt at low temperatures which saves fuel consumption and emissions of pollution and greenhouse gasses. The embodied CO_2 is therefore approximately 30% lower than cement manufacture [12] ensuring it is more sustainable and eco-friendlier as opposed to cement.

MATERIALS & METHODS

Experimental work was undertaken to establish the mechanical properties of non-hydraulic lime mortar containing a specified amount of PFA content. A series of tests were carried out to evaluate the cube compressive and flexural strengths. Sample preparation and testing were carried out in accordance with appropriate Standards as documented in this paper.

Test Materials

High calcium, fat lime putty (class A) matured for at least 120 days in accordance to BS EN 459 was used [2], x-ray diffraction (XRD) analysis was conducted to elucidate the chemical constituents. Soft building sand was used. The particle size distribution of the sand is given in table 3 and schematically shown plotted in Figure 1. Tests were carried out in accordance to BS 1200 [13] and the results indicate that the sand used complies with the requirements. **Table 3.** Sand Grading Test Results

Sieve Aperture Size	**Mass of sand passing sieve (g)**	**Mass of sand retained by sieve (g)**	**Cumulative sand passing sieve (%)**
6.30mm	1160.5	0.4	99.97
5.00mm	1160.5	0.0	99.97
2.36mm	1158.7	1.8	99.81
1.18mm	1151.3	7.4	99.17
600µm	980.2	171.1	84.43
300µm	199.4	780.8	17.18
150µm	34.2	165.2	2.95
75µm	8.2	26.0	0.71

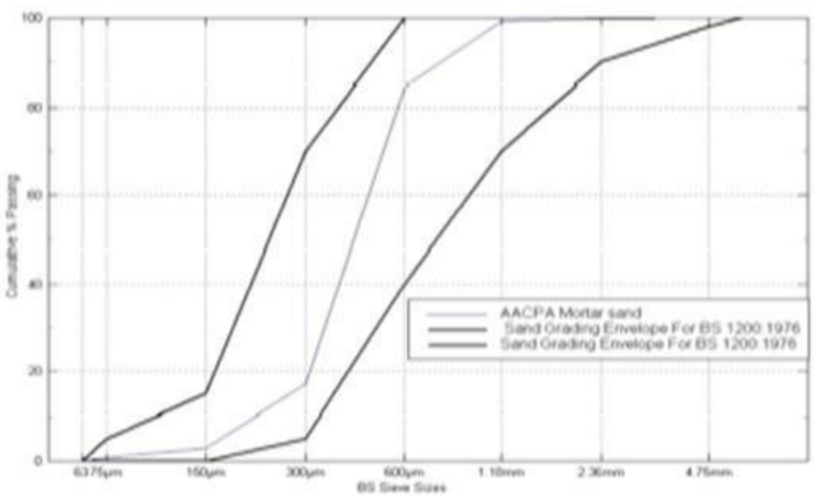

Fig. 1. Particle Size Distribution of sand (cumulative passing v sieve size).

Specimen Preparation

Mortar samples of the non-hydraulic mortar were produced to establish fresh and mechanical properties. Water was added so that the workability was consistent and corresponded to a 10mm penetration of the dropping ball test as suggested in BS 5628 [3], EN 1015:Part 3 [14] and BS 4551 [15]. Table 4 shows the mixes prepared which were in accordance with EN 998-2 [16]. The mix ratio was 1:3 of lime putty:sand by weight. The PFA was added as a percentage of the total weight, e.g. for 10% PFA mix, lime putty + sand = 4 + 12 = 16 kg, therefore 10% of 16 = 1.6kg of PFA.

Table 4. Lime Putty Mortar Mixes with PFA

Sample Name	**Lime Putty (kg)**	**Sand (kg)**	**PFA (kg)**	**PFA %**
Control (0% Mix)	4	12	0	0
2.5% Mix	4	12	0.4	2.5
5.0% Mix	4	12	0.8	5
7.5% Mix	4	12	1.2	7.5
10% Mix	4	12	1.6	10

Properties examined

A range of properties were examined during experimental work as shown in Table 5. In all testing, three specimens were broken at each test age. Tests were carried out in accordance with EN 1015:Part 11 [17].

Table 5. Mortar Properties and Testing Regimes.

Mortar Property	Specimen	Test Age (days)
Compressive cube strength	100 x 100 x 100 mm	28, 56, 91 & 180
Flexural strength	40 x 40 x 160 mm	91

Test specimens were demoulded after 24 hours of casting and then stored in a laboratory where a constant temperature of 20 °C was maintained throughout.

RESULTS AND DISCUSSION XRD analysis

Table 6 shows the analysis on lime putty. As can be seen there are two phases present, calcium carbonate (11%) and the predominant constituent, calcium hydroxide (89%). Lime putty is manufactured by slaking quicklime in clean water then leaving it to mature [1], i.e.

CaO reacts with H_2O to form $Ca(OH)_2$ (calcium hydroxide).

Table 6. XRD analysis on lime putty.

Major Phase	Chemical Formula	Approx. %
Calcium Carbonate	$CaCO_3$	11
Calcium Hydroxide	$Ca(OH)_2$	89

Tables 7 & 8 show the compressive and flexural strength results of the mortar mixes with figure 2 illustrating the compressive strength trends up to 180 days.

Table 7. Compressive strength of non-hydraulic lime putty mortar with PFA

Sample Name	PFA %	28 Days Compressive Strength (MPa)	56 Days Compressive Strength (MPa)	91 Days Compressive Strength (MPa)	180 Days Compressive Strength (MPa)
Control (0% Mix)	0	0.50	0.75	0.80	1.1
2.5% Mix	2.5	0.95	1.10	2.50	3.6
5.0% Mix	5	0.95	1.20	3.00	3.9
7.5% Mix	7.5	0.97	1.30	3.10	4.1
10% Mix	10	1.2	1.50	3.20	4.3

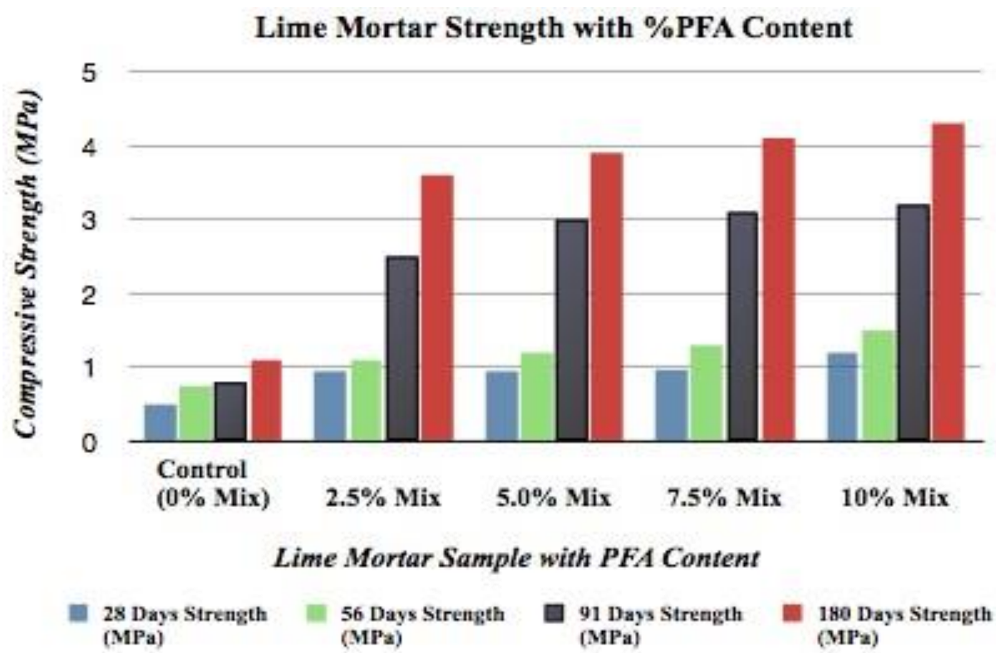

Fig. 2. Compressive strength of lime putty mortars with PFA at 28, 56, 91 and 180 days.

Table 8. Flexural strength of non-hydraulic lime putty mortar with PFA.

Sample Name	**PFA %**	**91 Days Strength (MPa)**
Control (0% Mix)	0	0.2
2.5% Mix	2.5	0.32
5.0% Mix	5	0.35
7.5% Mix	7.5	0.37
10% Mix	10	0.40

The control mix as expected has a slow rate of strength gain. Non hydraulic lime mortars are generally very weak mortars which require several weeks to gain working strengths and months or even years to gain maximum strength [12]; this is due to the fact that lime putty mortars, unlike cement and hydraulic limes which set hydraulically with the addition of water, gain strength (or cure) by absorbing carbon dioxide from the air. This process, known as carbonation, is a very lengthy process with most lime putty mortars reaching a strength of about 1.5 MPa after 365 days. This is a clear disadvantage as it can slow progress on a construction site and furthermore, the lime putty mixes can be more prone to failure caused by frost damage during the winter months, e.g. the water in the lime putty mortar mixes can freeze and exert an internal tensile force leading to delamination of the mortar bed, cracking and eventual failure. Therefore, it is highly desirable to accelerate the curing time. Just a small addition of PFA significant increases both the curing time and strength; 2.5% PFA addition nearly doubles the compressive strength at 28 days to about 1 MPa and an eventual strength of 3.6 MPa at 180 days. A 5% PFA addition has similar strengths at 28 and 56 days, however, the 180 day strength increases to nearly 4 MPa. An increase from 5 to 7.5% PFA has negligible effect on the strength, however, the 10% PFA mix had a 28 day strength of 1.2 MPa, which eventually increased to 4.3 MPa at 180 days. The increase in strength can be attributed to the pozzolanic reaction between $CaOH_2$ and SiO_2, is shown below [11]:

Calcium Hydroxide + Silica ---> Calcium Silicate Hydrate (CSH)

$3Ca(OH)_2 + 2[SiO_2]$ ---> $[3(CaO).2(SiO_2).3(H_2O)]$

The calcium silicate hydrate (CSH) phase is the major contributor to strength in concrete and cementitious materials [11]. Therefore, even with a minimal addition of the PFA pozzolan of 2.5% is sufficient to initiate the pozzolanic reaction and thus resulting in increased strength. It should also be borne in mind in masonry, the strength of the mortar should not be greater than the brick or block. The properties of all the lime putty mortars with PFA (tables 7 & 8) are in accordance as specified in BS 5628 [3], in fact the range of compressive strengths fall within both designations (iii) and (iv). Therefore, lime putty (non hydraulic lime mortars) with 2.5 or 5% PFA addition can be used in construction projects as a viable alternative to cement based mortars. The major benefit would be sustainability; as mentioned in the Introduction section, the cement industry emits three times more CO_2 than the aviation sector, therefore, there are serious implications regarding the use of cement based materials. As lime based materials have a 30% lower embodied CO_2 than cement [1,12], they offer a greener, more environmentally friendly option. Furthermore, lime based mortars have the added benefit of being able to accommodate greater wall movement and improved damp resistance in comparison to cement based mortars.

CONCLUSION

- Historically lime based materials have been used in construction for centuries. However, over the past 50 years cement based mortars are increasingly the preferred choice in the construction due to their quicker setting times.
- As the cement industry emits up to 10% of the global CO_2 emissions which is three times greater than the aviation sector, there are serious environmental implications regarding the use of cement based products.
- Lime based mortars have 30% lower embodied CO_2 in comparison to cement mortars, they also offer greater flexibility and improved damp resistance.
- The main drawback with lime based mortars is the slow setting time, however, this can be over come by adding PFA pozzolan.
- Non-hydraulic lime (putty) mortar with as little as 2.5% PFA addition (by weight) significantly accelerates the setting time with strengths comparable to both designations (iii) and (iv) mortars
- The strengths achieved for all lime putty mortars with PFA are in accordance with the minimum strength specified for designations (iii) & (iv) mortars as required in Table 1 of BS 5628:Part 1
- Non-hydraulic lime mortars with PFA offer a more sustainable alternative to cement based mortars with lower embodied CO_2.

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