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COMPRESSIVE AND FLEXURAL STRENGTH OF NON-HYDRAULIC LIME MORTAR WITH PFA POZZOLAN

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Abstract: Mortar for masonry is important because it provides the linkage between masonry units so enabling the composite to behave as a single material. The type of mortar used determines the flexural and compressive strength of the masonry. Nowadays most mortars used in construction are cement based. However, due to the heavily energy-intensive processes that are involved in its production the cement industry is responsible for up to 10% of global CO_2 emissions; therefore, there are serious environmental implications with the usage and application of cement mortars. A sustainable alternative are lime mortars which have 30% less embodied CO_2. Lime mortars confer benefits in comparison to cement based mortars such as accommodating a greater degree of wall movement and improved damp resistance. The main disadvantage with lime mortars is the longer setting time which can take up to 91 days in addition to the low strength. A way to overcome this is to add cement replacements (pozzolans). This paper investigates the properties of non-hydraulic (lime putty) lime mortar containing PFA (fly ash). Findings show a minimal amount of PFA addition of 2.5% doubles the mortar strength to 1 MPa within 28 days with an eventual strength of over 4 MPa achieved with 5% PFA. Therefore, non-hydraulic lime mortars with PFA offer a more sustainable alternative to cement based mortars without compromising setting time or strength whilst offering improved flexibility and breathability.

Keywords: Mortar, Non-hydraulic lime mortar, lime putty, PFA, pozzolan.

INTRODUCTION AND BACKGROUND

Mortar is a very important material in civil engineering as it bonds together bricks and blocks in dwellings. Traditionally there are two different types of mortars: lime and cement. Lime mortar is the oldest type and has been used for centuries. This was the preferred type of mortar until cement mortars were developed. There are essentially two different types of lime, non-hydraulic and hydraulic [1]. Lime is made by first burning chalk or limestone to form quick lime (calcium oxide or CaO) and then slaking the quicklime with water forming calcium hydroxide ($Ca(OH_2)$). If no clay is present in the original limestone or chalk, the resulting lime is said to be 'non-hydraulic'. Lime putty usually contains calcium hydroxide (approx. 90%) and calcium oxide (approx. 10%); it stiffens and eventually hardens by reacting with carbon dioxide which is present in air to form calcium carbonate once again; a process known as carbonation. Non-hydraulic lime is usually used in the saturated form known as lime putty. Lime putty is

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produced by slaking quicklime with an excess of water for a period of several weeks until a creamy texture is produced. Lime putty, often mixed with sand is used directly as a pure lime mortar, particularly in restoration and conservation work. It sets, not by reaction with sand and water, but only by carbonation and is therefore described as non- hydraulic. The carbonation process is very slow and therefore the mortar remains weak and vulnerable to damage for a significantly long period of time. A hydraulic lime or natural hydraulic lime (NHL) sets by hydration so it can set underwater [1,2]. For the NHL mortars, the lime is obtained from limestone which naturally contains an adequate percentage of silicates and/or aluminates in addition to calcium hydroxide. The process involves the burning of argillaceous or siliceous limestones followed by reduction to powder by slaking, with or without grinding. NHL comes in three European grades, NHL 2, NHL 3.5 and NHL 5; the numbers refer to the minimum compressive strength at 28 days as specified in EN 459 [2]. The NHL grades 2, 3.5 and 5 are also referred to as being feebly, moderately and eminently hydraulic, respectively. Both hydraulic and non-hydraulic lime mortars are breathable; hydraulic mortars have a quicker setting speed, however, non-hydraulic mortars can accommodate greater wall movement. The disadvantage with lime mortars is that they generally have longer setting times, this can delay construction time which can confer negative economic implications. 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 CO_2 for main constituents of reinforced concrete [11]

Material	Embodied CO_2 (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

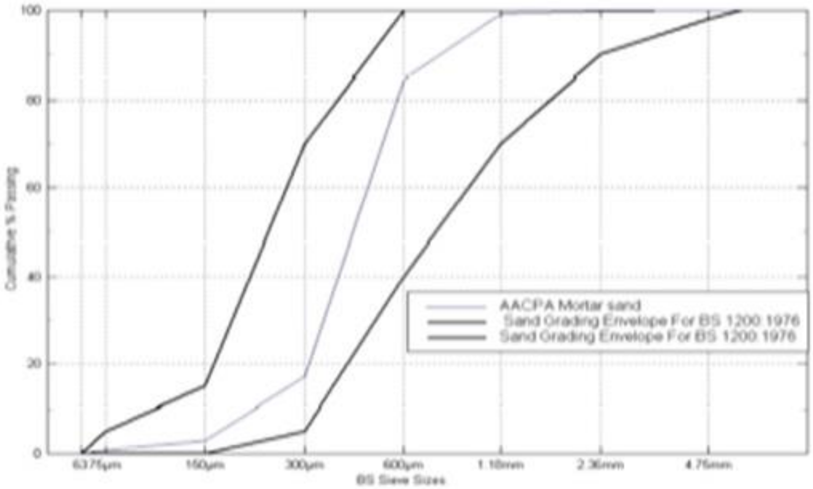

Fig. 1. Particle Size Distribution of sand (cumulative passing v sieve size).

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

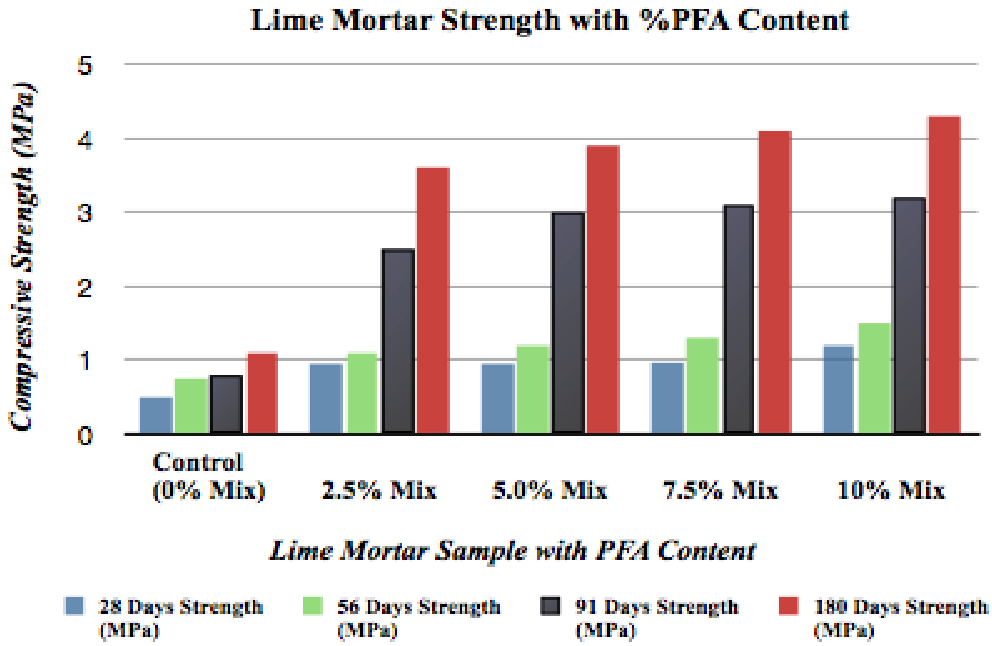

Fig. 2. Compressive strength of lime putty mortars with PFA at 28, 56, 91 and 180 days.

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)

$$3Ca(OH)_2 + 2[SiO_2] \longrightarrow [3(CaO).2(SiO_2).3(H_2O)]$$

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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