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Research Article

Compressive And Flexural Strength of Non- Hydraulic Lime Mortar with Metakaolin 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 heavy energy-intensive processes that are involved in its production the cement industry is responsible for up to 10% of global CO2 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 CO2. 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 e.g pozzolans. This paper investigates the properties of non-hydraulic (lime putty) lime mortar containing metakaolin (MK). Findings show a minimal amount of MK addition of 2% increases the mortar strength to 2 MPa within 28 days with an eventual strength of over 17 MPa achieved with 10% MK. Strengths satisfying minimum requirements for all four mortar designations were achieved with between 2-8% MK addition, mostly within 28 days ageing. Therefore, non-hydraulic lime mortars with MK 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; Metakaolin; Calcined Clay; 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 based. 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 three different types of lime, hydrated, non-hydraulic and hydraulic [1]. Figure 1 shows the lime cycle; 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 produced by slaking quicklime with an excess of water for a period of several weeks until a creamy texture is produced. Alternatively, it can be made by stirring hydrated lime into water, followed by conditioning for at least 24 hours. 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.

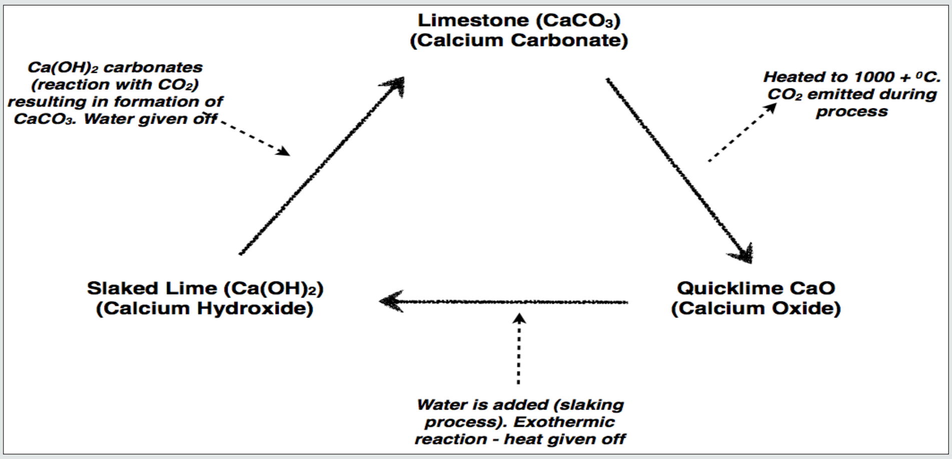

Figure 1: The Lime Cycle process.

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

Mortar Designation	Cement: Lime Ratio	Sand Ratio	Known as	Mortar Class	Typical Compressive Strength Range (MPa)
(i)	1:0 to 0.25$^1/_4$	3	1:3	M12	9 - 12
(ii)	1:0.5	4	1:1/2:4	M6	5 - 8
(iii)	1:1	6	1:1:6	M4	3 - 5
(iv)	1:2	8/9	1:2:9	M2	1.5 - 2.5

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 [3]. 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 up to 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 / less established 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, given most PCRs are either from industrial waste or not an energy intensive process. When cement reacts with water, Calcium Silicate Hydrates (CSH) form which is the major contributor to strength in mortars and concrete. 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 MK as this can potentially reduce the curing time and facilitate in alleviating a disadvantage associated with lime mortars. Metakaolin (MK) is a dehydroxylated form of the clay mineral kaolinite. It is obtained from manufacture of porcelain. China clay (mineral kaolin) is heated up to a temperature between 600-800°C to manufacture MK. This pozzolan was used for the first time in1960s in Brazil for construction of large dams. Originally, its use in concrete started in order to repair any damage caused by Alkali-Silica Reaction (ASR) [12]. Subsequent research has shown MK to be a very effective pozzolan in concrete; used as a cement replacement between 5-20% results in an increase in strength and improvement in durability properties. Indeed, unlike GGBS and PFA, MK concrete has impressive early age strengths. Furthermore, 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 [13] ensuring it is more sustainable and eco-friendlier as opposed to cement. Thus, a lime based mortar incorporating MK can potentially overcome the slow rate of strength development and become a more robust and sustainable alternative to cement based mortars.

Table 2: Embodied CO2 for main constituents of reinforced concrete.

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

Materials & Methods

Experimental work was undertaken to establish the mechanical properties of non-hydraulic lime mortar containing a specified amount of MK 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

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	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	0.71

High calcium, fat lime putty (class A) matured for at least 120 days in accordance with 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 2. Tests were carried out in accordance with BS 1200 [14] and the results indicate that the sand used complies with the requirements of the BS 1200 [14].

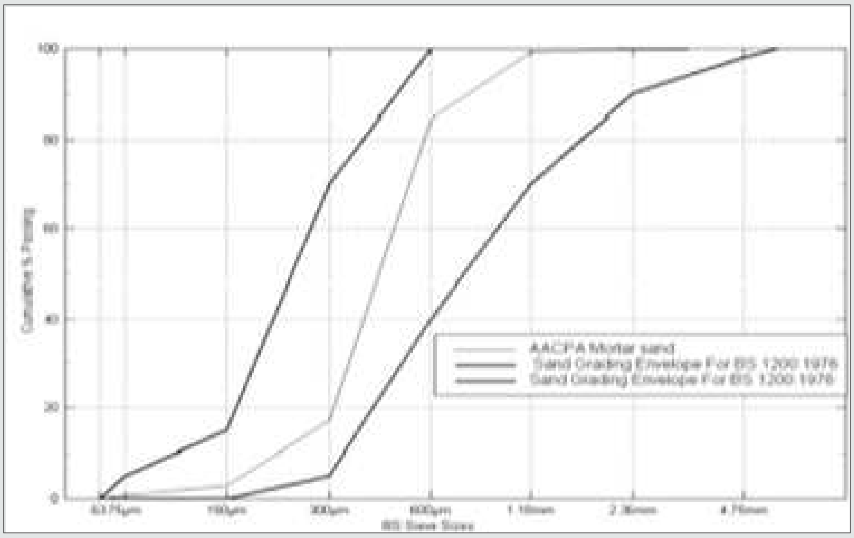

Figure 2: Particle Size Distribution of sand (cumulative passing v sieve size).

Specimen Preparation

Mortar samples of the non-hydraulic lime mortar were produced to establish fresh and mechanical properties. Water was added so that the workability was consistent and corresponded to an approximate 10mm penetration of the dropping ball test as suggested in BS 5628 [3]. EN 1015: Part 3 [15] and BS 4551 [16]. Table 4 shows the mixes prepared which were in accordance with EN 998-2 [17]. The mix ratio was the standard 1:3 of lime putty: sand by weight. The MK was added as a percentage of the total weight e.g, with a 1:3 ratio, if 'X' kg of lime putty is used, the amount of sand = 3X kg. Hence, total amount of lime and sand = 4X (X+3X). For 10% metakaolin addition, the amount would be 4X ÷ 10 (kg); this amount woud be added to the lime + sand mix.

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 Table 4. Tests were carried out in accordance with EN 1015: Part 11 [18]. 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.

Table 4: Lime Putty Mortar Mixes with MK.

Sample Name	MK %
Control (0% Mix)	0
MK2	2
MK3	3
MK3.5	3,5
MK4	4
MK6	6
MK8	8
MK10	10
MK12	12
MK14	14
MK16	16
MK20	20

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
Flexural strength	40 x 40 x 160 mm	91

Results & 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

Workability

Table 7 shows the workability details for the mixes. The workability of a mortar, also referred to as its consistency, can be defined as how easy it is to handle, its provision of a sufficient bond and a smooth surface finish. The water content of a mortar determines its consistency, typically more water added leads to a more workable mix. The ease of use whilst wet, directly effects the speed and accuracy with which the mortar can be used. The water content also has an effect of the properties of the hardened mortar, such as strength and durability. A higher water content will also have an adverse effect on durability as a higher water content leads to larger capillary pores in the hardened mortar, which when exposed to elements such as frost or chemicals will allow ingress and hence reduce the durability of the structure [13]. Although the higher MK mixes have a greater water demand, findings have shown that MK addition to concrete significantly improves the durability properties, e.g., many concrete dam structures contain MK [12]. For each mix, water was added to obtain a standard 10mm drop ball consistency. The results show the required amount of water per 1kg of dry material. There is a discernible trend showing a direct correlation between water demand and increase in MK content. This is in accordance with workability behaviour in concrete [12]. Whereas PFA and GGBS addition increases the workability of mortar and concrete [7], MK has the opposite effect which needs to be taken into account for design mixes.

Table 7: Workability details for mixes.

Mix	Water Volume Required per 1kg of Dry Material (ml)
MK 0%	15
MK 2%	23
MK 3%	29
MK 3.5%	30
MK 4%	35
MK 6%	57
MK 8%	75
MK 10%	96
MK 12%	125
MK 14%	131
MK 16%	140
MK 20%	217

Table 8 show the compressive strength results of the mortar mixes with Figure 3 illustrating the compressive strength trends up to 91 days. Table 9 and Figure 4 show a comparison and classification of the MK mortars with cement (CEM) based mortars as per BS 5628 [3]. Table 10 shows the flexural strength of the MK mortar mixes after 91 days curing. 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 [13]. 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 MK significantly reduces the curing time and increases strength; 2% MK addition increases the compressive strength at 28 days to 2 MPa, this is highly desirable especially for frost resistance. Table 8 and Figure 3 show up to 10% MK addition results in a substantial increase in strength, with 10% MK reaching over 17 MPa after 91 days. Figure 4 and Table 9 show how each MK mix can be classified in accordance (or a sustainable alternative) to CEM designation mortars, i.e., MKs 2 - 8% range all fall within the Designations (i) - (iv) as specified in BS 5628. 10% MK has potential application as a screed in construction, similarly also for MKs 12 & 14, although beyond 10% MK addition results in a subsequent decrease in strength. The flexural strengths (Table 10) compare favourably to cement based mortars [20]. The increase in strength for the lime putty mortar can be attributed to the pozzolanic reaction between $CaOH_2$ and MK, is shown below [11,12].

Table 8: Compressive strength of non-hydraulic lime putty mortar with MK.

Sample Name	MK %	28 Days Compressive Strength (MPa)	56 Days Compressive Strength (MPa)	91 Days Compressive Strength (MPa)
Control (0% Mix)	0	0,5	0,8	1
MK2	2	2	2	2,3
MK3	3	2,1	2,3	2,8
MK3.5	3,5	3,2	4,2	4,9
MK4	4	5,6	6,1	7,2
MK6	6	6,8	7,9	8,5
MK8	8	8,1	8,9	9,3
MK10	10	11,7	13,8	17,6
MK12	12	9,7	10,5	15,4
MK14	14	8	10,1	13,4
MK16	16	5,7	9,5	11,9
MK20	20	3,6	7,5	8,2

Table 9: Classification of lime putty mortar with MK in comparison to cement based mortars as per BS 5628 (at 91 days).

CEM Mortar Designation	CEM Mortar Compressive Strength (N/mm^2)	MK Mixes which comply (MK %)
(i)	8 - 12	6 & 8
(ii)	5 - 8	4
(iii)	3.5 - 5	3,5
(iv)	1.5 - 2.5	2 & 3
Potential Screed Applications	12 +	10, 12, & 14

Table 10: Flexural strength of non-hydraulic lime putty mortar with MK at 91 days.

Sample Name	MK %	91 Days Strength (MPa)
Control (0% Mix)	0	0.2
MK2	2	1.8
MK3	3	1.9
MK4	4	2.1
MK6	6	2.3
MK8	8	2.4
MK10	10	3.2
MK12	12	3.2
MK14	14	3.1
MK16	16	3.2
MK20	20	3

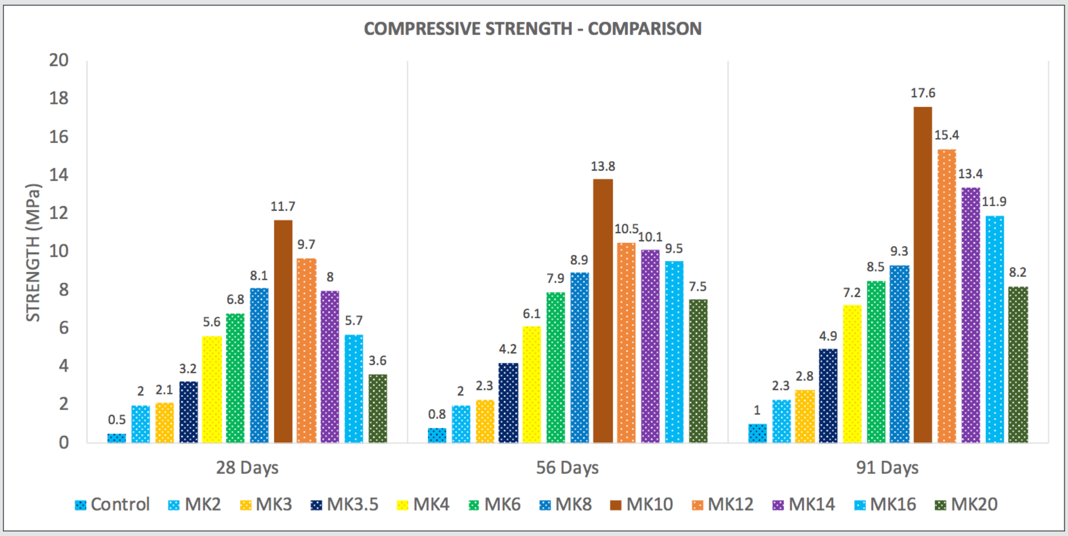

Figure 3: Compressive strength of lime putty mortar with MK at 28, 56 and 91 days.

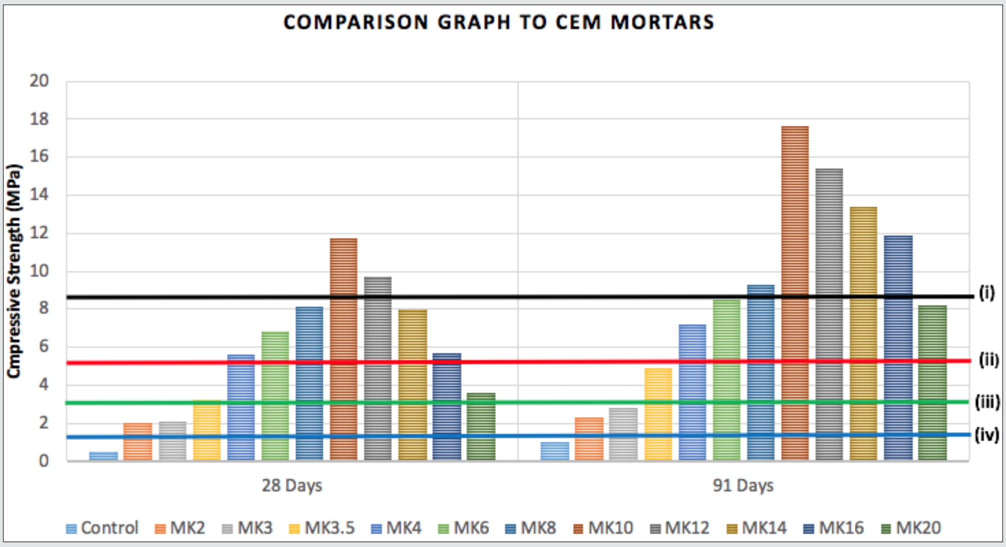

Figure 4: Comparison and classification of MK mortars with CEM mortars as specified in BS 5628.

Calcium Hydroxide + Metakaolin ---> Calcium Silicate Hydrate (CSH). 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 MK pozzolan of 2% 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 up to 8% MK (Figure 4 and Table 9) are in accordance as specified in BS 5628 [3], in fact the range of compressive strengths fall within all designations (i), (ii), (iii) and (iv). Therefore, lime putty (non-hydraulic lime mortars) with MK 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 [1,11]. 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

a) 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.

b) 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.

c) Lime based mortars have 30% lower embodied CO_2 in comparison to cement mortars, they also offer greater flexibility and improved damp resistance.

d) The main drawback with lime based mortars is the slow setting time, however, this can be overcome by adding MK pozzolan.

e) Non-hydraulic lime (putty) mortar with as little as upto 2% MK addition (by weight) significantly accelerates the setting time with strengths comparable to designations (iv) mortar. A 3.5% MK addition increases the strength to designation (iii) level.

f) The strengths achieved for all lime putty mortars with up to 8% MK addition are in accordance with the minimum strength specified for all designation mortars as specified in BS 5628: Part 1.

g) Non-hydraulic lime mortars with MK offer a more sustainable alternative to cement based mortars with lower embodied CO_2.

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