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# Compressive and Flexural Strength of Non-Hydraulic Lime Mortar with Slag (GGBS)

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**ABSTRACT**

Mortar for masonry is important because it provides the bond 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. Currently, 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 $CO_2$ 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 e.g pozzolans or slag. This paper investigates the properties of non-hydraulic (lime putty) lime mortar containing up to 20% ground granulated blastfurnace slag (GGBS). Findings show a minimal amount of GGBS addition of 2% doubles the mortar strength to 2 MPa within 91 days with an eventual strength of over 15 MPa achieved with 20% GGBS. Strengths satisfying minimum requirements for all four mortar designations were achieved with between 2 - 16% GGBS addition, all within 56 days ageing; with designations (i), (ii), (iii) & (iv) strengths being satisfied within 28 days. Therefore, non-hydraulic lime mortars with GGBS offer a more sustainable alternative to cement based mortars without compromising setting time or strength whilst offering improved flexibility and breathability.

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## 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.

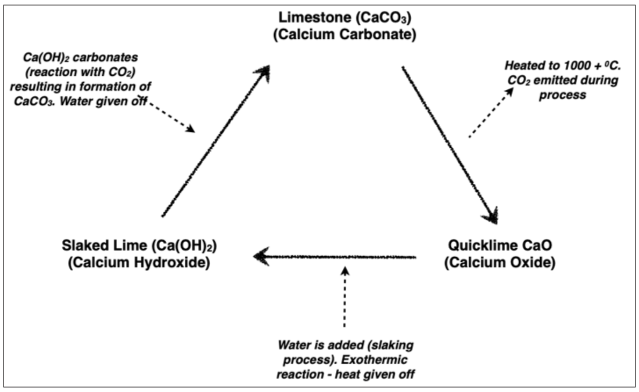


**Figure 1:** The Lime Cycle Process

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.

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 | 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 | 6 - 8.9 |
| (iii) | 1:1 | 6 | 1:1:6 | M4 | 3 - 5.9 |
| (iv) | 1:2 | 8/9 | 1:2:9 | M2 | 1.5 - 2.9 |

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 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 utilizing supplementary cementitious materials (SCMs) or partial cement replacements (PCRs), 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, 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.

**Table 2: Embodied CO2 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 direct cement replacement (GGBS). It is important to differentiate between a direct cement replacement and a pozzolan. A direct cement replacement is a type of cement substitute that can replace the Portland cement without requiring a pozzolanic activity [11]. The most common type of these replacements is GGBS, which is a by-product of the iron and steel industry, is a fine white powder. GGBS is chemically very similar to cement (Table 3) so can directly replace cement by up to 90% in some structural concrete [11]. However, the most common replacement is between 30 - 70% [11-13].

**Table 3: The chemical compositions and physical properties of GGBS and Portland cement [11]**

| Oxide | Composition | |
|---|---|---|
| | GGBS | Portland Cement |
| CaO | 41% | 65% |
| $SiO_2$ | 35 % | 20 % |
| $Al_2O_3$ | 11 % | 6 % |
| MgO | 2 % | 8 % |
| Colour | Off-white | Grey or White |

In concrete, the reactions between Portland cement, GGBS and water are complex. Portland cement reacts first with water by forming insoluble hydration products such as calcium silicate hydrate and at the same time it forms a more soluble product, calcium hydroxide, which migrates through the pore solution. The GGBS reacts with excess free calcium hydroxide which essentially acts as a catalyst to form calcium silicate hydrates (CSH) which reduces the size of capillary pores [11]. Given that most types of lime contain a significant amount of calcium hydroxide, it is expected a similar reaction will occur if GGBS is added to lime mortar and thus improve the strength and reduce the setting times by the formation of CSH. This paper, therefore, reports the findings of a study undertaken to verify the mechanical properties of non-hydraulic lime mortar containing GGBS as this can potentially reduce the curing time and facilitate in alleviating a disadvantage associated with lime mortars. 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 ensuring it is more sustainable and eco-friendlier as opposed to cement. Thus, a lime based mortar incorporating GGBS can potentially overcome the slow rate of strength development and become a more robust and sustainable alternative to cement based mortars [13].

## Materials and Methods

Experimental work was undertaken to establish the mechanical properties of non-hydraulic lime mortar containing a specified amount of GGBS 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, x-ray diffraction (XRD) analysis was conducted to elucidate the chemical constituents. Soft building sand was used in compliance with BS 1200 [2, 14].

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, EN 1015:Part 3 and BS 4551. Table 4 shows the mixes prepared which were in accordance with EN 998-2 [3, 15-17]. The mix ratio was the standard 1:3 of lime putty:sand by weight. The slag (GGBS) 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% slag addition, the amount would be 4X ÷ 10 (kg); this amount would be added to the lime + sand mix.

**Table 4: Lime Putty Mortar Mixes with GGBS**

| Sample Name | GGBS % |
|---|---|
| Control (0% Mix) | 0 |
| GGBS 2 | 2 |
| GGBS 4 | 4 |
| GGBS 5 | 5 |
| GGBS 6 | 6 |
| GGBS 8 | 8 |
| GGBS 10 | 10 |
| GGBS 12 | 12 |
| GGBS 14 | 14 |
| GGBS 16 | 16 |
| GGBS 18 | 18 |
| GGBS 20 | 20 |

### 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 5). Tests were carried out in accordance with EN 1015: Part 11 [18].

**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 |

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 |

### Workability

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]. Table 7 shows the workability details for the mixes, i.e. how much water (relative to solid content) was required for each mix to obtain a 10mm drop ball consistency/workability - the higher the value, the lower the water content. The results show a general trend whereby less water is required with an increase in GGBS content to obtain a consistent 10mm drop ball workability. This behavior is consistent and in accordance with the effect of GGBS in concrete mixes, i.e. an increase in GGBS addition results in improved workability [19].

**Table 7: Workability details for mixes**

| Mix | Ratio of solid/water content |
|---|---|
| GGBS 2% | 16 |
| GGBS 3% | 16 |
| GGBS 4% | 17 |
| GGBS 5% | 17 |
| GGBS 6% | 17 |
| GGBS 8% | 17 |
| GGBS 10% | 18 |
| GGBS 12% | 18 |
| GGBS 14% | 18 |
| GGBS 16% | 19 |
| GGBS 18% | 19 |
| GGBS 20% | 19 |

* Water was added to each mix to obtain a 10mm drop ball consistency

Table 8 show the compressive strength results of the mortar mixes with Figure 2 illustrating the compressive strength trends up to 91 days. Table 9 and Figure 3 show a comparison and classification of the GGBS mortars with cement (CEM) based mortars as per BS 5628 [3]. Table 10 shows the flexural strength of the GGBS mortar mixes after 91 days curing.

**Table 8: Compressive strength of non-hydraulic lime putty mortar with GGBS**

| Sample Name | GGBS % | 28 Days Compressive Strength (MPa) | 56 Days Compressive Strength (MPa) | 91 Days Compressive Strength (MPa) |
|---|---|---|---|---|
| Control (0% Mix) | 0 | 0.5 | 0.8 | 1.0 |
| GGBS2 | 2 | 1.3 | 1.5 | 2.1 |
| GGBS3 | 3 | 1.8 | 2.2 | 2.5 |
| GGBS4 | 4 | 2.1 | 2.6 | 3.1 |
| GGBS5 | 5 | 2.9 | 3.2 | 3.7 |
| GGBS6 | 6 | 4.6 | 5.1 | 5.8 |
| GGBS8 | 8 | 5.1 | 6.0 | 6.5 |
| GGBS10 | 10 | 8.0 | 8.9 | 9.7 |
| GGBS12 | 12 | 8.4 | 9.4 | 10.6 |
| GGBS14 | 14 | 8.9 | 10.0 | 11.2 |
| GGBS16 | 16 | 9.4 | 10.6 | 11.9 |
| GGBS18 | 18 | 10.7 | 11.9 | 13.1 |
| GGBS20 | 20 | 11.8 | 14.0 | 15.1 |

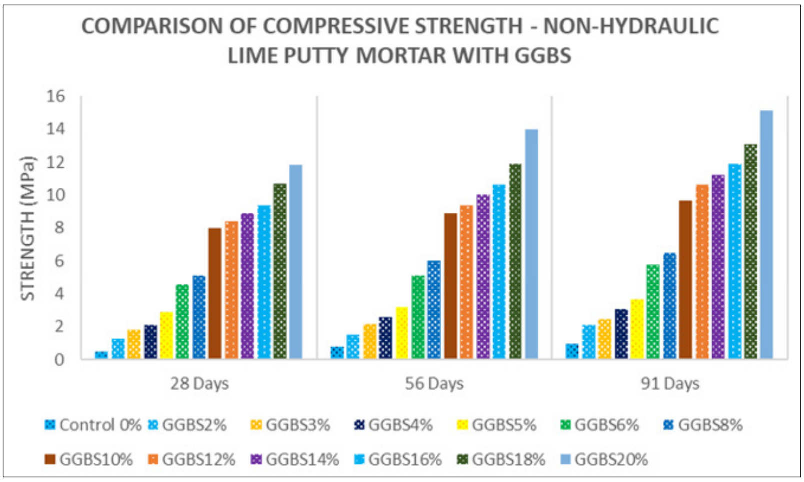


**Figure 2:** Compressive strength of lime putty mortar with GGBS at 28, 56 and 91 days

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

| CEM Mortar Designation | CEM Mortar Compressive Strength (N/mm$^2$) | GGBS Mixes which comply (GGBS %) |
|---|---|---|
| (i) | 9 - 12 | 10, 12, 14 & 16 |
| (ii) | 6 - 9 | 8 |
| (iii) | 3 - 5.9 | 4, 5 & 6 |
| (iv) | 1.5 - 2.9 | 2 & 3 |
| Potential Screed Applications | 12 + | 18 & 20 |

* Note: These are approximate strengths for each designation. Inevitably there are overlaps between the different categories

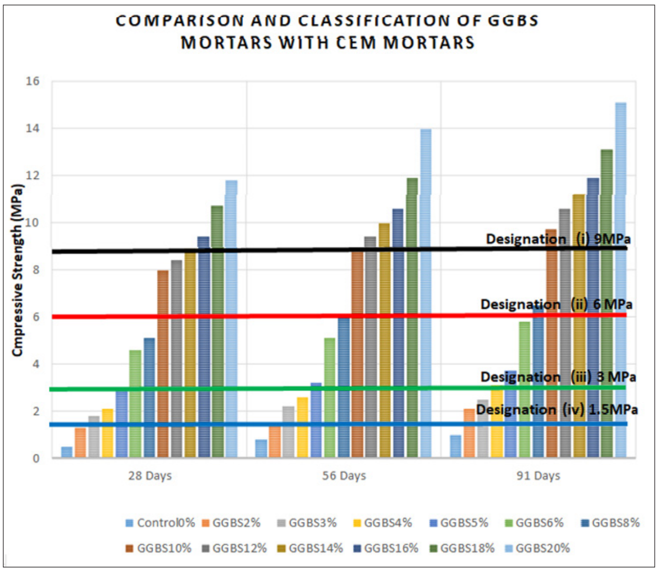


**Figure 3:** Comparison and classification of GGBS mortars with CEM mortars as specified in BS 5628 [3].

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

| Sample Name | GGBS % | 91 Days Strength (MPa) |
|---|---|---|
| Control (0% Mix) | 0 | 0.2 |
| GGBS2 | 2 | 1.8 |
| GGBS3 | 3 | 1.9 |
| GGBS4 | 4 | 2.1 |
| GGBS5 | 5 | 2.2 |
| GGBS6 | 6 | 2.2 |
| GGBS8 | 8 | 2.4 |
| GGBS10 | 10 | 2.5 |
| GGBS12 | 12 | 2.6 |
| GGBS14 | 14 | 2.7 |
| GGBS16 | 16 | 2.8 |
| GGBS18 | 18 | 3.0 |
| GGBS20 | 20 | 3.1 |

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, known as carbonation. This is a very lengthy process with most lime putty mortars reaching a strength of about 1.5 MPa after at least 180 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, i.e. 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. A minimum strength of 2 MPa is usually sufficient to resist sub ambient / winter temperatures.

Just a small addition of GGBS significantly reduces the curing time and increases strength; just as little as 2% GGBS addition doubles the compressive strength and 4% GGBS addition increases the compressive strength at 28 days to 2 MPa, this is highly desirable especially for frost resistance. Table 8 and Figure 2 show GGBS addition results in a substantial increase in strength, with strengths reaching over 15 MPa after 91 days (20% GGBS addition). Figure 3 and Table 9 show how each GGBS mix can be classified in accordance (or a sustainable alternative) to CEM (cement) designation mortars, i.e. GGBSs 2 - 16% range all fall within the Designations (i) - (iv) as specified in BS 5628. 18 - 20% GGBS has potential application as a screed in construction [20]. Further research is required at 20% + GGBS addition to ascertain strength gain or if higher strength screed required. The flexural strengths (Table 10) compare favourably to cement based mortars [21].

The increase in strength for the lime putty mortar can be attributed to the similar way GGBS concrete gains strength [11]. In this case the free $CaOH_2$ acts as a catalyst and promotes the formation of the calcium silicate hydrate (CSH) phase which provides the strength [11,12]. The CSH phase is the major contributor to strength in concrete and cementitious materials, e.g. mortars [11]. Therefore, even with a minimal addition of the GGBS of 2% is sufficient to promote the formation of the CSH phase 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 16% GGBS (Figure 3 & 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). It must be noted that a minimal GGBS addition of 10% is sufficient to impart designation (i) strengths. Therefore, lime putty (non hydraulic lime mortars) with GGBS 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, they offer a greener, more environmentally friendly option [1,11]. 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. This is particularly prevalent especially in many historical & grade listed buildings which were constructed using lime mortar and are still structurally robust after centuries.

**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 overcome by adding supplementary cementitious materials e.g. GGBS.
- Non-hydraulic lime (putty) mortar with as little as up to 4% GGBS addition (by weight) significantly accelerates the setting time with strengths comparable to designations (iii) and (iv) mortars.
- The strengths achieved for all lime putty mortars with up to 16% GGBS addition are in accordance with the minimum strength specified for all designation mortars as specified in BS 5628:Part 1; with only 10% required to impart designation (i) strength.
- Non-hydraulic lime mortars with GGBS offer a more sustainable alternative to cement based mortars with lower embodied $CO_2$.

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