Influence of loading rate and specimen geometry on lime mortar strength

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ABSTRACT: Compressive and flexural strength are important properties because they relate to the quality and durability of a material, and its suitability for a particular design or application. In addition, compressive strength is a principal parameter used to classify and compare materials and establish their requirements in building standards. Therefore, it is important to establish the parameters that affect these properties so that results are comparable. It is known that specimen size and shape, water content, curing conditions, aging and compaction determine the strength of mortars and concrete. This paper sets out the influence of loading rates, increasing from 5 to 900 Newton per second, and specimen geometry (cubes and half prisms) on the compressive and flexural strengths of hydraulic lime mortars. The limes used are NHL5, NHL2 and FL2 which develop strength as a result of hydration and carbonation. The paper concludes that compressive and flexural strength are a function of the loading rate, increasing significantly as the loading rate increases; and that the possible reason for this is that, at high strain rates, micro-cracks do not have sufficient time to search for paths of minimum energy but are forced to propagate along the shortest paths with higher resistance, and this increases the peak load at which the material fails thus increasing its strength. In addition, the results indicate that the shape and size of the specimens also impact strength (half prisms being on average 37% stronger than cubes). The ratio of length to height which determines how strains build up in the specimen is probably one of the main shape parameters that affect the strength measured.

KEY WORDS: Compressive strength; Flexural strength; Loading rate; Hydraulic lime mortar; Specimen shape.

1 INTRODUCTION

Compressive and flexural strength relate to the quality and durability of a material, and its suitability for a particular design or application. They are good indicators of long-term durability as, generally, stronger materials will have longer lives. When the stress carried by a material cannot be sustained, major strains result largely produced by displacement upon fracture surfaces or pore collapse mechanisms. On loading, Portland cement (PC) composites sustain major strains, undergoing elastic deformation with a marked brittle behaviour. In contrast, lime mortars and concrete sustain lower strains while they undergo a plastic-elastic deformation resulting in a marked plastic behaviour [1].

Compressive strength measures the resistance to an increasing crushing load and it is used as a principal parameter to classify materials and establish their requirements in building standards. For example, building limes are classified according to their compressive strength in EN459-1 [2], which also sets the standard strength requirements for hydraulic limes.

Flexural strength dictates the strength in bending; being therefore essential for building designers (it impacts the maximum lateral stress that a wall may take). In addition, flexural strength is important because it indicates strength in tension, for example, that induced by expansion due to freeze-thaw or salt crystallization. It also indicates how much movement the material will allow within the structure, thus adequate values can eliminate the need for expansion joints.

The strength of a composite is largely dependent on the hydraulic strength of its binder. The binders in this study are hydraulic limes (NHL5, NHL2 and FL2) which develop strength as a result of hydration and carbonation. At early ages, the excess water is lost and shrinkage occurs and almost simultaneously, carbonation begins. Carbonation is a slow process that leads to hardening as portlandite- $Ca(OH)_2$ transforms into calcite- $CaCO_3$ by the absorption of CO_2 from the atmosphere. The amount of hydraulic set depends on the hydraulic strength of the lime: in an eminently hydraulic lime such us NHL5, hydraulic set is significant and carbonation has a smaller impact on hardening and strength development, while in feebly hydraulic limes such us FL2 and NHL 2, carbonation is more significant and hydraulic set less relevant. The curing environment (temperature and humidity) impacts the speed of carbonation and hydration that lead to hardening, consequently affecting strength development and ultimate strength. Higher temperatures usually increase the rate of carbonation and hydration thus speeding strength development while low temperatures can impede hardening and strength development. Strength increases with age, due to the progress, over time, of the reactions responsible for hardening.

This paper investigates the effect of loading rates (increasing from 5 to 900 Newton per second) and specimen geometry (cubes and half prisms) on mortar strength and mechanical behaviour. The loading rates were selected to include those above, below and within standard rates; and the specimen shapes are those featured in standards and material testing recommendations.

Several factors (other than curing conditions, age and binder hydraulicity) influence strength including: binder/aggregate ratio, aggregate characteristics, porosity and density. Strength is also determined by workmanship, for example an excess of mixing water undermines strength. Particle size distribution is amongst the most important aggregate attributes that influence strength. It is well known that an adequate grain size distribution including a wide range of particle sizes triggers a physical filler effect whereby the smaller aggregate fills spaces between larger particles, and this enhances packing, increasing density and lowering porosity, thus leading to greater strength and durability. Previous studies have concluded that good grading enhances strength and bulk density simultaneously lowering porosity, water absorption and capillary suction [3-8]; and that an aggregate with small average particle size enhances strength [9-10]. It is also widely accepted that angular aggregate improves mechanical strength and bulk density lowering porosity, water absorption and capillary suction [3,4,8,11-15].

Porosity and density also impact strength. They depend on the properties of the raw materials and their compaction. Strength usually rises with furthering compaction, as this enhances density and lowers porosity. However, rising porosity by increasing the amount of binder has led to strength enhancement in hydrated lime (CL-calcium lime) and NHL5 mortars [3,9].The binder/aggregate ratio also affects strength, NHL5 and CL mortars increase compressive and flexural strength with increasing binder content [3,9]. Proportioning mortars by mass or by volume impacts strength because it affects binder/aggregate ratio: significantly more binder is used when prescribing proportions by volume because the aggregate is denser than the binder, therefore, when prescribing mortars by volume, the lower the density of the binder the higher the binder amount prescribed [16].

Previous authors have found relationships between specimen shape and strength in PC mortar and concrete: cubes are stronger than cylinders. A factor of 1.2 is used to convert cylinder to cube strength for normal-strength concrete. However, this factor becomes smaller as the concrete strength increases so that for high-strength concrete, the influence of specimen shape is much less significant [17]-citing Gonnerman 1925, Gyengo 1938 and Murdock and Kesler 1957. The influence of shape on strength also drops as the specimen size increases [17,18]: strength is an inverse function of the specimen size for both cubic and prismatic samples whereas for the larger cylinders the effect of size on strength is almost negligible.

Finally, loading rates also affect the ultimate strength and mechanical behaviour of materials. The compressive strength of PC concrete increases significantly as the strain rate increases [19, 20]; the fracture energy and peak load increase as a function of the loading rate [21] and [22]. The reason is not yet clear as the mechanisms involved in fracturing due to loading rate and/or duration are not fully known however, experimental evidence indicates that, high loading rates impact on the two stages at which fracture occurs. In the first stage, high strain rates delay the growth micro-cracks [20, 23]. In the second stage, micro-cracks propagate simultaneously, and micro-voids and micro-cracks nucleate and grow to induce discrete cracks. At this stage, at high loading rates, micro-cracking does not have sufficient time to search for paths of minimum energy or minimum resistance, thus micro cracks are forced to propagate along the shortest path with higher resistance and this increases the material strength – its fracture energy and peak load.

2 MATERIALS AND METHODS

2.1 *Mixing, curing and compaction*

Natural Hydraulic Lime (NHL) of strength 2 and 5 and a Formulated Lime (FL) of strength 2 complying with EN459-1 [24] were used. The aggregate was 5 mm sand sourced in Wexford. A standard ratio of 3:1 (sand: lime) was used; and the amount of water was fixed to produce flows as prescribed by EN459-2 [1] and Hanley and Pavía [16]. Mixing, moulding and compaction were carried out according to EN196-1[25]. Cubes ($50mm^3$) and prisms were moulded. The prisms comply with the flexural strength specimens specified in EN196-1 with dimensions 40x40x160 mm. The mortars were placed in the moulds in two layers immediately after mixing. The fist layer was compacted with sixty jolts of a metal rod, and the second layer added and compacted. The specimens were then covered with damp hessian fabric to prevent initial shrinkage and cured for 28days according to EN 459-2 [2].

2.2 *Compressive strength*

The load per unit area under which the specimen fails was measured in accordance with EN 196-1 [25]. Several tests were performed at different loading rates: 10, 100, 500 and 900N/s. A uniformly distributed load was applied at each loading rate until failure occurred, and the maximum force applied to the cube (*fc*) noted. Testing was carried out on the 28-35th day. The mean of six (half prisms) and three (cubes) for each loading rate was recorded and the compressive strength calculated using Equation 1 below.

$$Rc = fc/A \qquad (1)$$

Where;

Rc compressive strength, N/mm^2
fc maximum load applied at failure, Newton (N)
A cross sectional area, mm^2

2.3 *Flexural strength*

The flexural strength was tested using the centre point loading method, according to EN 196-1 [25], at four different loading rates: 5, 10, 50 (standard loading rate) and 100N/s. The prisms were placed in the centre of the rig and loaded uniformly until failure. The mean of three readings for each loading rate was recorded and the strength calculated using equation 2.

$$R_f = 3PL / 2d^3 \qquad (2)$$

Where;

R_f flexural strength, N/mm^2
P maximum load applied to the prism at failure, N
L span of supports, 100mm
d side of the cross section of the prism, 40mm.

2.4 *Initial flow*

The water demand to produce flow diameters as prescribed by EN459-2[1] and Hanley and Pavía [16] was measured according to EN 459-2. A truncated cone was placed in the centre of the flow table and filled with mortar. After 10 seconds, the mould was lifted and the mortar spread by jolting the plate, mechanically, 15 times at one jolt per second. The resulting diameter was measured in two perpendicular directions and the mean value recorded.

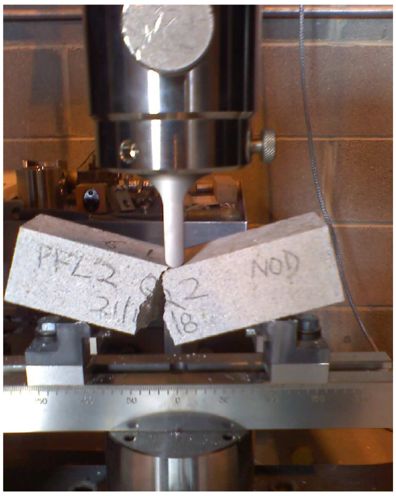

Figure 1. Flexural strength measured with the centre point loading method.

3 RESULTS AND DISCUSSION

3.1 Compressive strength

The compressive strength of cubes and half prisms of NHL 2 mortar at increasing loading rates appear in Figure 2. The strength of the cubes steadily increases from 1.91 to 2.30 N/mm^2 with increasing loading rates, while the half prisms show a general upward trend with the exception of the samples tested at 100 N/s. This can be due to anomalies in mixing and compaction. The half prisms are, on average, approximately 35% stronger than the cubes. The compressive strength of NHL5 mortars complies with the standard requirement of EN 459-2 [2] as this prescribes the strength of 5 N/mm^2, at 28 days, tested on half prisms at a loading rate of 400N/s. The compressive strength of the NHL5 mortars at increasing loading rates appears in Figure 3. As for the NHL2 mortar, the strength of the half prisms steadily increases from 5.76 to 6.16 N/mm^2 with increasing loading rates, with the exception of the samples tested at 500 N/s. The cube strength does not show a consistent trend. The half prisms are on average approximately 47% stronger than the cubes. The compressive strength of the FL2 mortar (Figure 4) shows a similar trend: the strength of both prisms and cubes is higher at higher loads (500 and 900 N/s), and the half prisms are stronger than the cubes (30% on average). The percentage variation in compressive strength between the lowest and the highest loading rate (10 and 900N/s) is included in Table 1. These results evidence an increase in the compressive strength of lime mortars as the loading rate increases agreeing with previous research on PC composites [19,20,21,22]. The NHL5 inconsistency can be due to an error in mixing and compaction. Deviations due to the nature of the material (natural source) may have contributed to this anomaly. In all mortars, the half prisms are significantly stronger than the cubes (37% stronger on average). This disagrees with former results on PC composites stating that strength is an inverse function of the specimen size [17,18] (according to this, the bigger half prisms should be weaker). However, while their volumes are comparable (cubes are 50mm3 while half prisms measure on average 40x40x80mm), the ratio of length to height is different (1:1 for cubes *vs* 2:1 for the half prisms). The length to height ratio determines how strains build up in the specimen, these will build up in a more uniform manner for the cubes as a result of the 1:1 ratio, and this can contribute to an early failure.

Table 1. Variation in compressive strength between the lowest and the highest loading rate (10 and 900 N/s).

Mortar	Cubes	half-prisms
NHL 2	+17 %	+6%
NHL 5	-15%	+7%
FL 2	+10%	+8 %

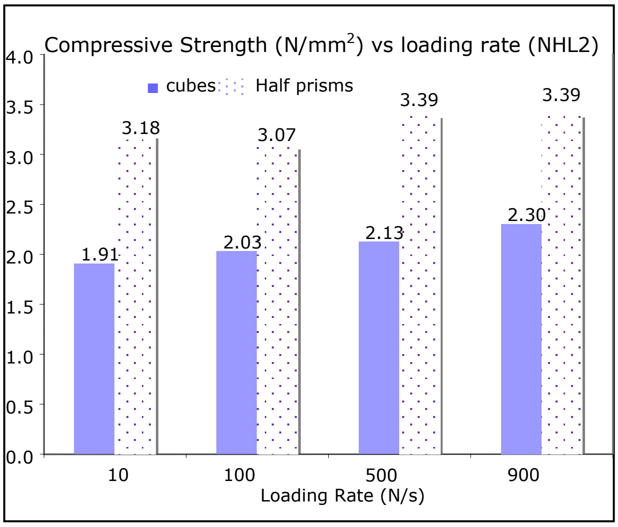

Figure 2. Compressive strength of NHL2 mortar at increasing loading rate.

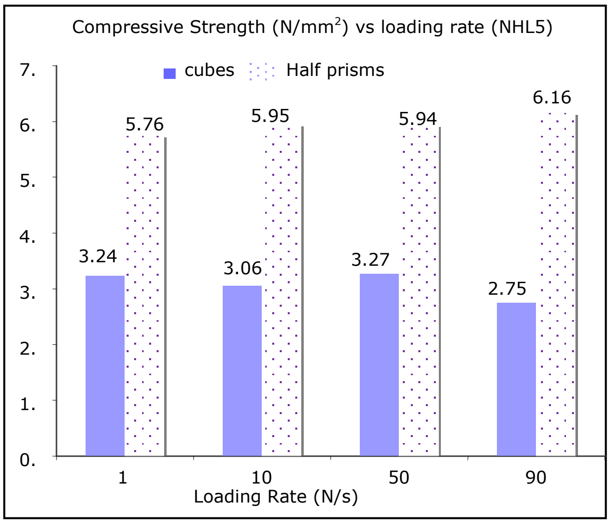

Figure 3. Compressive strength of NHL5 mortar at increasing loading rate.

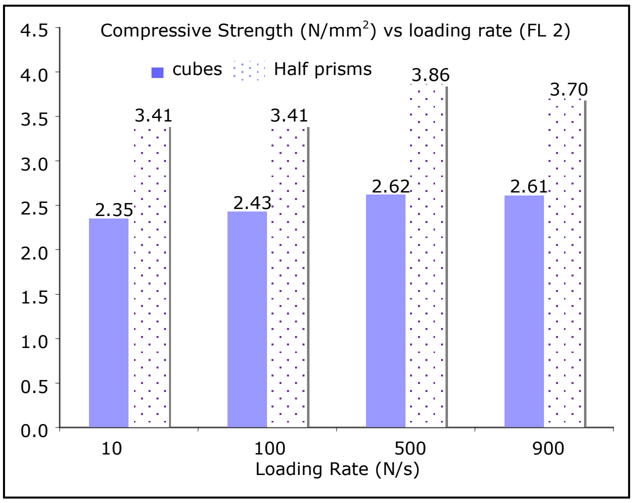

Figure 4. Compressive strength of FL 2 mortar at increasing loading rate.

3.2 Flexural strength

The flexural strength of the NHL2, NHL5 and FL2 mortars is included in figures 5, 6 and 7 respectively. As in the compressive strength results, there is a general upward trend in flexural strength as the loading rate increases with the exception of the NHL5 mortars. This inconsistency was expected, as the same specimens were used for both tests (as specified by EN196-1, the prisms were first tested in flexion and the remains then crushed under compression- Figure 1). As aforementioned, this anomaly is probably due to an error in mixing and compaction and common deviations inherent to the nature of the material. The percentage change in flexural strength between the lowest and the highest loading rate (5 N/s and 100N/s) is included in Table 2.

Table 2. Flexural strength variation between the lowest and the highest loading rate (5 and 100 N/s).

Mortar	% change
NHL 2	+20%
NHL 5	-13%
FL 2	+6%

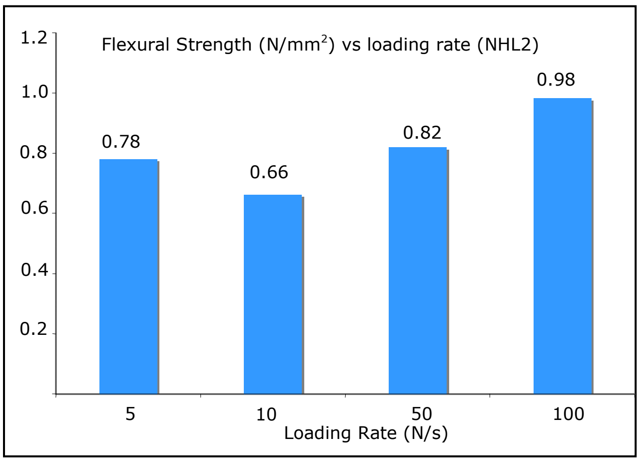

Figure 5. Flexural strength of NHL2 mortar at increasing loading rate.

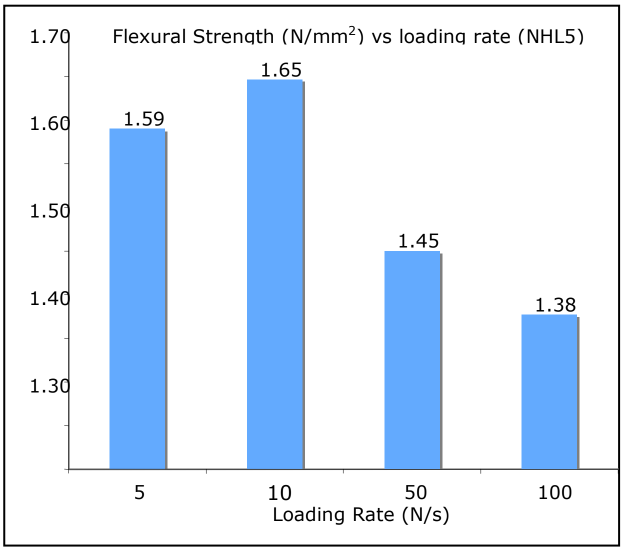

Figure 6. Flexural strength of NHL5 mortar at increasing loading rate.

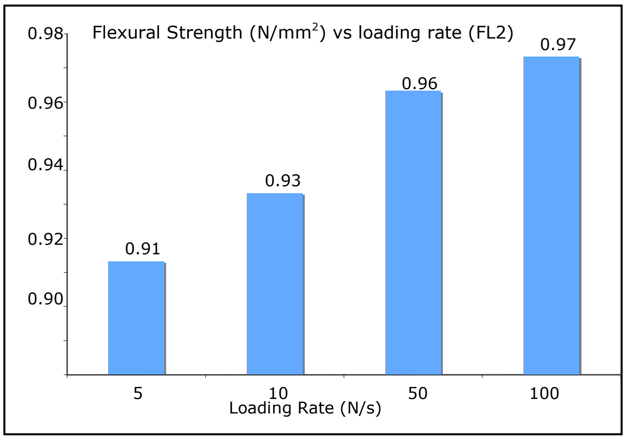

Figure 7. Flexural strength of FL2 mortar at increasing loading rate.

4 CONCLUSION

In view of the results, it can be concluded that the compressive and flexural strength of lime mortars are a function of the loading rate, increasing as the loading rate increases. Based on former experimental evidence, the possible reason for this is that, at high strain rates, microcracks do not have sufficient time to search for paths of minimum energy (minimum resistance) but are forced to propagate along the shortest paths with higher resistance, and this increases the peak load at which the material fails thus increasing its strength.
In addition, the results indicate that the geometry (shape and size) of the specimen also impacts strength (the half prisms were on average 37% stronger than the cubes). The ratio of length to height which determines how strains build up in the specimen is probably one of the main shape parameters that affect the strength measured.

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