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STRAIN RATE SENSITIVITY OF PURE HYDRATED LIME MORTAR

Ashraf G. Nayel ⁽¹⁾, Lorenzo Macorini ⁽¹⁾ and Christian Málaga-Chuquitaype ⁽¹⁾

(1) Imperial College London, UK

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Author contacts

Authors	E-Mail	Fax	Postal address
Ashraf G. Nayel	a.nayel21@imperial.ac.uk		Imperial College Rd, South Kensington, London SW7 2BU
Lorenzo Macorini	l.macorini@imperial.ac.uk		Imperial College Rd, South Kensington, London SW7 2BU
Christian Málaga-Chuquitaype	c.malaga@imperial.ac.uk		Imperial College Rd, South Kensington, London SW7 2BU

Corresponding author for the paper: Ashraf G. Nayel

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STRAIN RATE SENSITIVITY OF PURE HYDRATED LIME MORTAR

Ashraf G. Nayel ⁽¹⁾, Lorenzo Macorini ⁽¹⁾ and Christian Málaga-Chuquitaype ⁽¹⁾

(1) Imperial College London, UK

Abstract

Lime has been widely used as the main binding ingredient in mortars of historical masonry structures and in concrete before cement. Nowadays, the use of lime in structural applications is limited to the repair of historical masonry structures in addition to some modern constructions mostly in combination with cement. Lime production consumes less energy than cement production leading to a much lower carbon footprint than cement. Also, air limes absorb carbon dioxide from the air during their carbonation which fosters the reuse of lime in modern constructions. Construction materials show increments in the values of some of their mechanical properties when subjected to high strain rates caused by dynamic loads in comparison to low strain rates caused by static or nearly-static loads. The parameter that relates a material's dynamic mechanical properties to its static ones is the dynamic increase factor. In this study, pure hydrated calcium lime mortar without cement, without additives, and without admixtures is experimentally tested under a wide range of strain-rates. A drop-weight impact machine is used to achieve high strain rates. Both compressive and indirect tensile (splitting) strengths are investigated. This study aims to contribute towards an accurate evaluation of existing masonry structures with lime mortar under extreme loads, hence promoting lime in modern constructions.

Keywords: Lime mortar, Pure lime, Strain-rate, Sustainable binder, DIC.

1. INTRODUCTION

Lime has been used as the main binding constituent for mortars in historical masonry constructions and in concrete constructions across the world before the invention of cement. Lime has a proven durability and can be found in many existing historical structures. In comparison to cement mortar, lime mortar produces less carbon emissions overall. Calcination (burning) of a calcium carbonate such as limestone at 900°C produces Quicklime [1, 2] which is the main product that other types of limes are produced from. The temperature at which calcination takes place is less than the temperature needed for cement production. When quicklime is slaked, hydrated lime is the outcome. The hydrated lime can be lime putty, a thick creamy-like paste, that is obtained when excessive amount of water is used. On the other hand, when a controlled amount of water is used and the product is grinded, the outcome is dry hydrated lime which is also referred to as S lime, as per BS 4591:2015 [1]. Both forms of air lime are used in historical repairs [3]. These two forms of lime are aerial lime that set and harden via carbonation, which is a chemical process that needs carbon dioxide (CO₂). The absorption of CO₂ from the air during carbonation is another reason for the lower carbon footprint of aerial lime mortars compared to cement mortars. This motivates the promotion of a wider reuse of lime in modern constructions to help tackling the current environmental challenges.

Structures that employ lime in their construction, especially historical structures, like other structures can be susceptible to extreme loads such as blast loads. These extreme loads strain the material at higher rates compared to the more common quasi-static loads. Assessing the behaviour of existing masonry structures that utilize lime mortars, and the design of new structures incorporating lime against such extreme loads require a good understanding of their sensitivity to high strain rates.

Although there are some studies that investigate the strain rate sensitivity of masonry materials, the amount of work is still limited in comparison to materials such as concrete and steel, to date, there are no studies that have examined the sensitivity of lime mortars to high strain rates.

The dynamic bond strength of masonry was studied on triplets using drop hammer machine by Beattie et al. [4]. Enhancement in bond strength under dynamic loading was reported along with sensitivity to the boundary conditions of the triplet specimens. Split Hopkinson Pressure Bar (SHPB) and numerical simulations were employed to investigate the dynamic tensile strength of masonry cored specimens. Dynamic increase factors (DIFs), which are the ratio of the dynamic properties to their static counterparts, were reported for tensile bond strength of masonry as a function of the effective bond area by Burnett et al. [5]. A DIF of 1.5 was suggested for 75% effective bond zone. Strain rate sensitivity of clay bricks and cement-lime mortars under compression was examined using triaxial dynamic machine by Hao and Tarasov [6] with strain rates of up to 160 s^{-1} and 210 s^{-1} achieved for brick and mortar, respectively. Clay bricks with different strengths were examined using SHPB by Zhang et al. [7] under compression. A maximum value of 337 s^{-1} for strain rates were achieved for mid strength brick specimens. Dynamic compressive and splitting tensile strengths of different types of bricks and cement-lime mortar using SHPB were examined by Larcher et al. [8] with strain rates up to 189 s^{-1} achieved for clinker bricks under compression reported. Drop weight machine used to investigate the effect of high compressive strain rates on the hand-made clay bricks, cement mortar, and masonry prisms by Pereira and Lourenço [9]. Maximum strain rates of 193 s^{-1} , 176 s^{-1} , and 54 s^{-1} for mortar, bricks, and masonry specimens were attained, respectively. It can be appreciated from these studies that different testing machines were used to reach high levels of strain rates representative of those induced by blast loads. However, it can also be noticed that there is a lack of comparisons between various studies due to the limited number of these studies.

The influence of low rates of loading on natural hydraulic lime (NHL 3.5) and aerial lime (CL-90-S) mortars with 1:3 binder-to-aggregate ratio has been investigated by Zhang et al. [10]. An electromechanical universal testing machine was used to achieve three rates of loading, i.e., 5.0×10^{-4} , 5.0×10^{-1} , and $1.6 \times 10^1 \text{ mm/s}$. DIFs of 1.4 and 1.6 for ultimate compressive loads reported for NHL and aerial lime mortars respectively, and a 1.9 DIF was found for fracture energy for both mortars. In the present study, pure lime mortar is experimentally tested under different compressive and splitting tensile strain rates. The lime used is hydrated lime in powder form which will be referred as hydrated calcium lime (CL). To the authors' knowledge, this is the first study to report on the sensitivity of pure lime mortars to high strain rates.

2. EXPERIMENTS

2.1 Test specimens

Cylindrical specimens of $45 \text{ mm} \pm 1 \text{ mm}$ diameter and $50 \text{ mm} \pm 1 \text{ mm}$ height (height to diameter ratio of 1.11) are tested under both indirect tension (splitting) and compression. A constant size of specimens is maintained for both quasi-static and dynamic tests, to ensure a consistent comparison of strengths and to investigate the sensitivity to changes in strain rates. For dynamic tests, the shape, aspect ratio, and size of the test specimens were designed to balance between ensuring dynamic equilibrium, uniform strain rate within the specimen, minimizing the inertia effect, and avoid resonance, while maintaining an acceptable volume of the material. These considerations lead to the use of smaller size specimens compared to standard quasi-static only tests. A 3:1 (aggregate: lime) ready-mixed aerial lime mortar, gauged by volume, is used in this study. This mortar has applications in historical repair and block/bricklaying. A pure lime mortar with hydrated calcium lime as binder and

fine to medium aggregate as a bulking medium is used in this study without additives or admixtures to set the basis for other types of mortars in later studies. The size and size distribution of aggregates highly affect the strength of lime mortars [11]. A blend of irregular (sharp) and spherical (soft) fine aggregates with a particle size distribution as presented in Table 1 is used in the preparation of the mortar.

Table 1: Particle size distribution of aggregate

Sieve size [12]	Percentage retained	
	Irregular sand	Spherical sand
> 5 mm	0.98	0
< 5 mm > 2.36 mm	12.75	0.35
< 2.36 mm > 1.18 mm	14.86	0.50
< 1.18 mm > 600 μm	14.70	0.98
< 600 μm > 300 μm	39.55	38.53
< 300 μm > 150 μm	14.53	53.80
< 150 μm > 75 μm	2.48	5.20
< 75 μm	0.15	0.64

Cylindrical specimens with 45 mm diameter and 50 mm height were cast on two layers in poly vinyl chloride (PVC) formworks. Afterwards, the specimens were vibrated on a vibrating table for three minutes at intermediate vibration frequency. Then, excessive parts of the fresh mortar were removed, and the top surface levelled with a stainless-steel putty knife. Specimens were left inside moulds for at least two days before being demoulded. Aerial limes harden and acquire their strength through carbonation process which requires carbon dioxide, the curing of the lime mortars in this study included exposing the specimens to air. The curing process recommend in [13] was followed. The mortar specimens were left in the lab environment for the first seven days. Then they were moved to a controlled-humidity room for 21 days. Finally, the specimens were removed from the control room and left in the lab environment again until the day of testing. The minimum overall curing time for the specimens before testing is four to five months under splitting and six months under compression, respectively. This obeys to laboratory logistic constraints and preparation time for each specimen. This curing time is essential for the relatively slow carbonation process and to gain enough strength over time [14]. Different stages for mortar preparation are shown in Figure 1.

2.2 Test setup

Quasi-static displacement control tests were performed using an electromechanical universal test rig by Instron which has been recently calibrated. A rate of 0.1 mm/min for both splitting and compression was adopted. Strains were measured on external surfaces of specimens via digital image correlation (DIC). Two cameras of two Megapixel resolution were positioned in a stereo mode to enable 3D strain measurements. A sampling rate of one Hertz (one frame per second) was used. The synchronization of the load produced by the Instron machine, and the videos recorded by the DIC system was ensured via the DAQ system.

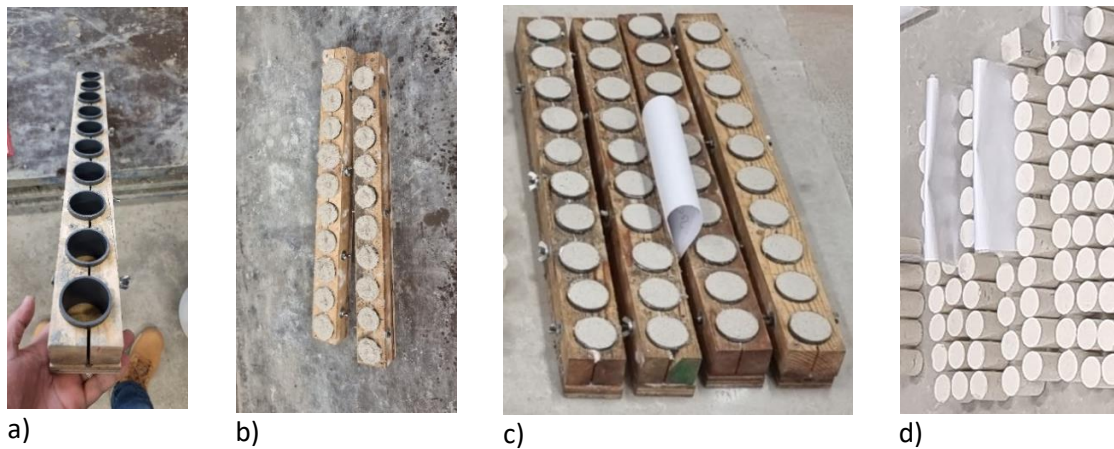


Figure 1: Preparation of mortar: a) typical mold; b) vibration; c) mortar in molds after surface treatment in lab environment; d) demolded specimens in ambient lab conditions.

Dynamic tests were carried out using an Instron Dynatup HV9250 drop tower. Specimens were positioned on top of a load cell within the rig. The whole test area was fully covered by transparent polycarbonate sheets for safety against the flying debris. A drop mass of $7.0 \text{ kg} \pm 1.0 \text{ g}$ was used. Strains were measured using DIC by means of two high-speed Phantom cameras (V611 and V711) installed in a stereo mode. The camera with lowest resolution (V611) was set as the main camera, while the V711 was set as a secondary camera to ensure equal sampling speeds. The V611 camera has a sampling speed of 6242 frames per second (fps) at its full resolution of 1280×800 increasing at lower resolutions. Fields of view are cropped to the areas of interest in splitting and compression to reach the largest possible sampling speeds of the cameras. A sampling speed of 37863 fps with resolution of 352×352 pixels was achieved in splitting tests, while a 67714 fps and 256×256 resolution was achieved for compression tests. A sampling rate of 25 sample per frame was used. Various test scenarios were carried out by changing the drop height (and impact velocity) of the impactor to produce different strain rates. Figure 2 shows the set ups for both quasi-static and dynamics tests.

The indirect tensile (splitting) tests were performed by laying the specimens horizontally inside a custom-made steel Brazilian device. Two bearing strips cut from 3.0 mm thick hardboard sheets with 50 mm length, same length as that of the specimens, and 3.5 mm width were positioned one on the top and one at the bottom of the specimens as per [15, 16]. The compression specimens were oriented vertically, and two layers of 0.127 mm plastic Fluorinated ethylene propylene (FEP) were positioned between the top and bottom surfaces of the specimens to reduce the effect of friction.

In quasi-static testing, a steel hinge with two rotating parts was used to help in initial seating at the beginning of loading. This rotating hinge was placed on the upper jaw of the Brazilian apparatus in the splitting tests, while in the compression tests it was placed on top of another loading platen. For dynamic tests, the rotating hinge was replaced with three layers of 3.0 mm thick hardboards to act as pulse shaper for the incident impulse. A minimum of three specimens were tested in each quasi-static and dynamic scenario under both splitting and compression.

Speckle patterns were optimized for the two setups as per [17] and applied over the specimens' regions of interest (ROI). For splitting tests, the ROI is the base surface of the cylindrical specimen, while for compression tests it is the lateral surface of the specimen.

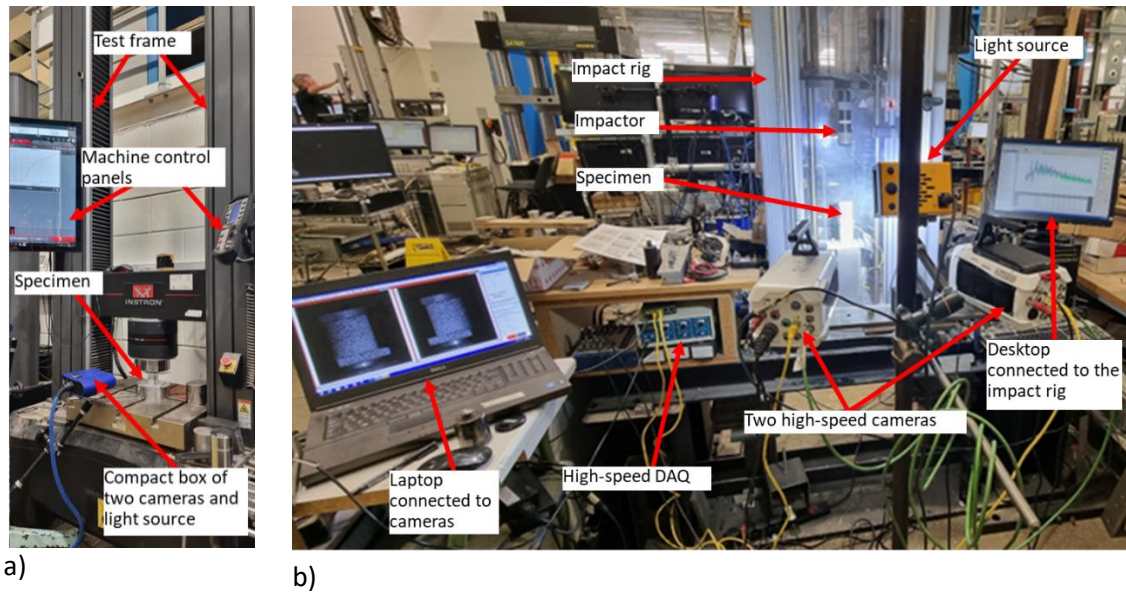


Figure 2: Test setups: a) quasi-static setup; b) dynamic setup.

The feature size of the applied speckled patterns was 4 to 5 pixels in size with random distribution, round edges, and density of around 50% white and 50% black. Calibration of the DIC system was carried out prior each series of tests using a stepped (3D) calibration plate and fit error kept lower than 0.1 pixel. During the stereo DIC processing, the size of subset or mesh size selected to ensure an average of 4 features were included inside each subset. Speckle patterned specimens for DIC are presented in Figure 3.

3. RESULTS AND DISCUSSION

Strains measured through DIC were combined with stresses readings to examine the strain rate sensitivity of the pure hydrated CL lime mortar. In splitting tensile tests, the applied load is converted into an equivalent tensile stress based on the theory of elasticity for isotropic material. Compression stresses on the other hand calculated as the load divided by the loaded cross-sectional area of the specimen.

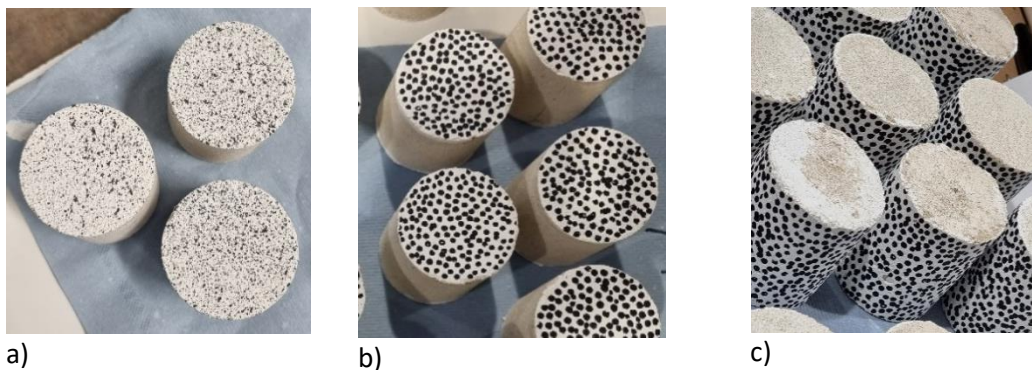


Figure 3: Speckle patterns: a) splitting specimens for the quasi-static DIC system; b) splitting specimens for the dynamic DIC system; c) compression specimens for the dynamic DIC system.

Strains were obtained with the commercial DIC software LaVision (DaVis 10.2) using virtual area strain gauges over the regions of interest. Horizontal transversal strains were calculated for splitting tests and vertical axial strains were calculated for compression tests. For dynamic tests, the two recorded high-speed videos were cropped then imported and combined in the LaVision DaVis software to make one stereo video. Calibration was then applied, and the stereo records were processed. Typical strain analysis outputs are presented in Figure 4 for splitting tests and in Figure 5 for compression. Strains were then combined with the load signals and the dynamic stress-strain diagrams were constructed. To determine the strain rate the specimens' material experiences at each loading scenario, strains were differentiated with respect to time. Since the strain rate varies with time like the stresses and strains do, the strain rate for each test considered as the maximum strain rate along the period of loading within the area under the stress-strain diagram, which was always just after the ultimate strength.

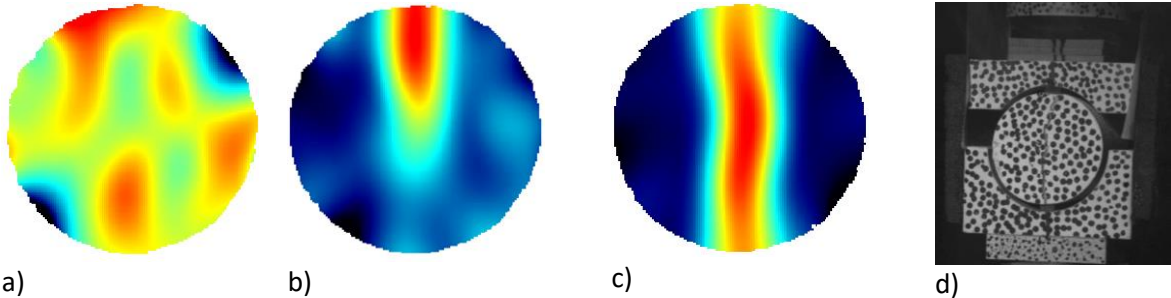


Figure 4: A specimen under splitting: a) DIC horizontal transversal strain contours before impact; b) just at impact; c) after impact; d) typical cracked specimen.

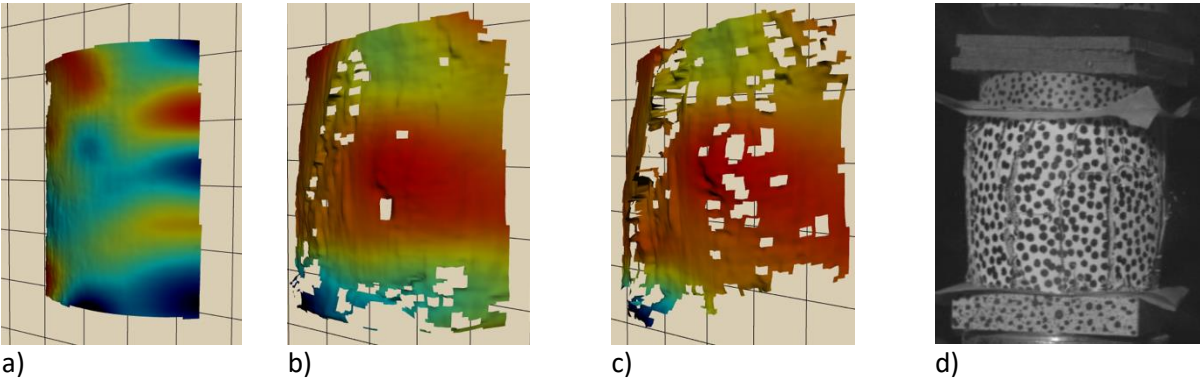


Figure 5: A specimen under compression: a) DIC vertical axial strain contours before impact; b) just at impact; c) after impact; d) typical cracked specimen.

The sensitivity of hydrated CL mortars to strain rates is expressed as an increase in the tensile and compressive strengths with increasing strain rates. Strain rates, ultimate strengths, and dynamic increase factors are reported for splitting tensile tests and compression tests in Figure 7. It is noted that the rate of straining experienced by the pure hydrated CL mortar under splitting tension is much higher than that experienced under compression. The tensile strength of the mortars is more sensitive to the strain rate than the compressive strength. The variation of DIFs with strain rate is presented in Figure 6 for splitting tensile and compressive strengths.

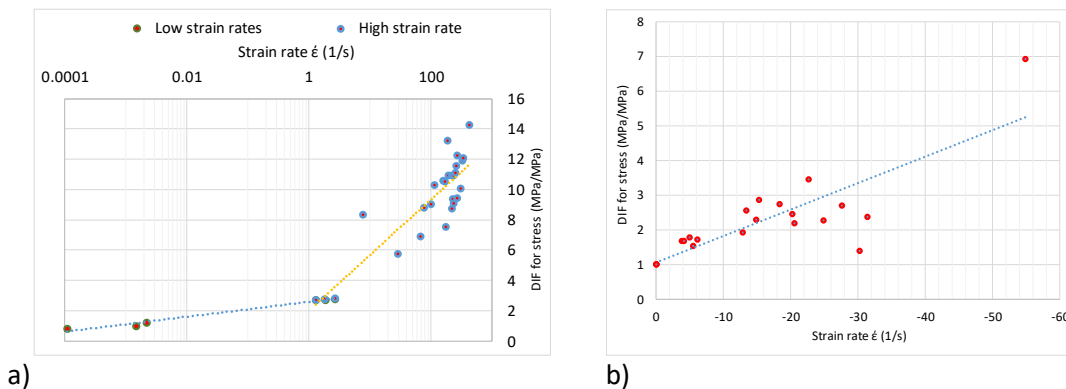


Figure 6: Variation of stresses dynamic increase factors with strain rate: a) splitting tension; b) compression.

Given the fragility of the pure aerial lime mortar under study, it is not easy to grind the loading surfaces to ensure smooth and horizontally parallel surfaces in compression, which can lead to nonuniform loading of the specimen. This could be the reason for the dispersion of the compression results compared to splitting results.

Typical failures of specimens are shown in Figure 4 and Figure 5 for both quasi-static and dynamic loading. Under splitting tension, failure is characterised by a full depth vertical crack that splits the specimen into nearly two equal parts. This is the typical failure pattern for Brazilian splitting tests. Compression specimens on the other hand showed columnar failure where multiple nearly vertical cracks formed all around the specimen with small cones left from the material after complete crushing. This columnar compressive mode of failure indicates low friction between the specimen and loading platen [18], which can be attributed to the use of double layers of FEP at the top and the bottom of the specimen.

4. CONCLUSIONS

The strain rate sensitivity for a pure hydrated CL lime mortar has been investigated for the first time via a series of quasi-static and impact tests of cylindrical specimens with aspect ratio of 1.11. Indirect tensile strength and compressive strength tests have been performed. The following conclusions can be offered:

- The challenges associated with treating the loading surfaces of the specimens under compression can lead to increased dispersion in the results.
- The pure hydrated lime mortar is more sensitive to high strain rates during dynamic splitting tensile stresses than during dynamic compressive stresses.
- Relationships between DIFs and strain rates for ultimate strengths in tension and compression have been presented.

The results of this study will contribute towards an accurate structural assessment of existing historical masonry structures constructed with hydrated lime mortar as the main binder subjected to extreme loads that induce high rates of straining in the material. The range of strain rate values explored in this study is representative of rates caused by static and dynamic actions such as permanent dead loads, on the one hand, and transient impact loads or collisions, on the other hand.

Pure hydrated lime mortar, which is an aerial lime, is more sustainable than cement mortar as it needs lower temperatures in manufacturing and absorbs carbon dioxide from the air during the carbonation

process. Hence, the structural reuse of this mortar in modern constructions is highly recommended and worth promoting.

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