Quantification of impact of lime on mechanical behaviour of lime cement blended mortars for bedding joints in masonry systems

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Abstract: In the case of blended lime-cement mortars used for bedding joints in masonry systems, substitution of cement with lime in the binder involves changes in strength and stiffness. However, extensive quantification and correlation of these changes in mechanical properties appear to be scarcely explored in existing literature. This work aims at providing a methodical experimental campaign, targeting 14 different lime-cement mixes with the quantity of lime in the binder varying from 10% to 75% (by volume), binder-aggregate (B/Ag) ratios - of 1:3, 1:4, 1:5 and 1:6 at 6 different curing ages from 7 to 180 days. Changes in compressive strength and flexural strength were expressed as functions (equations) of lime content in the binder, B/Ag ratio and curing age. Every 1% increment in the quantity of lime in the binder led to approximately 1.4% decrease in mechanical strength of the mortar with respect to the reference (10% lime in the binder). Furthermore, correlation(s) between ultrasound pulse velocity (UPV), density, compressive and flexural strength have also been explored. Compressive strength divided by flexural strength provided an almost constant value for all lime-cement compositions at all ages (ratio ~ 3), decreasing as a function of B/Ag ratio in the mix. The work has been concluded with a discussion on trends in E-modulus (4-18 GPa) and open porosity (23%-27%) as a function of lime content in the binder of the mix and the age of the mortar.

Keywords: lime-cement masonry mortars; workability; mechanical strength; static E-modulus; ultrasound velocity (UPV);

1. Introduction

The technical role of bedding mortar in masonry construction is often primarily discussed with regard to adhesion, load bearing and setting of units [1,2]. Deformability, workability, shrinkage, freeze-thaw resistance and vapour transmission are some other parameters that are considered relevant [3]. Ideally, there is a necessity for each of these parameters of the mortar to be tailored with regard to the type of masonry unit and construction typology used. It is indeed difficult for any individual binder to fulfil all requisite criteria of a suitable mortar and that is why, the two most commonly used binders namely air lime and cement are often mixed together on different building sites across the world [4]. Mortars with air lime are often credited with good workability, an ability to accommodate deformation, and vapour permeability [5]. On the other hand, mortars with cement are known for fast setting, high strength and stiffness [6]. A mix of the two binders however leads to an interesting set of properties that may be adapted based on their respective proportions used in the binder, and this has been investigated by some researchers [4,5].

Arandigoyen *et al.* [7] conducted several tests of mechanical strength for lime-cement mortars and reported lower strength for mixes with greater quantities of lime in them. However, they did not establish a quantitative correlation between strength of the mortar and quantity of lime in the binder. Macharia [8] states that a 30% addition of lime in a cement mortar leads to a 70% difference in strength compared to a cement mortar. However, Cizer [9] found that a 30% addition of lime leads to 40% lower strength of the mortar. If the data presented by Haach *et al.* [10] is analysed, it is possible to note that 50% substitution of cement by lime, leads to approximately 50% change in strength of the mortar. So while it is clear that an increase in quantity of lime in the binder leads to mortars of lower strength, there seems to be no consensus on the amount of decrease in strength, as observed by different researchers. The properties of lime particles such as specific surface area, particle size distribution and formulation composition change a lot, depending on the type of lime being used, which in turn may significantly impact the mechanical properties at the mortar level. It is possible that the lack of consensus, noted by researchers may be due to the use of different types of lime and cement, and therefore there is a need for an extensive, systematic campaign which uses consistent conditions and raw materials to quantify trends in lime-cement mortars.

In the case of static Young's modulus [11], the pattern found was similar to that of compressive strength. If data gathered from different works is systematically put together, an increase in the quantity of lime, leads to a smaller value of stiffness of the mortar, yet no single work was found to focus specifically on the evolution of stiffness of mortar as a function of lime content in the binder with respect to time for long periods of curing [10,12,13]. Research on the topic of evolution of stiffness in lime-cement mixes for early ages has been conducted by the authors of the current work, solely focussing on the first 7 days of curing [14]. With regard to porosity, the general trend found was an increase in open porosity of blended pastes and mortars occurs with increasing quantities of lime in the binder [9,15]. Macharia found that porosity increases with the increase in lime content of the binder up to 45% by mass, followed by a subsequent decrease in porosity [8]. Interestingly, Arandigoyen *et al.* [1] found open porosity (around 20%) to be independent of the lime-cement proportion in the binder. Once again the lack of unanimity in quantitative values of open porosity of lime-cement mortars is evident. Very little work was found to focus on ultrasound pulse velocity (UPV) measurements of lime-cement mortars, far less so, correlating those values with other parameters like mechanical strength or density. The work of Palomar *et al.* [16] explored some of these aspects for a mix 1:1:6 (cement, lime, sand) with regard to porosity, UPV and thermal conductivity but focused primarily on the presence of fibres and clay.

It is widely acknowledged that, for a target value in the flow table test, an increase in the quantity of lime in the binder leads to an increase in the water-binder ratio of the mix which improves its workability [17-19]. This has been attributed to the greater specific surface area of lime (when compared with cement) and subsequently its greater water retention capacity. However, there is not much work available attempting to quantify this impact on water-binder ratio as a function of lime in the binder or binder-aggregate ratio of the mortar, for a targeted workability. This could be useful to create a ‘rule of thumb’ for lab or field work, for a given set of materials.

The influence of aggregates on strength and porosity of lime-cement mortars is far less debated. It is fairly well accepted that an increase in the quantity of aggregates leads to a reduction in strength of lime-cement mortars, increase in open porosity of the mortar and an increase in water-binder ratio of the mortar mix [7,18]. However, a quantitative discussion on this subject was not found.

Based on the literature review conducted, it may be concluded that while some researchers have established a few trends in the mechanical behaviour of lime-cement mortars, there is a general lack of quantification of these parameters as a function of the amount of lime or cement in the binder [4,5,7,20,21]. Furthermore, within the set of empirical observations, certain contradictory trends were discovered, thus justifying the need for a systematic experiment campaign which analyses basic mechanical parameters as a function of lime content in the binder and binder content in the mix. This research work focuses on 14 lime-cement mortars with lime in the binder varying from 10% to 75% and includes binder aggregate ratios of 1:3, 1:4, 1:5 and 1:6, in order to quantify the impact of these variations on mechanical behaviour of masonry mortars. The parameters measured for all 15 mortars include compressive strength, flexural strength, ultrasound velocity and hardened density at 7, 14, 28, 90 and 180 days of curing age. Water binder ratio with respect to a targeted flow table value (175±10 mm) has been expressed as a function of quantity of lime in the binder and binder-aggregate ratio, both by volume. E-modulus and open porosity were measured at 7, 28 and 90 days of curing age for 3 mortar mixes with binder aggregate ratio of 1:3 and varying lime content in the binder. Furthermore, an attempt has been made to obtain correlations between different parameters based on empirical data which may serve as useful rules of thumb on field, counter checks for lab based measurements and associations that may be used in numerical modelling.

2. Materials and research description

2.1 Material description and sample preparation

The choice of materials was guided by representativity of the studied mortars, but also strongly influenced by the aim of repeatability in the experimental campaign. It was necessary to ensure control over different scientific variables involved and therefore the type of cement chosen was Portland cement, CEM I – 42.5R, despite the knowledge that CEM II is more often employed in field applications [4,7]. Based on the composition of different types of cement recommended by EN 197-1 [22], compared to CEM II , CEM I is permitted up to 30% less variation in its additional constituents apart from clinker. This 30% permitted variation includes materials like silica fumes, calcined Pozzolana, burnt shale, limestone and fly ash among others, all of which may themselves have different compositions depending on the location of production. Therefore, CEM I seemed more suited for reducing the number of possible variables in the mortar mixes and increasing chances of reproducibility in this experimental campaign as well as replication by other researchers. Properties of the cement were obtained from the production sheet of the manufacturer for the corresponding batch (ACM-040/2016). The Blaine specific surface and density were 3508 cm^2/g and 3.12 g/cm^3 respectively. The clinker composition consisted of 62.2% of C_3S and 12.6% of C_2S. The bulk density of the material was measured in the laboratory and found to be 0.93 g/cm^3. The type of air lime chosen was CL 90-S. According to the recommendations of EN 459-1 [23], it has the greatest amount of available lime and least amount of variation permitted in other chemical constituents. Once again, the choice was based on being representative and minimizing possible variables in the mortar mixes. The BET specific surface area and density were 150000 cm^2/g and 2.24 g/cm^3 respectively. The mean value of its particle size distribution was reported between 5.5-6.5 μm [PSD – $d_{(laser\ refusal\ at)}$: d_2-90.38%, d_5-60.77%, d_{10}-30.61%, d_{25}-10.90%, d_{32}-8.01%, d_{40}-5.71%, d_{50}-3.78%, d_{63}-2.26%, d_{80}-1.19%, d_{90}-0.82%, d_{125}-0.16%, d_{200}-0.00%]. These properties were obtained for the concerned batch of lime from the production sheet of the manufacturer for the corresponding batch (Control number 90000998782). The bulk density of lime was found to be 0.36 g/cm^3, as measured in the laboratory. Chemical analysis of the type of lime and cement used has been displayed in Table 1, in which LOI refers to loss on ignition. According to the manufacturers, LOI was measured based on the definition of the parameter in EN 459-2:2010 [24].

Table 1: Chemical analysis of the main components of hydrated air lime and Portland cement

	CaO (%)	SiO_2 (%)	MgO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	K_2O (%)	SO_3 (%)	LOI (%)
Lime	74.35	0.12	0.68	0.06	0.05	0.013	0.197	25
Cement	63.4	20.55	1.75	4.27	3.2	0.77	3.05	2.05

Sand with a customized particle range of [0.063,4] mm [Figure 1] was chosen as aggregate, respecting the standard BS 1200-1976 [25]. The bulk density of the aggregate was determined to be 1.60 g/cm^3. Prior to each casting in this experimental campaign, the aggregates were heated at 105°C and cooled down to room temperature overnight, to maintain consistency in the moisture content of the mixes. Similarly, the binder materials were also pre-conditioned in an environment of 20°C for at least 7 days before casting of each new batch of mortar.

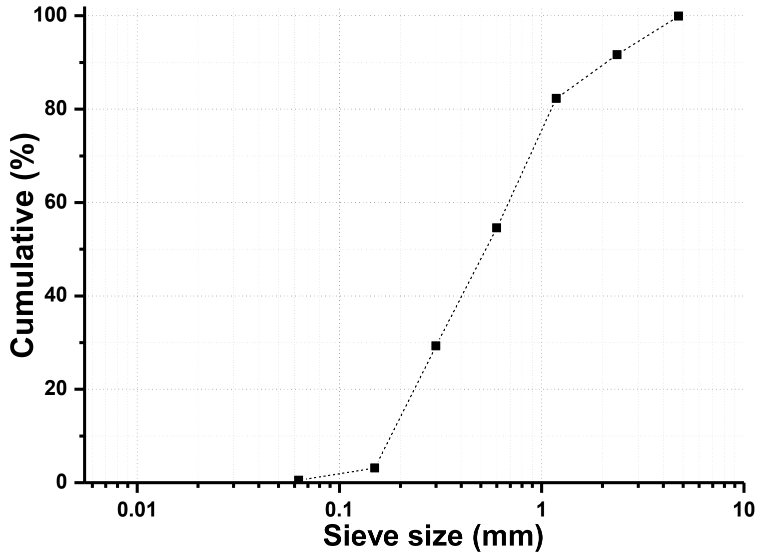

Figure 1: Particle size distribution of aggregate [0.063, 4] mm

Fourteen different lime-cement mix compositions [Table 2] were chosen, to assess mechanical properties of lime-cement blended mortars. Independent variables included lime content in the binder (by volume), binder-aggregate ratio (by volume) and different curing ages (number of days) of the mortar. Binder aggregate ratios of 1:3, 1:4, 1:5 and 1:6 were tested, expressed in % by volume as 33%, 25%, 20% and 17% respectively, while the quantity of lime in the binder was varied from 10% to 75%, by volume. The notations adopted denote the proportion of different constituents of the mix by volume, for example 1C3L12S represents 1:3:12 mix ratio of cement C, lime L and sand S, respectively. Furthermore, to make it convenient for the reader, all graphs have been provided with quantity of lime in the binder (by volume) in parenthesis adjacent to the name of the mix, for example 1C3L12S (75%). All proportions were converted to mass by using apparent densities of cement, lime and sand, for the sake of consistent measurement of raw materials.

Table 2: Composition of blended lime-cement mortars (for 1 m^3 of mortar produced) w/b denotes water-binder ratio

Nomenclature (Lime content by volume %)	Cement:Lime:Sand (Volume)	Binder:Aggregate (Volume)	Cement (kg)	Lime (kg)	Water (kg)	w/b ratio (By weight)	w/b ratio (By volume)
9C1L30S (10%)	9:1:30	1:3	315.2	13.4	288.1	0.88	0.77

3C1L12S (25%)	3:1:12	1:3	262.7	33.4	295.6	1.00	0.79
2C1L9S (33%)	2:1:9	1:3	233.5	44.5	303.1	1.09	0.81
1C1L6S (50%)	1:1:6	1:3	175.1	66.8	303.1	1.25	0.81
1C2L9S (67%)	1:2:9	1:3	116.8	89.0	325.0	1.58	0.87
1C3L12S (75%)	1:3:12	1:3	87.6	100.1	331.2	1.76	0.88
3C1L16S (25%)	3:1:16	1:4	197.0	25.0	300.0	1.35	1.07
2C1L12S (33%)	2:1:12	1:4	175.1	33.4	312.5	1.50	1.11
1C1L8S (50%)	1:1:8	1:4	131.3	50.1	312.5	1.72	1.11
1C2L12S (67%)	1:2:12	1:4	87.6	66.8	300.0	1.94	1.07
2C1L15S (33%)	2:1:15	1:5	140.1	26.7	300.0	1.80	1.33
1C1L10S (50%)	1:1:10	1:5	105.1	40.1	320.6	2.21	1.42
1C2L15S (67%)	1:2:15	1:5	70.1	53.4	293.8	2.38	1.31
1C1L12S (50%)	1:1:12	1:6	87.6	33.4	325.0	2.69	1.73

A target value of 175±10 mm, as per the flow table test [26], was chosen to determine water-binder (w/b) ratios of the mixes. It was important to make the mixes feasible in terms of use on field and this chosen interval of 165-185 mm falls in the range of workability assessed as suitable in the work of Hendrickx [17]. In such work, an international panel of six masons were invited and asked to qualitatively assess the suitability of freshly prepared batches of mortar. They prepared mixes which could be categorized as light, lean, dry or fluid and so on. Light meant that the mortar is easy to stir and apply to the bricks, lean referred to the mortar being poor in binder - dry referred to the mix being too viscous while fluid implied too much water content. Parameters such as the mortar 'sticking to the brick', 'easy to spread on the mortar bed' and 'not stiffening too fast due to loss of water' were also discussed. Taking all such factors into account, the mixes prepared by the masons (which included lime-cement mortars, among others) were tested on the flow table and most suitable mixes were found to range between 155-185 mm.

For all experiments except for E-modulus, prismatic specimens of size (40×40×160) mm^3 were adopted and the mixes were cast and compacted, with equipment specifications as recommended by standard EN 196-1:2005 [27]. In the case of measurement of Young's modulus, cylindrical specimens were cast with diameter 60 mm and height 120 mm. Each cylindrical specimen was subjected to vibration of 10 seconds twice during casting; with the mould first being half filled and consequently completely filled to assist removal of air bubbles. For curing, standard EN 1015-11:1999 [28] was used as a reference, such that the specimens were kept at 20±1°C and 95±5% RH for the first 7 days and thereafter at 20±1°C and 60±5% RH, up to the age of testing. Demoulding was also determined according to standard EN 1015-11:1999 [28], it was done after 2 days for most of the mixes and after 5 days for the mix 1C3L12S (75%) with more than 50% lime in the binder, by mass.

2.2 Details of experiments

Consistency (workability) of all the mixes was measured in the fresh state by using the flow table method recommended by EN 1015-3 [26]. Tests of unconfined uniaxial compressive and flexural strength and measurement of ultrasound velocity and density were carried out for all mixes at 7, 14, 28, 90 and 180 days of curing age. It must be mentioned that despite high lime content (or low B/Ag ratios) in some of the mixes, it was not difficult to test them in flexure or compression in the early ages (7, 14 or 28 days). Some of the mortar specimens had to be handled with extra care, but the test itself was not affected in any of the mixes.

Three point bending test was used to measure flexural strength of the specimens according to standard EN 1015-11 [28]. Three specimens of each mix from the same batch were tested at each age using displacement control at 0.006 mm/s and a preload of 150 N. The resulting halves from the flexural test were used to measure unconfined uniaxial compressive strength. Preload applied was also of 150 N, the load applied was at a rate of 50 N/s and the results were assessed from an average of the 6 halves of the 3 samples tested for flexural strength [28]. In parallel, a set of specimens for each mix, cast on the same day were kept without destruction. These specimens were used for recording change in weight (density) and ultrasound pulse velocity (UPV). UPV was measured along the length of the prismatic specimens (160 mm), using probes that were 25 mm in diameter for emitting and receiving P-waves of

150 kHz frequency. Standard ultrasound (UPV) lab equipment, Pundit (Proceq) was used for this purpose. Static Young's modulus was measured for three mixes with binder-aggregate ratio 1:3, at curing ages of 7, 28 and 90 days using the method of unconfined cyclic compression test adapted from EN 12390-13:2013 for concrete and cement based materials [29]. A pre-load of 50 N was applied on all specimens, followed by four cycles of loading and unloading, each ramp lasting 60 seconds and reaching a maximum load of one-third of the maximum compressive strength of the mix at that age [30]. This value of maximum uniaxial unconfined compressive strength was attained by testing three cylindrical (diameter 60 mm, height 120 mm) specimens at each age prior to measuring E-modulus, using displacement control at a rate of 0.012 mm/s. The loading surface of the specimens was smoothened using epoxy resin, to ensure even application of load, since a cutting machine could cause micro-cracks along the length of the specimens.

Open porosity was measured at 7, 28 and 90 days of curing age for three mixes with binder-aggregate ratio 1:3 and lime content 25%, 50% and 67% by volume. The principle of measurement was based on the RILEM recommendations by RILEM TC 25-PEM for deterioration of stone, which measures the percentage of pores accessible to water as a proportion of the bulk volume of the sample [31]. However, duration of subjecting the specimens to vacuum and immersion in water was modified to 3 hours from 24 hours, tailored for mortars.

2.3 Assessment of repeatability

A set of 3 specimens from each mix were kept aside for testing UPV and density at each curing age up to 180 days. Specimens that were used for measuring compressive strength were also used to measure UPV. The aim was to check the difference in UPV obtained from the two different sets of the same mix at the same curing age, as a means of quality control or repeatability within the same batch of each mix. The difference in UPV values of the different batches was mostly found to be less than 5% for most mixes, in some cases extending up to 13% (for less than 10 data points). These mixes happened to have either large quantities of lime in the binder or high binder-aggregate (B/Ag) ratios. Similarly, in order to be sure of repeatability in measurement of compressive strength, two different mixes with less than and more than 50% lime content, namely 2C1L9S (33%) and 1C2L9S (67%) were tested on two different occasions, curing ages of 15 days and 7 days respectively. The difference in the two batches of 1C2L9S (67%) was found to be 1.5% and for 2C1L9S (33%) was found to be 0.6%. Both these differences may very well lie in the range of individual variation of any mortar mix tested for compressive strength even in early ages [Table 3]. From a scientific point of view, it was thus found acceptable to correlate different properties of UPV, compressive strength and density of the same mixes cast on the same day but in different batches.

2.4 Representation of different factors used in analysis

Results collected from each test have been treated to identify potential patterns and correlations between different properties. For each parameter tested, the experimental value has been considered as the dependent variable and the independent variables included one, some or all of the following; Lime content in the binder expressed in % by volume, binder-aggregate ratio (B/Ag) expressed in % by volume (i.e. mix with B/Ag ratio of 1:4 is $\frac{1}{4}$ = 0.25 or 25%) and the curing age (expressed in number of days) at which the test has been conducted. Wherever relevant, average values of results have been supplemented with coefficient of variation (CoV) in paranthesis. Wherever the term reference has been used, it refers to the mix with maximum strength in the corresponding context, to normalize values and subsequently facilitate comparison. If the primary variable is lime content in the binder, the reference is the mix with 10% lime or 90% cement in its binder (by volume), regardless of the B/Ag ratio used. For example, in the case of 1:3 B/Ag ratio, the reference would be 9C1L30S (10%). The reason for choosing such reference was also that, for a given B/Ag ratio, it is similar to the composition of a cement mortar (which would have 0% lime in the binder) and yet may retain the label of lime-cement masonry mortar from a practical point of view. If the primary variable is B/Ag ratio instead, the reference would be the mix with maximum B/Ag ratio 1:3, regardless of the quantity of lime in the binder. Furthermore, any (single or multiple) linear regression performed in this work, which had more than 3 data points resulted in a p-value notably less than 0.05, indicating statistical significance of the result [32]. The tests also resulted in high F-values, much greater than 1 (in all scenarios), further emphasizing the statistical significance of their results [32]. However, when regression was performed with three data points, the p-value exceeded 0.05 in some cases, despite reasonable R^2 values (generally > 0.94, in some cases ranging till 0.85). The data was not rejected in these cases because p-value is calculated from R^2 values and sample size, and having only 3 data points would require exceptionally high R^2 values to result in p-values less than 0.05. Since inadequacy of data points in these cases could lead to unreliable conclusions based on p-values, values > 0.05 were also considered acceptable.

3. Results and discussion

3.1 Consistency and associated water-binder ratio

For each mix composition, several trials were carried out to assess the quantity of water required to attain a workable (175±10 mm) mortar. It was observed that for the same B/Ag ratio, the requisite water for the mix changed each time the quantity of lime in the binder was varied. It was possible to identify a linear pattern which related the amount of lime in the binder (by mass) with the water-binder ratio [Figure 2]. It was also discovered that each time the binder-aggregate ratio was changed; the linear relation had to be recalibrated. In fact, if the quantity of lime in the binder was kept constant and the B/Ag ratio was changed, it was possible to observe the influence of the latter on the w/b ratio required to attain the target flow value. And therefore, a multiple linear regression was performed and Equation 1 is presented to correlate the quantity of lime in the binder and the B/Ag ratio with the water-binder ratio of each mix (R^2=0.93, p-value=1.803E-7, F-value=87.07).

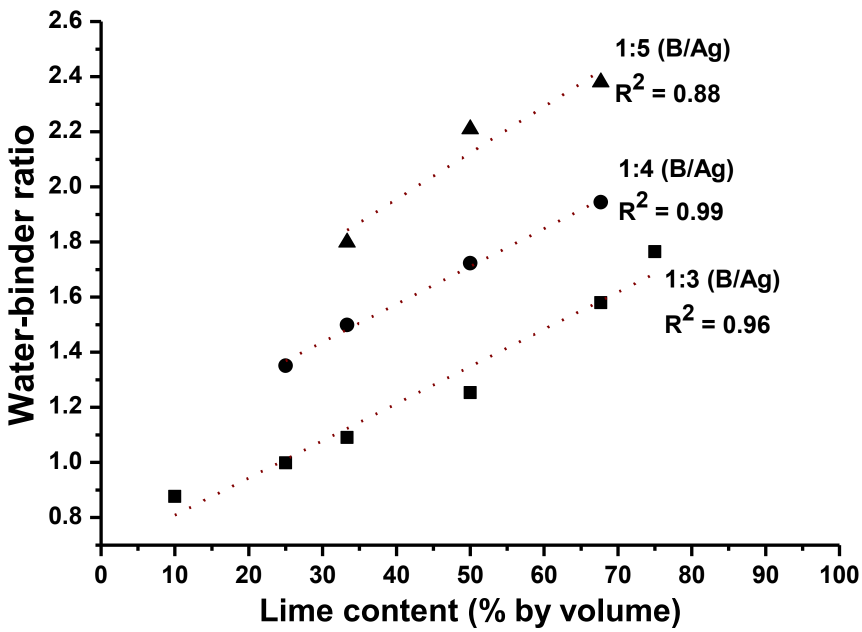

Figure 2: Water-binder ratio of mix expressed as a function of lime content in the binder (by volume) in the workability range of 175±10 mm (measured in flow table test)

$$\frac{w}{b} = 2.715 + 0.014\,x - 0.063\,z \qquad (1)$$

Where $\frac{w}{b}$ indicates the water-binder ratio (by weight), x is $\frac{\text{Lime}}{\text{Lime+Cement}} \times 100$, the amount of lime in the binder (% by volume) and z is $\frac{\text{Binder}}{\text{Aggregate}} \times 100$ (by volume). Predicted values from this equation were compared with actual values used to define this equation, and the maximum error was found to be less than 10% in most cases, except for the mix 9C1L30S (10%) in which the error went up to ~15%. Input data for this equation consisted of all 14 mixes.

It must be mentioned that the relationship presented [Equation 1], is valid only for the materials tested. If the nature of any of the materials is changed (lime, cement or sand) or if other conditions such as ambient temperature or relative humidity are varied, the equation must be recalibrated. The purpose of this relation is to help the practitioner to adopt a thumb rule in the field or in the lab. This might reduce the numerous trials that are required for arriving at a 'desirable' consistency of a workable mix [17].

3.2 Compressive strength

The values of compressive strength obtained in this experimental campaign range from 0.4 to 13 MPa [Table 3]. It was important to verify if these values were realistic for the set of chosen parameters and therefore comparison with existing literature was performed. It is recognized that a direct comparison is not possible because among other factors, different researchers use different types of lime or cement. However, an assessment of the general ranges of data is feasible. Arandigoyen *et al.* [7] present one of the widest range of data of compressive strength of lime-cement blended mortars, but they seem to be higher (5-13 MPa) than those obtained here (2-9 MPa, for the corresponding mixes tested in this campaign). The reason for this could be the use of a lower water-binder ratio and consequently lower value of workability obtained by them. It is difficult to verify this because it has not been mentioned explicitly. Values presented by Cizer [9] seem to be in the range of 5-35 MPa, considerably higher than those presented here. But the flow value was targeted is between 120-130 mm which could explain the difference, since the lower the amount of water used in the mix, the greater is the strength of the mix obtained [18]. Data on blended lime-cement mortars presented by Haach *et al.* was found to be similar to the values obtained in this experimental campaign for approximately the same consistency [10,18].

Table 3: Compressive strength (f_c) of lime-cement blended mixes at different dates (7, 14, 28, 90 and 180 days). CoV is the coefficient of variation

Mix	f_c [MPa]	%	f_c [MPa]	%	f_c [MPa]	%	f_c [MPa]	%	f_c [MPa]	%

(Lime content)	7d	CoV	14d	CoV	28d	CoV	90d	CoV	180d	CoV
9:1:30 (10%)	8.94	3.6	10.64	9.6	12.11	4.4	12.22	8.0	11.29	7.4
3:1:12 (25%)	7.66	3.5	9.91	5.0	9.95	3.6	9.28	0.6	9.92	6.3
2:1:9 (33%)	6.09	2.8	7.36	4.9	8.13	6.6	8.57	6.0	8.73	9.7
1:1:6 (50%)	4.12	5.5	5.41	8.8	4.68	6.3	6.23	6.9	6.31	3.9
1:2:9 (67%)	1.48	6.7	1.89	29.0	2.39	2.6	2.45	6.7	2.69	10.5
1:3:12 (75%)	0.63	9.0	1.16	7.2	1.37	3.3	1.53	3.1	1.55	6.7
3:1:16 (25%)	4.59	6.6	6.46	1.4	6.02	2.1	7.05	4.8	7.85	3.5
2:1:12 (33%)	3.23	5.7	5.03	3.2	5.09	9.5	5.73	3.5	6.34	2.6
1:1:8 (50%)	2.31	1.1	3.12	8.7	3.00	8.2	3.53	5.4	3.09	9.6
1:2:12 (67%)	0.77	7.0	1.37	6.6	1.42	9.0	1.19	12.0	1.45	6.1
2:1:15 (33%)	1.86	13.0	2.83	9.5	3.08	7.6	3.26	12.4	3.69	10.1
1:1:10 (50%)	1.31	3.2	1.77	15.6	1.59	18.9	1.74	17.9	1.99	5.0
1:2:15 (67%)	0.46	8.0	0.83	8.9	0.86	7.0	0.86	8.6	0.89	12.8
1:1:12 (50%)	0.85	12.2	1.34	22.2	1.39	17.5	1.19	12.0	1.34	14.9

3.2.1 Impact of lime content in binder

For a given B/Ag ratio, 1:3 ratio in [Figure 3], compressive strength has been expressed as a function of the amount of lime in the binder for different curing ages tested; 7, 14, 28 , 90 and 180 days. The reference at each curing age, as mentioned in Section 2.3 corresponds to the strength of the mix with 10% lime in its binder, in this case 9C1L30S (10%). The y-axis corresponds to compressive strength (MPa) denoted by f_c and the x-axis corresponds to lime content in the binder (% by volume) also denoted by x. The slope of each line denotes the change in value of compressive strength for unit change in lime content (% by volume) of the binder. The slope obtained was normalized by dividing it with the strength of the reference mix, for each case. This has been expressed as ΔStrength (%) which is the (slope/strength of reference mix). The slope or 'change in strength of mortar for unit change in lime content in binder' was normalized (with the strength of the reference mix in each case) in order to facilitate comparison at different ages. Since the strength of the mixes evolves with time, comparison of absolute values of slopes (changes in strength) could lead to potentially misleading conclusions. Furthermore, normalizing the change in strength also permitted comparison of mixes with the same binder compositions, across different B/Ag ratios.

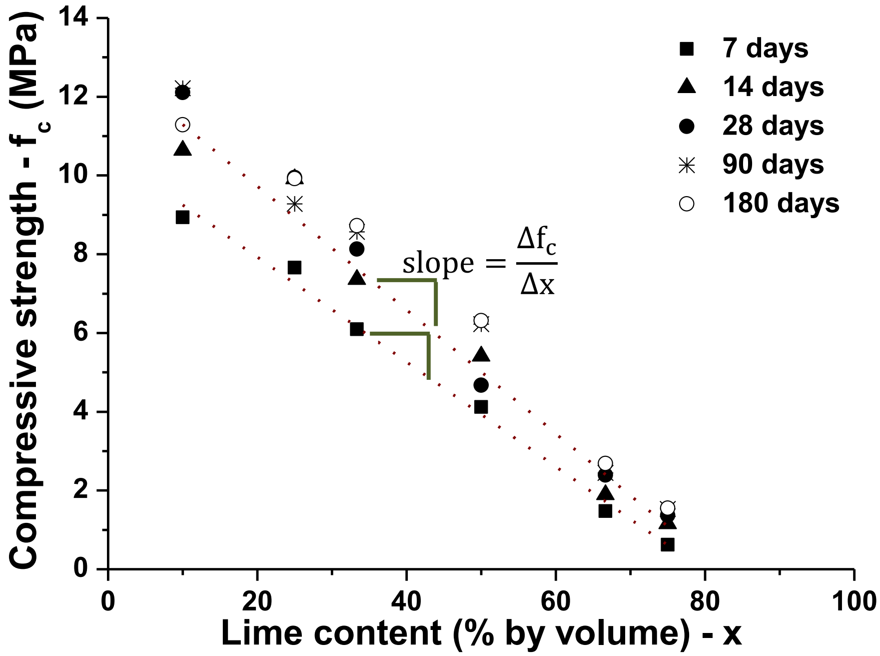

Figure 3: Compressive strength expressed as a function of lime content in the binder (by volume), for B/Ag ratio 1:3 (by volume)

For a given B/Ag ratio and curing age, Table 4 quantifies how much the strength of a mix is expected to change with respect to the reference mix (10% lime in the binder), as a function of the lime content in its binder. For 1:3 B/Ag ratio 7 mixes were used (10% to 75% lime content) for the linear regressions at each age, for 1:4 B/Ag ratio 4 mixes were used (25% to 67% lime content) and for 1:5 B/Ag ratio, 3 mixes were used (33% to 67% lime content) at each curing age. R^2 and ΔStrength (%) values for each case have been presented in Table 4. These values make it possible to theoretically estimate the strength of a mix with a specified quantity of lime in the binder at a chosen curing age or B/Ag ratio if the strength of the reference mix (10% lime in the binder) has been tested. For example, at the age of 90 days, for a B/Ag ratio 1:3, the change in strength is specified as -1.28% in Table 4. This implies that 1% increase of lime in the binder, leads to 1.28% lower strength than the reference mix. So if the strength of the reference mix (9C1L30S (10%)) is tested at 90 days of age (12.22 MPa), and the strength of a mix with 50% lime in the binder is to be estimated (1C1L6S (50%)), then the increase in lime content is 50-10=40%, then the change in strength should be 40*(-1.28) = -51.2%, i.e. 12.2 – (51.2%*12.2) = 5.96 MPa. The actual value recorded from the test was 6.22 MPa. Difference in the measured and estimated value is less than 5%. Furthermore, it is possible to observe that regardless of the curing age, the change (%) in strength was not very different; 1.4% for B/Ag ratio 1:3 and 1.5% for B/Ag ratios 1:4 and 1:5, for every 1% increase in lime content of the binder. As a conclusion from all mixes, on average, 1% increase of lime in the binder by volume, leads to 1.4% loss in compressive strength.

Table 4: Data showing change (%) in compressive strength of different mixes, normalized with respect to reference for 1% increase of lime content in binder (as a function of lime content in binder)

Change (%) in strength of mixes with respect to reference, for every 1% increase in lime content						
Reference mix – 10% lime or 90% cement in binder (by volume)						
Fixed - B/Ag	1:3		1:4		1:5	
Data points – Lime content (vol%)	10, 25, 33.3, 50, 66.7, 75, 90		25, 33.3, 50, 66.7		33.3, 50, 66.7	
Age	R^2	ΔStrength (%)	R^2	ΔStrength (%)	R^2	ΔStrength (%)
7	.99	-1.44	.97	-1.53	.98	-1.45
14	.98	-1.39	.99	-1.49	.99	-1.42
28	.99	-1.41	.99	-1.46	.96	-1.48
90	.99	-1.35	.99	-1.53	.98	-1.49
180	.98	-1.31	.98	-1.57	.98	-1.51
Average of all ages (CoV)	.99(.8%)	-1.38(3.7%)	.99(1.3%)	-1.52(2.8%)	.98(1.3%)	-1.47(2.3%)

3.2.2 Impact of binder aggregate ratio

Similar regression analyses were performed to assess the impact of B/Ag ratio, by expressing compressive strength as a function of B/Ag ratio, at different curing ages for certain lime contents in the binder, i.e. 33%, 50% and 67% by volume. An example has been shown for 50% lime content in the binder [Figure 4] where the y-axis is the compressive strength (MPa) denoted by f_c and the x-axis corresponds to B/Ag ratio, expressed in % and denoted by z. The slope of each line denotes the change in value of compressive strength for unit change in binder content (%

by volume) in the mix. Once again, since the slope obtained is in absolute values of MPa, it was normalized by dividing it with the strength of the reference mix, for each case. This has been expressed as ΔStrength (%) which is the (slope/strength of reference mix).

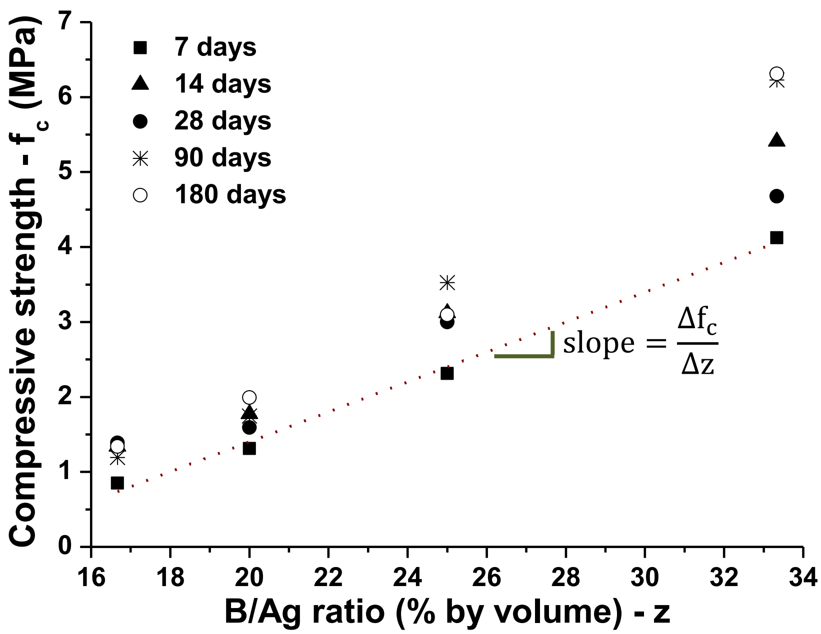

Figure 4: Compressive strength expressed as a function of B/Ag ratio of the mix (by volume), with 50% lime in the binder (by volume)

R^2 values and change in strength of mortar associated with every 1% decrease in binder content of the mix, for each of the cases has been displayed in Table 5. It may be possible to generalize and state that regardless of the age of the mix and the quantity of lime in it, every 1% decrease in the B/Ag ratio of the mix (% by volume) leads to approximately 5% lower strength of the mortar, with respect to the reference mix with 1:3 B/Ag ratio [Table 5]. Again it is noted that such results are valid only for the data presented in this work and may not be extrapolated beyond the mentioned range, without further testing.

Table 5: Data showing change (%) in compressive strength of different mixes, normalized with respect to reference for 1% decrease in B/Ag ratio

Change (%) in strength of mixes with respect to reference, for every 1% decrease in B/Ag ratio (% by volume)
Reference mix – B/Ag ratio 1:3 or 33%

Fixed - Lime content (vol%)	33		50		67	
Data points – B/Ag	1:3, 1:4, 1:5		1:3, 1:4, 1:5, 1:6		1:3, 1:4, 1:5	
Age	R^2	ΔStrength (%)	R^2	ΔStrength (%)	R^2	ΔStrength (%)
7	.99	-5.30	.99	-4.91	.99	-5.29
14	.98	-4.46	.99	-4.72	.98	-4.04
28	.99	-4.63	.98	-4.46	.99	-4.85
90	.99	-4.52	.99	-5.06	.97	-5.12
180	.97	-4.13	.98	-4.96	.99	-5.31
Average of all ages (CoV)	.99(1.2%)	-4.61(9.3%)	.98(1.6%)	-4.82(4.9%)	.98(1.07)	-4.92 (10.7%)

3.2.3 Global analysis

After treatment of compressive strength as a function of individual parameters, an attempt was made to express compressive strength as a function of all three relevant factors, namely lime content in the binder (% by volume), curing age (number of days) and binder content in the mix (% by volume). 13 mix compositions were tested at 5 different ages to obtain this relationship [Equation 2]. The mix 1C1L12S (50%) was not taken into account in this regression because it was the only one with a B/Ag ratio of 1:6.

$$f_c = \gamma\,(-\,0.1296\,x + 0.3556\,z + 0.0084\,t) \qquad x \le 50\%;\ \{R^2 = 0.94,\ F = 1100,\ p \sim 0\}$$
$$f_c = \gamma\,(-\,0.0085\,x^{1.5} + 1.112z^{0.5} + 0.0554\,t^{0.5}) \qquad x > 50\%;\ \{R^2 = 0.85,\ F = 232,\ p \sim 0\} \qquad (2)$$

Where the dependent variable represents the compressive strength, the first independent variable x represents the amount of lime in the binder {10, 25, 33, 50, 67, 75} (% by volume), the second independent variable z is the B/Ag ratio {1:3, 1:4, 1:5}, expressed in % (by volume), the third independent variable is time {7, 14, 28, 90, 180} expressed in number of days (curing age), and γ is a coefficient of prediction or safety, in this case of general prediction it is equal to 1. It may be observed that for equal to or less than 50% lime in the binder, compressive strength is linearly dependent on B/Ag ratio, time of testing and lime content in the binder. However, for more than 50% lime in the binder, the relationship is non-linear and may be expressed as a power law [Equation 2]. The maximum absolute error with regard to Equation 2 was ~ ±1.5 MPa [Figure 5]. Since, this equation was obtained from fitting of data, the error between values predicted from the regression and experimental values can be positive or negative [Figure 5]. Therefore, to ensure that the predicted values are lower than the experimental values in more than 95% of the cases, the coefficient (γ) may be employed to provide a lower bound of prediction, equal to 0.7 in this case.

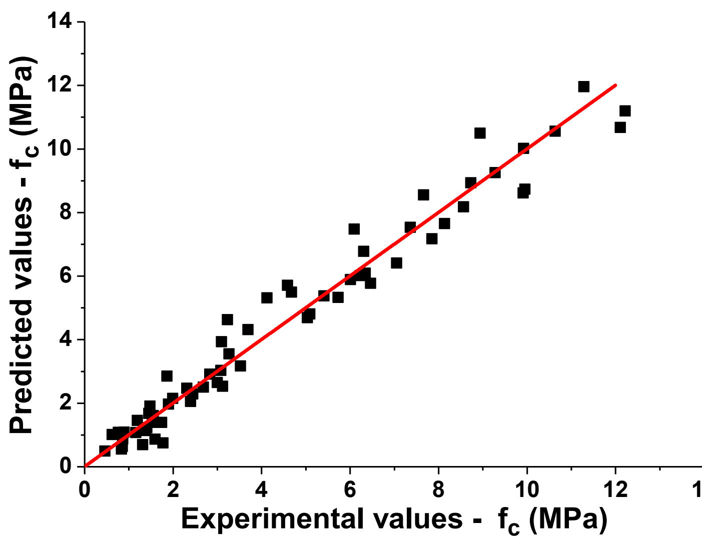

Figure 5: Comparison of experimental and predicted values (from Equation 2) of compressive strength (MPa)

3.3 Flexural strength

Globally, it may be observed that the values of flexural strength obtained in this experimental campaign range from 0.04 to 4 MPa [Table 6]. As pointed out in the section of compressive strength [Section 3.2, Table 4], it is necessary to check if the values obtained were realistic or not, for a given set of conditions. Once again it was found that if similar consistency (flow value) is targeted, flexural strength attained in blended lime-cement mortars falls in the range of data found in the current experimental campaign, as observed from the work of Macharia [8].

Table 6: Flexural strength (f_f) of lime-cement blended mixes with coefficients of variation

Mix (Lime content)	f_f [MPa] 7d	%CoV	f_f [MPa] 14d	%CoV	f_f [MPa] 28d	%CoV	f_f [MPa] 90d	%CoV	f_f [MPa] 180d	%CoV

9:1:30 (10%)	2.67	0.10	3.15	0.04	3.89	0.12	3.15	0.12	3.75	0.07
3:1:12 (25%)	1.95	6.60	2.58	2.70	2.76	7.02	3.22	4.47	3.64	4.22
2:1:9 (33%)	1.52	5.64	2.32	0.87	2.60	8.59	2.52	2.59	3.03	5.54
1:1:6 (50%)	1.23	4.84	1.69	4.04	1.96	5.97	2.14	6.69	2.31	2.01
1:2:9 (67%)	0.41	7.70	0.70	11.25	0.69	4.50	0.86	6.29	0.99	2.90
1:3:12 (75%)	0.28	4.50	0.44	10.83	0.48	15.96	0.58	7.62	0.61	10.46
3:1:16 (25%)	1.23	2.31	1.72	11.22	2.10	6.55	2.35	12.64	2.95	3.43
2:1:12 (33%)	1.12	9.30	1.50	6.41	2.09	1.65	2.09	2.54	2.26	9.87
1:1:8 (50%)	0.70	10.18	0.95	17.31	1.08	11.92	1.20	3.93	1.24	4.74
1:2:12 (67%)	0.30	6.11	0.53	8.14	0.52	10.24	0.50	0.55	0.51	13.68
2:1:15 (33%)	0.66	5.05	0.99	9.18	1.16	0.84	1.26	6.80	1.30	7.24
1:1:10 (50%)	0.37	14.65	0.58	10.97	0.64	3.31	0.66	13.85	0.74	8.99
1:2:15 (67%)	0.21	2.87	0.34	14.31	0.35	37.89	0.36	10.10	0.39	14.82
1:1:12 (50%)	0.29	3.40	0.42	20.91	0.50	17.31	0.48	9.72	0.51	11.69

3.3.1 Impact of lime content in binder

Data for flexural strength was assessed in the same way as for compressive strength with the first variable being lime content in the binder. To illustrate the same, an example has been provided, for B/Ag ratio 1:3 with flexural strength varying as a function of lime content in the binder (by volume) for different curing ages (7, 14, 28, 90 and 180 days) [Figure 6]. Plots similar to Figure 6 may be drawn for B/Ag ratios 1:4 and 1:5. In each case the reference mix would have 90% cement in the binder (by volume).

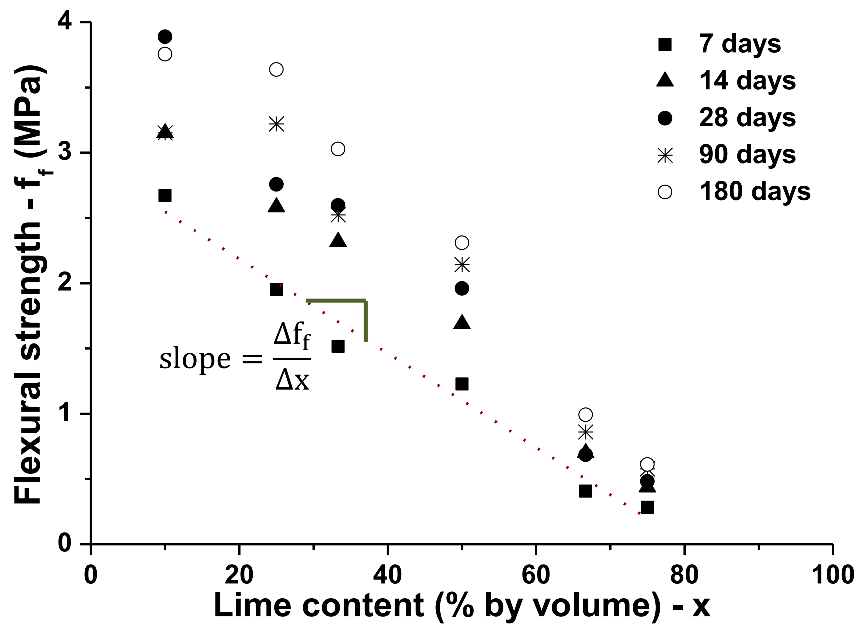

Figure 6: Flexural strength expressed as a function of lime content in the binder (by volume), for B/Ag ratio 1:3 (by volume)

Again the slope of each line [Figure 6] denotes the change in flexural strength of a mix with respect to the reference mix, for every 1% increase in the lime content of the binder (by volume). If the slope is divided by the strength of the reference mix in each case and expressed in % as ΔStrength (%), normalized change in strength may be obtained for different scenarios. Table 7 displays this data for B/Ag ratios 1:3, 1:4 and 1:5 for 5 different curing ages. Linear regression was performed for the mixes and the corresponding R^2 values have also been presented. It appears that regardless of the curing age at which the test is performed, every 1% increase in the quantity of lime in the binder, leads to approximately 1.3%, 1.5% and 1.4% change in strength of the mix for B/Ag ratios of 1:3, 1:4 and 1:5 with a reference mix that has 10% lime in its binder. As a conclusion from all mixes, on average, 1% increase of lime in the binder by volume, leads to 1.4% loss on the flexural strength, similar to compressive strength.

Table 7: Data showing change (%) in flexural strength of different mixes, normalized with respect to reference for 1% increase of lime content in binder (As a function of lime content in binder)

Change (%) in strength of mixes with respect to reference, for every 1% increase in lime content			
Reference mix – 10% lime or 90% cement in binder (by volume)			
Fixed - B/Ag	1:3	1:4	1:5

Data points – Lime content (vol%)	10, 25, 33, 50, 67, 75, 90		25, 33, 50, 67		33, 50, 67	
Age	R^2	ΔStrength (%)	R^2	ΔStrength (%)	R^2	ΔStrength (%)
7	.98	-1.42	.99	-1.42	.97	-1.42
14	.99	-1.32	.99	-1.35	.98	-1.37
28	.98	-1.36	.96	-1.46	.97	-1.44
90	.93	-1.23	.99	-1.48	.97	-1.47
180	.96	-1.26	.99	-1.57	.98	-1.43
Average of all ages (CoV)	.97(2.4%)	-1.32(5.6%)	.99(1.5%)	-1.46(5.5%)	.97(0.6%)	-1.43(2.5%)

3.3.2 Impact of B/Ag ratio

Linear regression analyses were performed and flexural strength was expressed as a function of B/Ag ratio for different curing ages. An example has been presented for 50% lime content in the binder [Figure 7] where the y-axis is the flexural strength (MPa) denoted by f_f and the x-axis corresponds to B/Ag ratio, expressed in % and denoted by z. Similar plots may be obtained if lime content in the binder is fixed at 33% or 67%. Regardless of the lime content, the reference is treated as the mix with B/Ag ratio 1:3 (ratio expressed as 33%) by volume. In Figure 7, for each case ΔStrength (%) was calculated by normalizing the slope, i.e. slope divided by the strength of the reference mix, expressed in percentage.

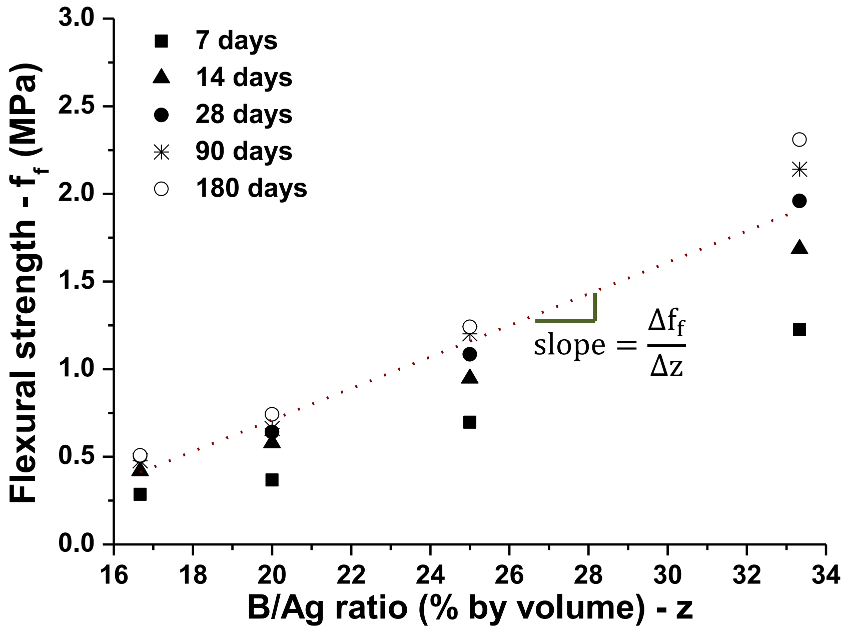

Figure 7: Flexural strength expressed as a function of quantity of binder in the mix (by volume), for 50% lime in the binder (by volume)

Table 8 summarizes how much the strength (ΔStrength (%)) of a mortar will change with respect to the reference mix for every 1% decrease in B/Ag ratio of the mix (% by volume). It may be noted that when the lime content in the binder is 33% or 67%, the change in strength of the mortar is approximately 4% and when the lime content is 50%, the change is approximately 5%, for 1% decrease in B/Ag ratio of the mix. The reference in this case would be the mix with B/Ag ratio 1:3 (expressed as 33%) by volume. As a conclusion from all mixes, on average, 1% decrease in B/Ag ratio if the mix by volume, leads to 4.5% loss on the flexural strength, so a value of 5% may be assumed, similar to compressive strength.

Table 8: Data showing change (%) in flexural strength of different mixes, normalized with respect to reference for 1% decrease in B/Ag ratio (expressed in % by volume)

Change (%) in strength of mixes with respect to reference, for every 1% decrease in B/Ag ratio (% by volume) Reference mix – B/Ag ratio 1:3 or 33%						
Fixed - Lime content (%)	33.33		50		66.67	
Data points – B/Ag	1:3, 1:4, 1:5		1:3, 1:4, 1:5, 1:6		1:3, 1:4, 1:5	
Age	R^2	ΔStrength (%)	R^2	ΔStrength (%)	R^2	ΔStrength (%)

7	.97	-4.02	.99	-4.86	.99	-3.58
14	.99	-4.29	.99	-4.69	.96	-3.67
28	.91	-3.82	.98	-4.71	.98	-3.48
90	.90	-3.47	.99	-4.88	.99	-4.52
180	.96	-4.06	.99	-4.88	.96	-4.81
Average of all ages (CoV %)	.94(4.52)	-3.93(7.81)	.99(0.27)	-4.80(1.92)	.98(1.41)	-4.01(15.15)

3.3.3 Global analysis

Again an attempt was made to express this range of values as a function of curing age (number of days), binder aggregate ratio by volume (B/Ag ratio) and lime content in binder (by volume) [Equation 3].

$$f_f = \gamma\,(-\,0.03612\,x + 0.1032\,z + 0.0046\,t) \qquad x \leq 50\%;\ \{R^2 = 0.90,\ F = 694,\ p \sim 0\}$$

$$f_f = \gamma\,(-\,0.0024\,x^{1.5} + 0.3117\,z^{0.5} + 0.0862\,t^{0.3}) \qquad x > 50\%;\ \{R^2 = 0.81,\ F = 231,\ p \sim 0\} \qquad (3)$$

Where the dependent variable represents the flexural strength, the first independent variable x represents the amount of lime in the binder {10, 25, 33, 50, 67, 75} (% by volume), the second independent variable z is the B/Ag ratio {1:3, 1:4, 1:5}, expressed in % (by volume), the third independent variable is time {7, 14, 28, 90, 180} expressed in number of days (curing age), and γ which may be considered as a coefficient of prediction is equal to 1 for general fitting of the data. The B/Ag ratio 1:6 was not considered in the regression either, since only one mix was tested with this composition, namely 1C1L12S (50%). The nature of the relationship for flexural strength was found to be of exactly similar to that of compressive strength; linearly dependent on B/Ag ratio, time of testing and lime content in the binder for equal to or less than 50% lime in the binder and non-linear for more than 50% lime in the binder (expressed as a power law) [Equation 3]. The maximum absolute error with regard to Equation 3 was ~ ±0.7 MPa [Figure 6]. Again, to ensure a lower bound of predicted values in more than 95% of the cases, the coefficient (γ) may be employed to provide a lower bound of prediction, equal to 0.7 in this case as well.

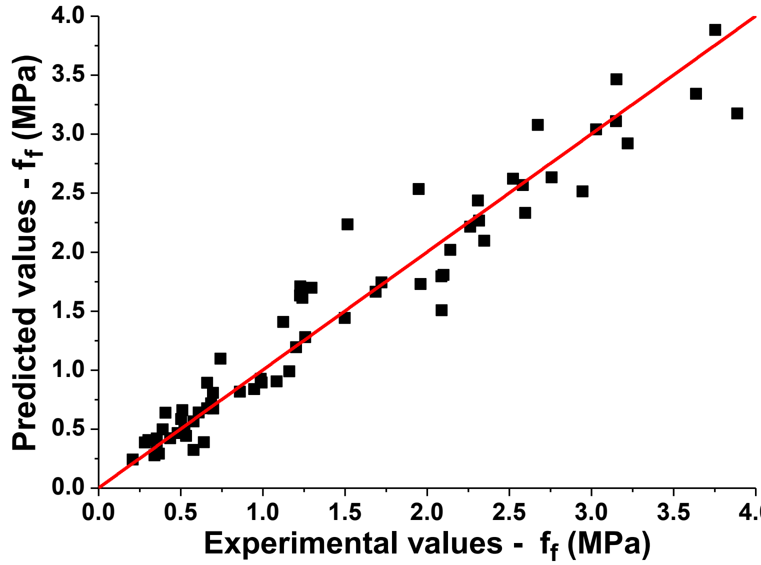

Figure 8: Comparison of experimental and predicted values (from Equation 2) of flexural strength (MPa)

3.4 Correlation between compressive strength and flexural strength

Using the 70 input points available, an attempt was made to find a relation between compressive and flexural strength [Table 9]. It was discovered that compressive strength divided by flexural strength gave an approximate value of 3 for almost all the 70 data points. The value of the fraction mostly varied between 2.5 and 3.5 depending on the curing age. The values were averaged over different curing ages and have been presented for each mix with the respective coefficient of variation, which does not exceed 16% for any mix.

Table 9: Values of f_c/f_f for lime-cement blended mixes

Average value of f_c/f_f at each curing age for different mixes								
Mix (Lime content)	B/Ag (Vol)	7d	14d	28d	90d	180d	Average	CoV
9:1:30 (10%)	1:3	3.34	3.38	3.11	3.88	3.01	3.34	10.0%
3:1:12 (25%)	1:3	3.93	3.84	3.61	2.88	2.73	3.40	16.4%
2:1:9 (33%)	1:3	4.02	3.18	3.13	3.40	2.88	3.32	13.0%
1:1:6 (50%)	1:3	3.36	3.21	2.39	2.91	2.73	2.92	13.2%
1:2:9 (67%)	1:3	3.63	2.71	3.49	2.85	2.71	3.08	14.5%
1:3:12 (75%)	1:3	2.21	2.65	2.84	2.65	2.55	2.58	9.0%

3:1:16 (25%)	1:4	3.73	3.75	2.86	3.00	2.67	3.20	15.8%
2:1:12 (33%)	1:4	2.87	3.36	2.44	2.75	2.80	2.84	11.7%
1:1:8 (50%)	1:4	3.32	3.29	2.77	2.93	2.49	2.96	11.9%
1:2:12 (67%)	1:4	2.53	2.57	2.69	2.37	2.85	2.60	6.9%
2:1:15 (33%)	1:5	2.82	2.87	2.65	2.59	2.85	2.76	4.5%
1:1:10 (50%)	1:5	3.57	3.07	2.48	2.64	2.68	2.89	15.2%
1:2:15 (67%)	1:5	2.22	2.45	2.41	2.44	2.29	2.36	4.2%
1:1:12 (50%)	1:6	2.98	3.20	2.76	2.50	2.64	2.82	9.8%

Furthermore, all the values of f_c/f_f are averaged for each B/Ag ratio and are presented with the respective coefficients of variation [Table 10]. It is possible to observe that the ratio of compressive to flexural strength moved from 3 to 2.7 with a decrease in the quantity of binder in the mix, i.e. 1:3 to 1:5. The B/Ag ratio 1:6 was not included in Table 10 because only one data point was available in such case. This thumb rule could prove useful as a counter check for experimental results.

Table 10: Averaged values of f_c/f_f for lime-cement blended mixes as a function of B/Ag ratio for different proportions of lime content in the mixes

Averaged value of f_c/f_f at all ages (7, 14, 28, 90 and 180 days)		
B/Ag ratio	Average	CoV
1:3	3.11	10.2%
1:4	2.90	8.6%
1:5	2.67	10.2%

3.5 UPV measurements

While UPV serves as a good complementary method to follow the general trend of setting or hardening kinetics of different mixes, the method by itself does not really provide direct quantitative assessment of the stiffness of the material being tested [33,34]. In this experimental campaign, it was found that for any given B/Ag ratio, as the content of lime in the binder increases, UPV and compressive strength both decrease. However, when any single mix was tested over time, UPV was not found to be proportional to compressive strength. In order to find a direct relationship, the density of each mix was also taken into account. It was found that at each curing age - t (expressed in number of days) and for any given B/Ag ratio, it was possible to find a linear relationship between a function of UPV (m/s) and a function involving the compressive strength (f_c in MPa) and density (ρ in kg/m^3) of the hardened mix. An example of this has been provided in Figure 9, where the y-axis corresponds to $Y(t) = UPV(t)^2$ the x-axis corresponds to $X(t) = \rho(t)^{1.5} f_c(t)^{0.5}$ and t = 14 days. The inspiration for this relation stems from knowledge of basic mechanics [35] where the square of UPV is directly proportional to Young's modulus (E) and from knowledge of behaviour of concrete [36,37] where the product $\rho^a f_c^{\,b}$ is proportional to Young's modulus (E) (where values of a and b proposed may vary, but are commonly equal to 0.5). However, for the experimental data obtained from this research, the product $\rho^{1.5} f_c^{\,0.5}$ was found to be the most suitable fit.

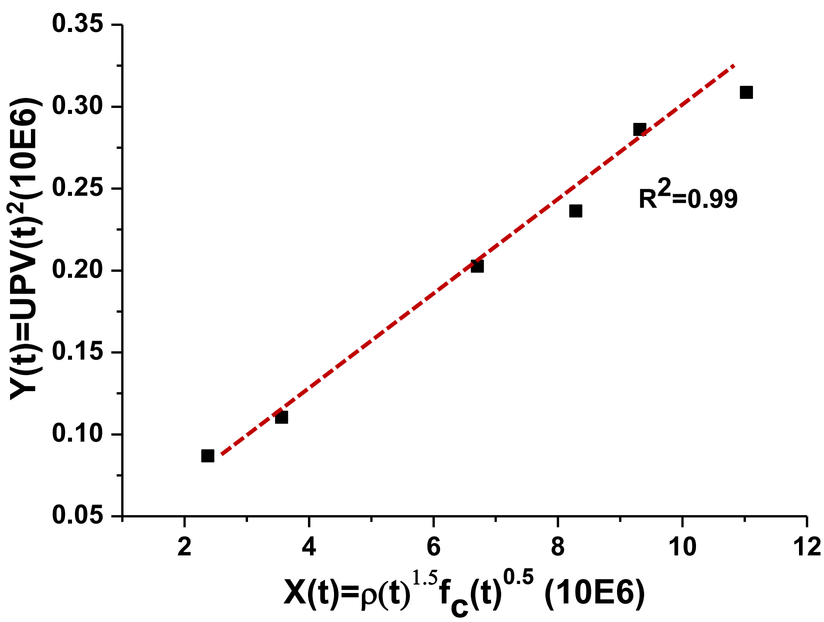

Figure 9: Correlation between ultrasound velocity and a function of density and compressive strength as a function of varying lime content (by volume) at t = 14 days of age, with binder aggregate ratio 1:3

Keeping the B/Ag ratio constant, the relationship [Figure 9] was tested at different curing ages as a function of lime content in the binder for different mixes [Table 11]. It may be noted that almost all R^2 values are above 0.97 except for two values of 0.94. However, when the same principle was applied as a function of binder content in the mixes (B/Ag ratio) keeping the lime content constant, the R^2 values were found to be lower [Table 12]. Most of the R^2

values were found to be above 0.95 implying a good linear fit of the data. Some of the R^2 values were found to be as low as 0.85. There was only one R^2 value which was found to be exceptionally low 0.098 which is being treated as an outlier, due to the lack of any apparent explanation. Therefore while in theory, the proposed relationship should work in principle for any given set of data, it seems to be more suited for the variable 'quantity of lime in the binder', based on R^2 values in Table 11.

Table 11: Linear regression performed on sets of data for different ages, correlation between ultrasound velocity, compressive strength & density. Variable - Lime content % by volume (10, 25, 33, 50, 67, 75, 90)

R^2 values as a function of lime content			
Fixed - Age | B/Ag ratio	1:3	1:4	1:5
Data points – Lime content (%)	10, 25, 33, 50, 67, 75	25, 33, 50, 67	33, 50, 67
7	.999	.993	.999
14	.991	.989	.999
28	.974	.998	.958
90	.943	.987	.985
180	.942	.985	.999

Table 12: Linear regression performed on sets of data for different ages, correlation between ultrasound velocity, compressive strength & density. Variable - B/Ag ratios (1:3, 1:4, 1:5, 1:6)

R^2 values as a function of B/Ag ratio			
Fixed - Age | Lime %	33	50	67
Data points – B/Ag	1:3, 1:4, 1:5	1:3, 1:4, 1:5, 1:6	1:3, 1:4, 1:5
7	.998	.997	.993
14	.975	.963	.975
28	.865	.882	.982
90	.849	.990	.951
180	.950	.998	.098

The relationship expressed in this segment between UPV, density and compressive strength could serve multiple purposes, of which the most evident would be quality control. Furthermore, once the equation is established for a given set of materials at any curing age, the compressive strength of specimens can be estimated without breaking them, simply be measuring their density and UPV. Additionally, extrapolation of data obtained from the equations of this relationship may potentially provide data for later ages, with a good level of accuracy. It could prove especially useful in terms of non-destructive evaluation of mortars containing lime and cement.

3.6 Evolution of static Young's modulus and open porosity

Static Young's modulus obtained for the three mixes, 1C2L9S (67%), 1C1L6S (50%) and 3C1L12S (25%) at all ages of testing (7, 28 and 90 days) exhibited a wide range of values varying from approximately 4 to 18 GPa (Table 13). At all ages, increasing the amount of lime in the binder led to lower values of stiffness in the mortar (Figure 10). It was also possible to observe that increase in values of stiffness between 28 and 90 days, was greater for mixes with more lime in the binder, i.e. 5.4%, 7.4% and 12.2% for the mixes 3C1L12S (25%), 1C1L6S (50%) and 1C2L9S (67%) respectively. A more gradual increase in stiffness due to the presence of lime may be attributed to carbonation [20].

Table 13: E-modulus values of lime-cement blended mixes at different curing ages

Mix (% Lime content)	Curing age (Coefficient of variation)		
	7 (%CoV)	28 (%CoV)	90 (%CoV)
3C1L12S (25%)	16.34 (15.0)	16.56 (3.5)	17.45 (1.8)
1C1L6S (50%)	9.82 (7.0)	10.89 (2.6)	11.69 (10.8)
1C2L9S (67%)	4.84 (8.5)	5.49 (7.7)	6.16 (4.6)

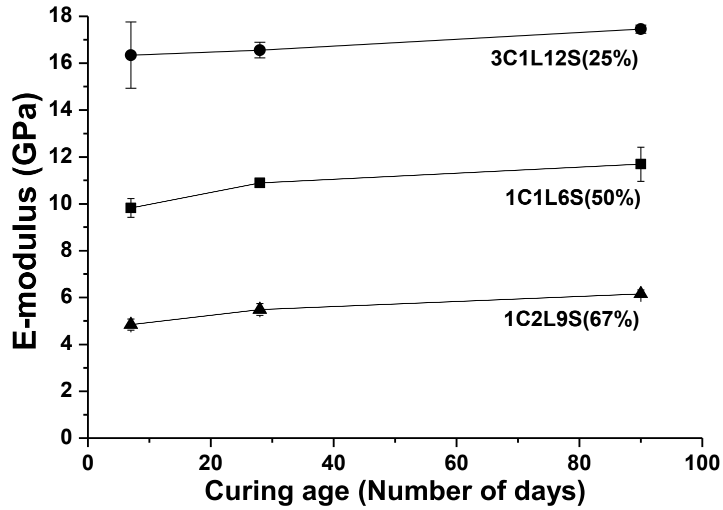

Figure 10: Evolution of Young's modulus with time as a function of lime content in the mix (by volume)

While feasibility of the general range of values obtained could be validated from literature (3 to 24 GPa), existing data classifying E-modulus of the mortar as a function of lime content in the binder could not be identified for a direct comparison [10]. Furthermore, the evolution of the ratio of E-modulus to compressive strength (E/f_c) with time has been plotted in Figure 11. This ratio was found to lie in the range of 400-1800, which was similar to ratios found in literature [38,39]. The evolution of this ratio with time is especially interesting from an engineering perspective since mixes with a higher E/f_c ratio would be more prone to cracking, because of stiffness evolving much faster than the capacity to withstand loads (ultimate strength). It may also be observed from Figure 11, that in mixes with greater quantities of lime, the E/f_c ratio is lower, offering relatively lower risks of cracking from early ages.

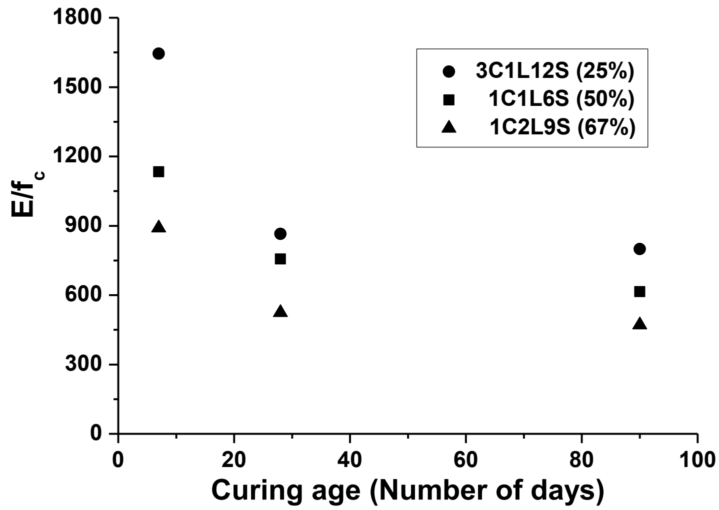

Figure 11: Evolution of ratio of E-modulus to compressive strength (E/f_c) with time

Open porosity was measured for the same three mixes, 1C2L9S (67%), 1C1L6S (50%) and 3C1L12S (25%) at ages of 7, 28 and 90 days [Table 14]. B/Ag ratio was kept constant at 1:3 and the lime content was kept at three distinct values 25%, 50% and 67%. While globally the values seemed to vary little and lay between 23% and 27% it was possible to identify two trends. First, that open porosity decreases with age for all mixes. This trend has been verified by other authors and may be attributed to both hydration and carbonation (especially in later ages) [8]. The second trend is the increase in porosity with increase in lime content of the mix, which seems to align with the conclusion of Cizer [9]. The reason for this has been attributed to an increased specific surface area of lime compared to cement particles, which increases the demand of water to achieve the same consistency of the mix [9].

Table 14: Open porosity of lime-cement blended mixes at different curing ages

Mix (% Lime content)	Curing age in days (Coefficient of variation)		
	7 (%CoV)	28 (%CoV)	90 (%CoV)
3C1L12S (25%)	25.7 (1.7)	25.5 (1.6)	23.3 (2.1)
1C1L6S (50%)	27.0 (0.6)	24.2 (0.7)	24.1 (0.3)
1C2L9S (67%)	27.4 (1.1)	26.0 (0.9)	25.8 (1.4)

4. Conclusions

The aim of this work has been to quantitatively assess basic mechanical properties of mortars as a function of lime content in the binder, B/Ag ratio and curing age of the mortar. Whether the application is current day masonry structures or repair in existing constructions, mortars may involve the use of cement and lime in varying proportions. For properties like workability, mechanical strength and stiffness, it is important to know the extent of variation in each of their values as a function of the mortar composition and curing time. This information can facilitate the choice of an appropriate composition of mortar, also taking into account the properties of unit that composes the masonry. Apart from understanding the trade-offs and benefits associated with partial replacement of cement with lime at different ages, an attempt has been made to find useful correlation and rules of thumb that can be used on the field, or explored further from an academic point of view. Conclusions of this research work may be summarized in the following points:

1) Changes in compressive strength and flexural strength were expressed as linear functions of different parameters such as lime content in the binder, B/Ag ratio and curing age in single equations. Depending on the B/Ag ratio, every 1% increment in the quantity of lime in the binder led to approximately 1.4% loss in mechanical strength of the mortar with respect to the reference (10% lime in the binder). In the case of a fixed lime-cement ratio in the binder, every 1% decrease in the B/Ag ratio of the mix led to about 5% lower mechanical strength of the mortar, with respect to the reference (B/Ag ratio of 1:3).
2) Compressive strength divided by flexural strength provided an almost constant value for all lime-cement compositions at different curing ages (ratio ~ 3). This ratio was found to be 3.1, 2.9 and 2.7 for the B/Ag ratios 1:3, 1:4 and 1:5 respectively, i.e. the ratio was found to decrease with increasing B/Ag ratios.
3) It was possible to establish reasonable linear relationships between UPV and a function of density and compressive strength of lime-cement mixes, at different ages, for specified B/Ag ratios. These regression analyses make it possible to estimate the value of compressive strength of the mix simply by measuring the density and UPV of the mortar specimens, for the raw materials used in this campaign.
4) Static Young's moduli of mixes 1C2L9S (67%), 1C1L6S (50%) and 3C1L12S (25%) were found to range between 4-6 GPa, 9-11.5 GPa and 16-17 GPa between 7 and 90 days of curing age. Stiffness of all mixes continued to evolve beyond 28 days of age, attributed to the presence of lime and its carbonation. Furthermore, greater quantities of lime, led to more gradual evolution of stiffness on a relative scale. At 90 days of age, the ratio of E/f_c was found to lie between 450 and 900.

5) Open porosity was found to increase slightly with increasing lime content in the mix lying in the range of 23% to 27%. It was also found to decrease with time.

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