EVALUATION OF THE BEHAVIOUR OF LIME AND CEMENT BASED MORTARS EXPOSED AT ELEVATED TEMPERATURES

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Abstract. *Exposure to fire and elevated temperatures is diachronically a significant decay factor, influencing the stability of structures. Cement and lime-based mortars have a different behavior when exposed at elevated temperatures, usually testified by the post-fire preservation state of historic and contemporary constructions. In this paper, the correlation of their properties is envisaged, in order to identify the key elements of their performance. To this direction, five compositions of cement and lime based mortars were manufactured and tested, after their exposure at 200°C, 400°C, 600°C, 800°C and 1000°C. The binders used concerned CEM I42.5N (C), hydrated lime (L) and natural pozzolan (P), while the systems applied regarded C, C:L (1:1), L, L:P (1:1) and L:P:C (1:0.8:0.2) (parts per weight). The aggregates used were natural of siliceous origin and their gradation varied from 0-4mm to 0-8mm. The B/A ratio was 1/2 by weight and the W/B ratio was adjusted in order to maintain workability around 15±1cm. The physico-mechanical properties of the specimens, were recorded before and after their exposure at the selected temperatures. From the evaluation of the results, it was concluded that the mortars' behavior was different at the early temperature rate (up to 600°C) according to their type, whereas the results were more comparable at the extreme temperature level. Generally it was observed that although the initial strength of the lime-based mortars was low (1-4MPa), they presented a more stable and efficient performance at the elevated temperatures, rendering them probably more resistant at the first stages of fire actions. Cement-based mortars seemed to present a better performance at the highest temperatures of 800°C and 1000°C.*

1 INTRODUCTION

Fire has been diachronically a significant decay factor of historic and modern structures, leading to extreme damages and loss of their stability. The post-fire state of constructions maybe related to several factors, such as the fire characteristics (i.e. heating rate, fire duration, maximum temperature), the ground plan of the building, as well as the type and properties of building materials.

The influence of fire on concrete has been studied from the beginning of the 20th century (1922) [1], while during the last decades research has been induced [2-6]. Researchers focus on various assets, such as the analysis of fire scenarios (heating rate, exposure temperature and time), the performance of building materials at elevated temperatures, the design and testing of fire-resistant materials, as well as the development and application of post-fire assessment and repair strategies [4-10]. Relevant Standards and Recommendations exist, providing accumulated data (RILEM TC 129-MHT, RILEM TC 200-HTC, EN 1991-1-2 Eurocode 1, EN 1992 Eurocode 2, ISO 834-11:2014, BS 476-3:2004) [10-15].

The temperature/time development curves, as given by the Standards (Fig. 1), show that the maximum temperature attained during a fire, is around 1100-1200^oC, while the temperature rate may vary [16]. During the first 30 minutes of the action, temperature is rapidly increased up to 822^oC. Due to the difficulty of simulating such an extreme temperature rate at laboratory level and in order to study the performance of building materials at elevated temperatures, researchers propose a development rate ranging from 5 to 10^oC/min [1-9].

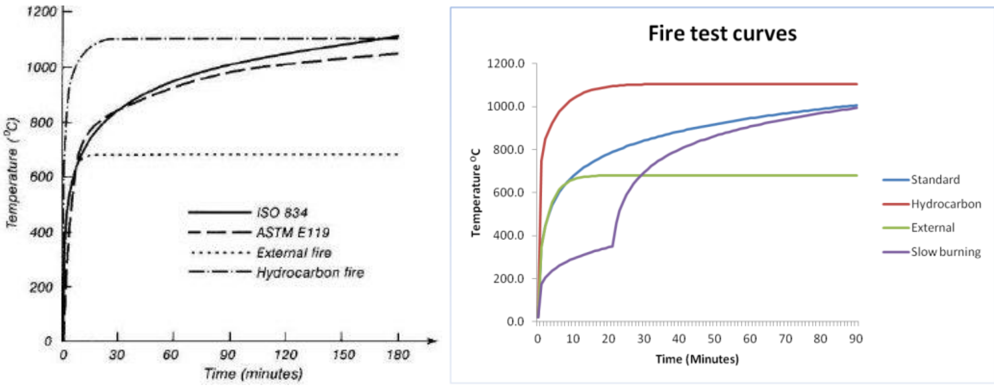

Figure 1: Temperature / time development standard curves during fire action [16]

When subjected to fire, specific properties of materials are influenced, regarding both physico-mechanical and chemical characteristics [1-6]. Since mortars are heterogeneous materials, elevated temperatures influence both their paste and aggregates in different ways and according to their constituents and thermal strains (expansion of aggregates, shrinkage deformations of the paste) [1-6]. Their post-fire pathology symptoms, usually concern colour change, spalling, cracking, delamination, and deformation [7-9].

According to literature, between 100-200°C, the free moisture of the materials evaporates, while above 250°C the dehydration or loss of the bonded water begins [1-6]. Above 300°C the silicate hydrates of the cement paste (C–S–H gel) decompose and above 500°C portlandite, influencing the stability of the matrix [4]. Aggregates function according to their origin, whereas siliceous aggregates seem to be more resistant than calcareous ones [4].

In the case of cement-based mortars, the residual strength is maintained for temperatures up to 300°C, while between 300°C and 500°C it is decreased around 15-40% [1-6]. Above 550-600°C, it is minimized and secondary chemical reactions occur (decarbonisation of carbonates in both the cement paste and the aggregates) [4]. Usually above 800°C, complete disintegration of the constituents begins.

In the case of lime-based mortars [7, 17], compressive strength is significantly increased up to 600^oC (almost doubled). It is reduced at 800^oC (around 50% of the initial value) and minimized at 1000^oC. Generally, lime-based mortars exhibit a good performance throughout the tested temperatures, maintaining their mass and volume until 1000^oC.

In the present paper, an effort has been made to comparatively study the performance of cement and lime-based mortars at elevated temperatures. To this direction, five compositions were manufactured and exposed at 200ºC, 400ºC, 600ºC, 800ºC and 1000ºC. The binders used concerned CEM I42.5N (C), hydrated lime (L) and natural pozzolan (P), while the systems applied regarded C, C:L, L, L:P and L:P:C.

The purpose of the study was to envisage the behaviour of contemporary and traditional binding systems, found in mortars of modern or historic structures. Repaired historic constructions are also related, where traditional and cement based materials coexist, due to improper restoration works or specific demands.

2 MATERIALS AND METHODS

During the experimental work, five compositions of cement and lime-based mortars were manufactured and tested. The binding agents used concerned CEM I42.5N, hydrated lime (L) and natural pozzolan (P), while the systems applied regarded C, C:L (1:1), L, L:P (1:1) and L:P:C (1:0.8:0.2). The aggregates were natural of siliceous origin and their gradation varied from 0-4mm to 0-8mm.

In order to reduce the water demand, a sulphate free, polycarboxylate superplasticizer was added in a proportion of 1% w/w of binders. The Water/Binder (W/B) ratio was adjusted for achieving workability of 15±1cm, according to EN1015-3. The manufacture and curing of the mortar specimens was according to EN1015-11, while totally 16 specimens (dimensions 4x4x16cm) of each composition were manufactured and tested. In Table 1 the constituents and proportions of the mortar series are presented.

Table 2: Constituents and proportions of the mortar series

Raw materials	Mortar series / Parts of weight				
	C	CL	L	LP	LPC
Cement I42.5	1	0.5	-	-	0.5
Hydrated lime	-	0.5	1	0.5	0.4
Natural pozzolan	-	-	-	0.5	0.1
Sand of siliceous origin, pale colour (0-4mm)	2	2	1.4	1.4	1.4
Gravel of siliceous origin (4-8mm)	-	-	0.6	0.6	0.6
Super plasticizer (1% w/w of binders)	√	√	√	√	√
W/B ratio	0.36	0.44	0.85	0.57	0.54
Workability (cm) (EN1015-3:1999)	15.5	15.0	14.8	15.5	14.7

Twenty-eight days after their manufacture, the physico-mechanical properties of the mortar compositions were recorded, regarding porosity and apparent specific gravity (RILEM CPC 11.3), water absorption coefficient due to capillary action (EN 1015-18:2002), dynamic modulus of elasticity (BS 1881-203:1986), flexural and compressive strength (EN1015-11:1999).

Two specimens of each mortar composition were subjected to elevated temperatures (200ºC, 400ºC, 600ºC, 800ºC and 1000ºC), according to former research work [7, 9, 17]. For the experiment, an electric furnace was used, where the temperature rate and duration time could be manually set (Fig. 2). The heating scheme followed (maximum temperature, heating rate, exposure time and cooling rate) was based on former research work [7, 9, 17] and was aligned with relevant research [1-6]. The methodology concerned heating rate 5^{o}C/min, exposure duration to the maximum temperature 2h and cooling rate 2^{o}C/min (Fig.2).

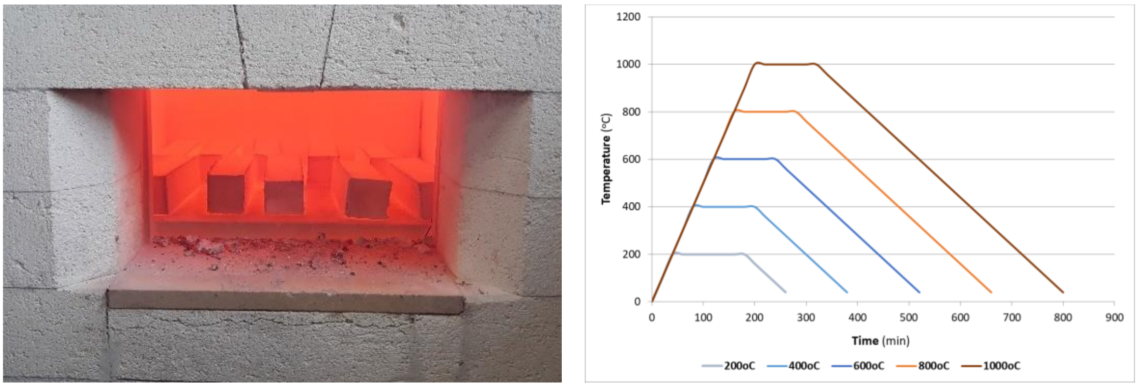

Figure 2: Electric furnace (left) and heating scheme (rate, exposure time, cooling rate) (right)

After the exposure to each temperature, the specimens maintained for 24h at laboratory conditions and their weight and dimensions were recorded, in order to estimate their mass and volume changes. Their physico-mechanical characteristics were tested, regarding porosity, apparent specific gravity, dynamic modulus of elasticity, flexural and compressive strength. Macroscopic observation of the specimens and colour determination (according to the Munsell chart) were also attained. All the results were comparatively evaluated in order to record their performance at elevated temperatures.

3 RESULTS AND DISCUSSION

3.1 Physico-mechanical characteristics

The physico-mechanical properties of the mortar specimens at the age of 28 days are presented in Table 2. The characteristics concern porosity, apparent specific gravity, dynamic modulus of elasticity, flexural and compressive strength, while the water absorption coefficient due to capillary action is presented in Figure 3.

Table 2: Physico-mechanical properties of the mortar compositions at the age of 28 days

Mortar series	Porosity (%)	Ap. Spec. Gravity	Dyn. Mod. of Elasticity (GPa)	Flexural strength (MPa)	Compressive strength (MPa)
C	8.68	2.15	37.55	9.93	60.79
CL	18.8	1.93	25.11	6.01	17.46
L	30.86	1.65	1.36	0.12	0.87
LP	16.66	1.84	13.32	1.12	3.15
LPC	16.15	1.90	16.22	1.70	4.20

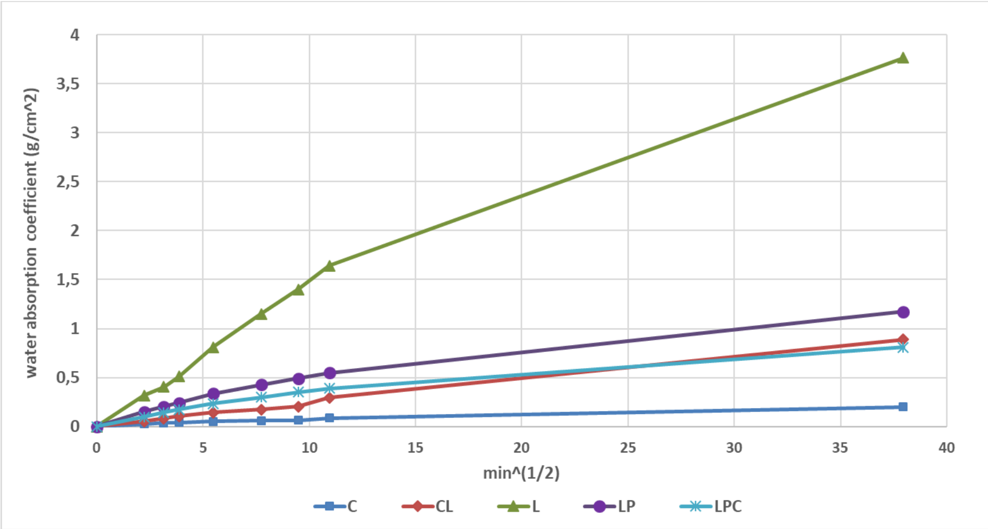

Figure 3: Water absorption coefficient of the mortar compositions (28d)

From the evaluation of the results (Table 2) it was asserted that with the substitution of 50% of cement with lime (CL), the porosity was doubled (18.8%), while the mechanical characteristics, especially compressive strength, were significantly decreased. Flexural strength dropped from 9.93MPa (C) to 6.01MPa (CL) and compressive strength from 60.79MPa (C) to 17.46MPa (CL). In the case of lime-based mortars, the substitution of 50% of lime with natural pozzolan (LP) resulted in a significant decrease of porosity (16.66%) and increase of strength. Flexural strength was increased from 0.12MPa (L) to 1.12MPa (LP) and compressive strength from 0.87MPa (L) to 3.15MPa (LP). The substitution of 20% of natural pozzolan with cement (LPC), slightly decreased porosity and increased mechanical properties around 30%.

As expected, water absorption coefficient was significantly high in the case of the lime mortar (L) and low in the cement one (C) (Fig.3). CL and LPC compositions presented almost the same behavior, while LP showed slightly higher values.

3.2 Performance at elevated temperatures

The performance of the mortar compositions was recorded after their exposure at the elevated temperatures (200°C, 400°C, 600°C, 800°C and 1000°C). Their physico-mechanical properties, regarding volume and mass change, color alterations, porosity, apparent specific gravity, dynamic modulus of elasticity, flexural and compressive strength, were comparatively evaluated.

The volume change of the specimens presented the same trend in all compositions (Fig. 4). At 200°C, a short expansion was observed, which was more intense for composition L (3.6%), while at 400°C a volume decrease was recorded ranging from 0.5 to 5%. The lowest values were recorded for C and CL compositions. At 600°C and 800°C a slight volume increase was observed for L, LP and LPC, while C and CL showed volume reduction. At 1000°C all volume change was minimized. Compared to all compositions, C presented the more extreme volume loss above 400°C, ranging from 1.5-4.5%.

Regarding mass change (Fig.5), all compositions, except C, presented the same trend, with decreasing values from 200 to 1000°C (7-21%). The highest decrease was observed for L.

Composition C presented a different behavior with a slight mass increase at 200°C and further reduction. The highest mass loss was recorded at 400°C (4.6%).

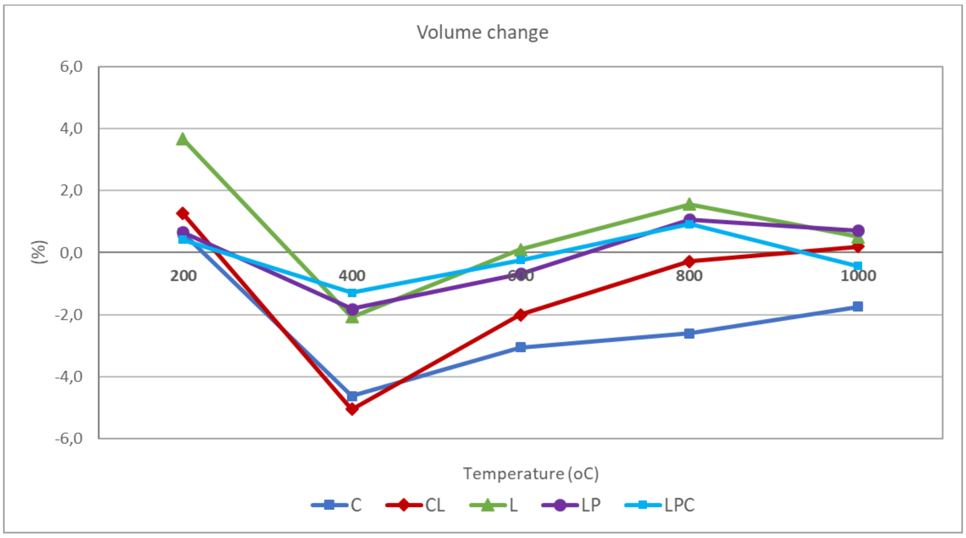

Figure 4: Volume change of the mortar specimens, exposed at elevated temperatures

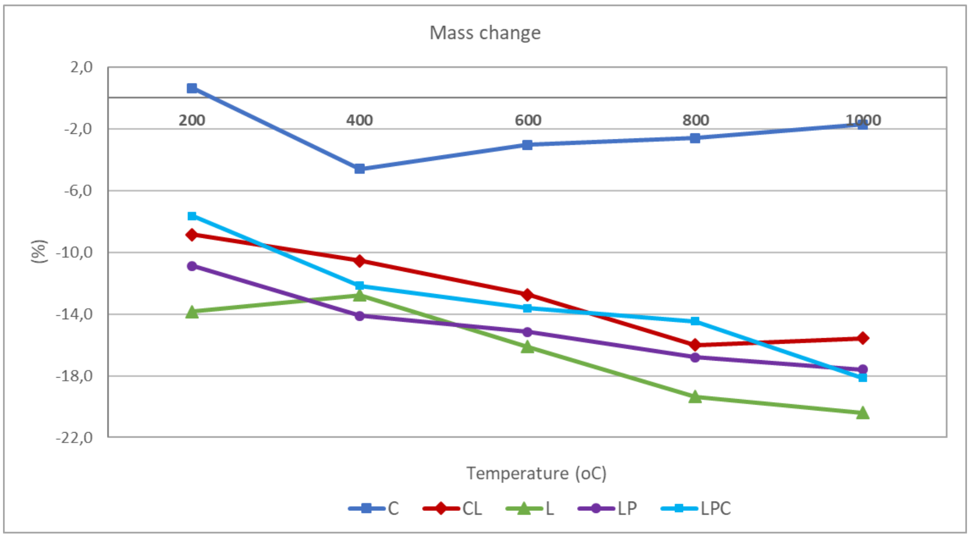

Figure 5: Mass change of the mortar specimens, exposed at elevated temperatures

Regarding porosity and apparent specific gravity (Fig.6), the performance of the specimens presented some similarities. Porosity was generally increased up to 600°C (except of L) in all cases. C had the highest increase up to 800°C with values ranging from 8 to 25% (at 1000°C there was a decrease to 20%). CL presented a lower increase up to 600°C from 20 to 30%. LP and LPC had the same behavior with an increase from 18 to 34% up to 600°C and a further decrease. Composition L presented the lower fluctuations at all temperatures, with a short decrease of values (31-28%). Apparent specific gravity was reduced throughout the elevated temperatures (10-15%). The greatest fluctuations were recorded in compositions C and L.

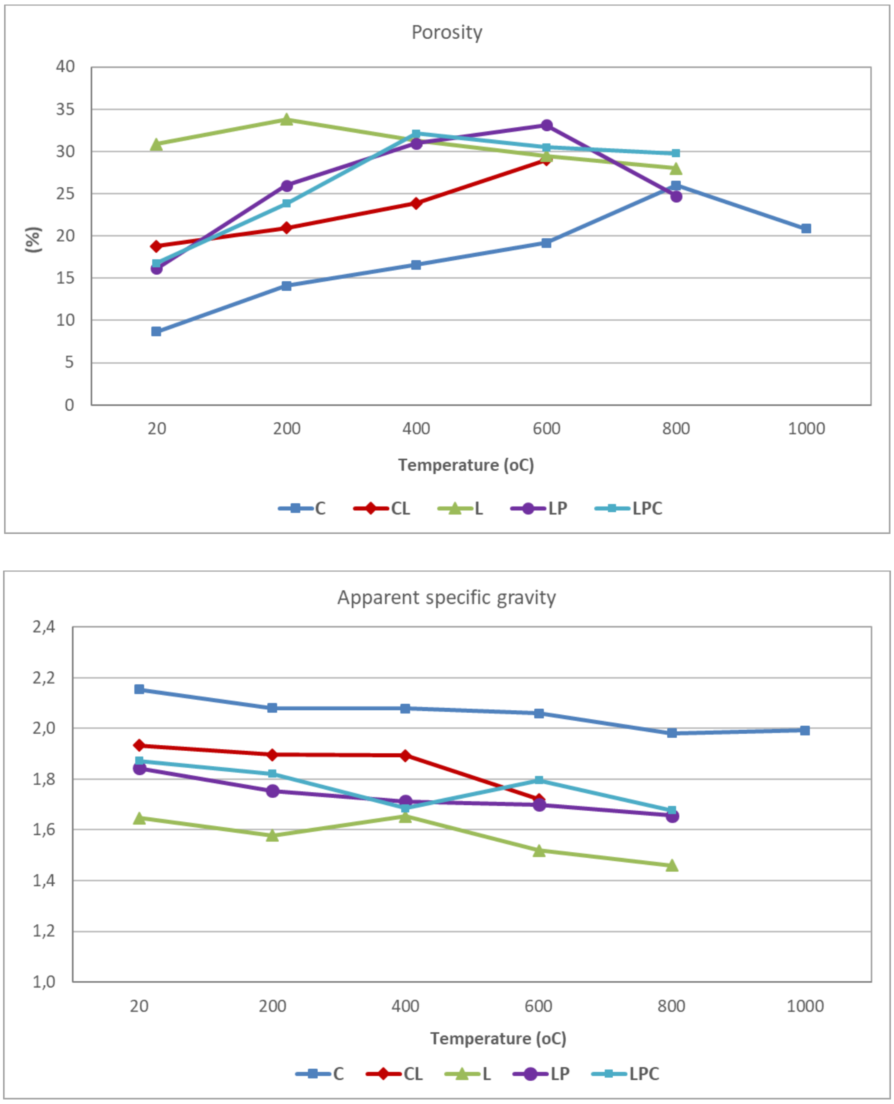

Figure 6: Porosity and Ap. Specific gravity of the mortar specimens, exposed at elevated temperatures

Concerning the mechanical properties of the mortar specimens, it was generally observed that dynamic modulus of elasticity was decreased throughout the temperature increase (Fig.7). At 200°C, compositions C and CL presented a decrease of the initial values around 25-30%, while LP and LPC showed a reduction of 10-15%. At 400°C there was a further decrease around 45% for C and CL and 70% for LP and LPC, while at 600°C and further all values where minimized. Composition L, presented a different behavior, maintaining the initial value up to 600°C.

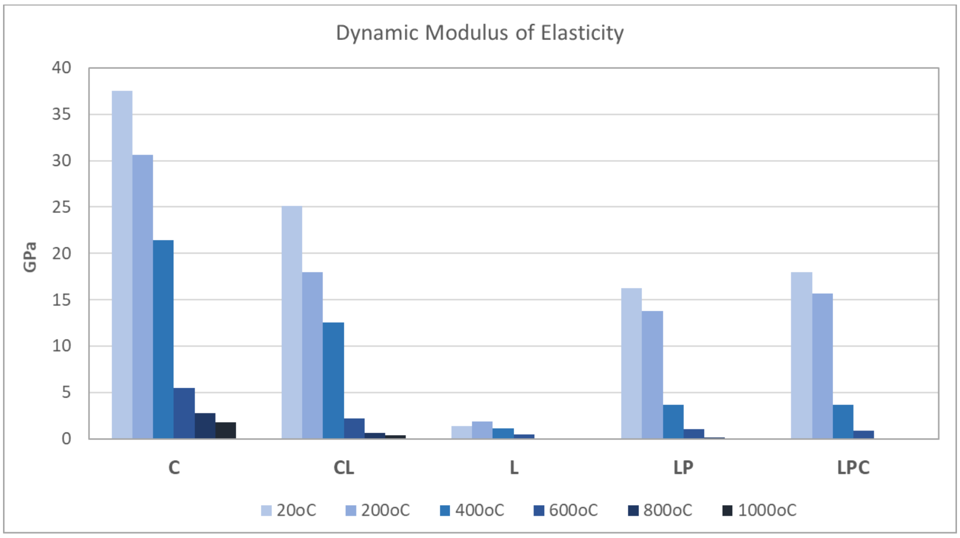

Figure 7: Dynamic Modulus of Elasticity of the mortar specimens, exposed at elevated temperatures

In flexural strength (Fig.8), compositions had a different behavior, according to their type. Although the values were decreased throughout the elevated temperatures for C, in the rest compositions there was a strength increase at 200^{o}C (mainly in CL). The values were further decreased, especially above 600^{o}C. In composition L, values maintained at a low level (~0.3MPa) throughout all temperatures.

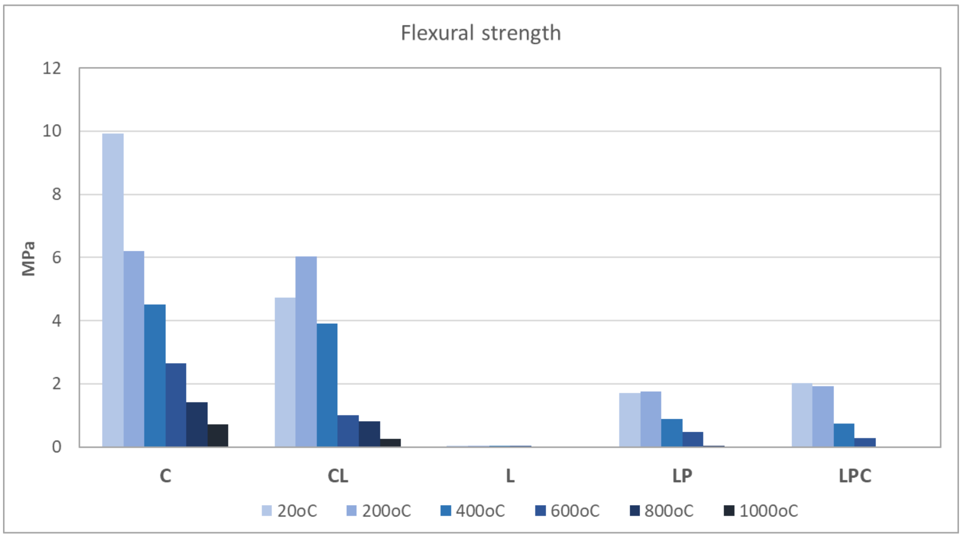

Figure 8: Flexural strength of the mortar specimens, exposed at elevated temperatures

Compressive strength values (Fig.9), also presented fluctuations among the compositions. As it is presented in Figure 10, C showed a gradual (almost linear) strength loss throughout all temperatures (30% at 400^{o}C and 45% at 600^{o}C) leading to a final loss of 85% (61→10MPa). Composition CL had a strength increase at 200 and 400^{o}C (30-40%), while it was significantly reduced at 600^{o}C (~50%) and minimized at 1000^{o}C (17.5→4.5MPa). Compositions L, LP and LPC showed a strength increase up to 600^{o}C (around 20-100%) and a further strength decrease at 800 and 1000°C. The highest strength increase was observed for LP at 400°C (100%), while the lowest loss was shown for L at 800 and 1000°C (20-30%).

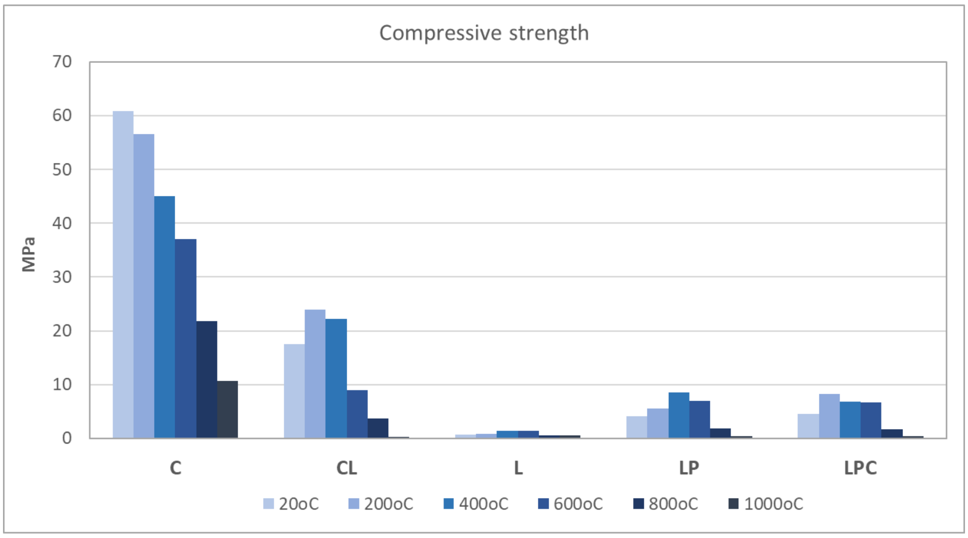

Figure 9: Compressive strength of the mortar specimens, exposed at elevated temperatures

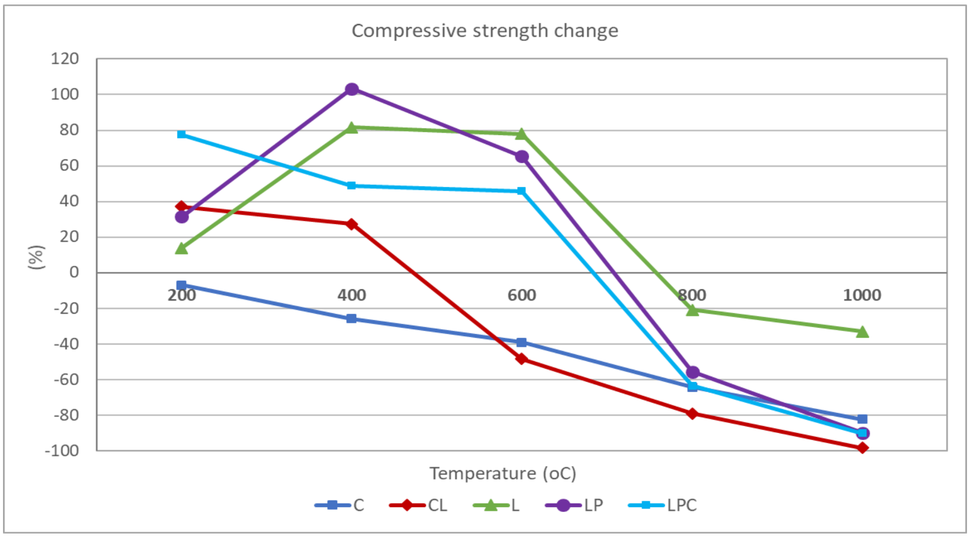

Figure 10: Compressive strength changes of the mortar specimens, exposed at elevated temperatures

The structure of the specimens, after their exposure at the elevated temperatures was generally maintained, as presented in Figure 11. At 600°C limited spalling and color alterations were observed, which were more intense at 800 and 1000°C. Composition L was cracked at 800 and severely damaged at 1000°C, while LPC also presented extreme damages at 1000°C. Regarding the more extreme color changes (according to the Munsel scale), compositions C and CL were converted from GLEY 2, 7/1 light bluish gray and GLEY 2, 8/1 light bluish gray respectively to GLEY 2, 8/1 light greenish gray.

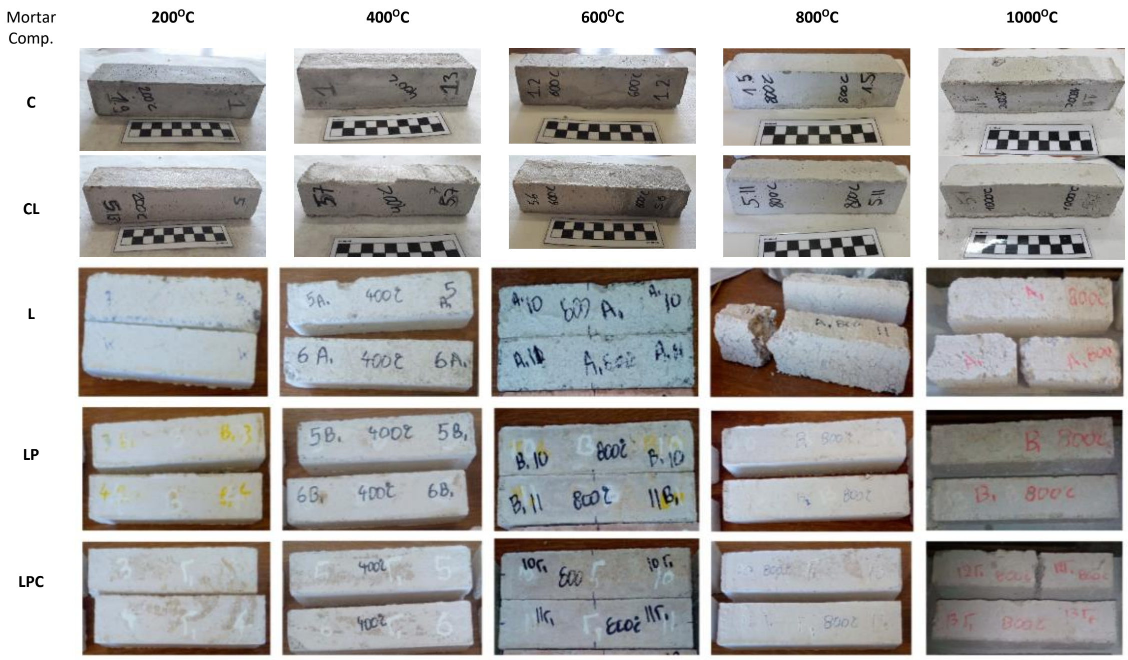

Figure 11: Macroscopic photographs of the mortar specimens, exposed at elevated temperatures

4 CONCLUSIONS

The performance of building materials at elevated temperatures, is a significant factor influencing their maintenance and preservation state. In the present study, an effort was made to assess the resistance of mortars made by contemporary and traditional binders, showing that the initial strength level of materials may not be the key element of their performance.

According to the research results, cement-based mortars (composition C) presented significant decay when exposed at elevated temperatures. High volume reduction was recorded (2-4%), extreme increase of porosity (values are tripled, 8→24%), while mechanical properties were significantly influenced. At 600°C strength loss was around 45-75%, with the flexural strength to be severely affected (flexural strength: 10→2.5MPa, compressive strength: 60→38MPa). At 1000°C flexural and compressive strength was reduced around 85-90%.

When lime was added in the mixture (CL), the physical properties were enhanced throughout the elevated temperatures. Mechanical characteristics were maintained (with a slight increase) up to 400°C and were further reduced at 600°C (50% for compressive and 80% for flexural strength). At 1000°C they were minimized.

In the case of lime-based mortars, a slight volume change was recorded, whereas the mass change was extreme (8-20%). Porosity values were almost doubled (16→30%) except for the pure lime mortar (L), which presented the lowest fluctuations (29-34%). Mechanical properties and especially compressive strength was enhanced up to 600°C (around 80% in the case of LP) and were minimized at 1000°C. The pure lime mortar (L) was the one to present the lowest strength loss at 800 and 1000°C (20-30%).

It is therefore asserted that, contradictory to the cement-based mortars, lime-based binding systems (C:L, L:P, L:P:C) presented a generally good behavior, up to the limit of 600°C, maintaining both their physical and mechanical properties. However, at the highest temperatures of 800 and 1000°C cement-based mortars seemed to present a better performance.

Concluding, it is noticed that the binding system significantly influences the overall behavior of the mortars at elevated temperatures. The addition of lime in traditional or contemporary mortar systems seem to be benefited in the case of extreme temperatures. However, more oriented research should be made in order to further document the physico-chemical reactions taking place in the mortar matrix.

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