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Research Article

Increasing Durability of Weak Lime Mortars Using Saturated Solution of Calcium Hydroxide or Barium Hydroxide, Aachen City Wall, Germany, Case Study

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Abstract

The current paper deals with the impact of repeated treatments with saturated solutions of calcium hydroxide (limewater) or barium hydroxide (barium water) on consolidating a friable lime-mortar. The influence of lime or barium water treatment on various properties of the created lime-mortar is mainly on the mechanical properties as well as durability limits of the consolidated lime mortar. It was examined in detail by means of tests conducted on non-standard specimens prepared from a poor mortar of 1:8 volume lime-to-sand ratio that is very similar to that of Aachen City walls in its present state. The traditional limewater and barium hydroxide treatment were further compared with distilled water and limewater with added meta-kaolin. Limewater treatment of a specific lime mortar was selected to be effective after large number of applications (200 saturations) into a weak lime mortar. No consolidating effect of distilled water on the compressive strength (cohesion) of the tested mortar with a low lime content (1:8) was observed. The mechanical characteristics of the tested mortar were not improved by treatment with limewater with added meta-kaolin. Barium hydroxide treatment significantly increased the compressive strength and durability of the tested lime mortar.

Keywords: Lime mortar; Consolidation; Calcium hydroxide; Barium hydroxide; Durability limits

Introduction

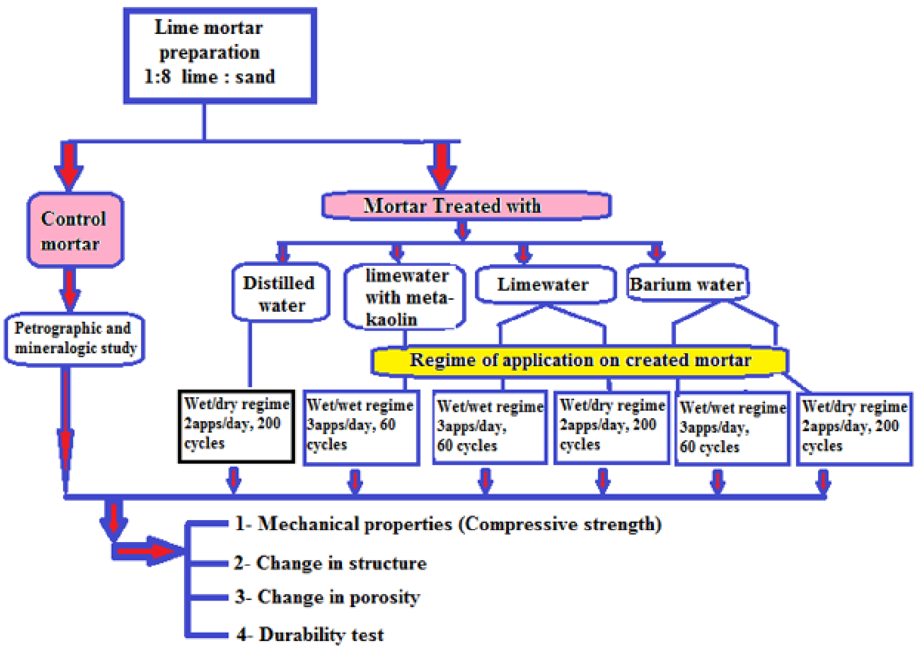
Lime mortars have been broadly used in the Medieval period in building as it has been considered as friendly mortar to the building stones as well as to the environment. Chester City walls at Chester City, UK as well as other Medieval structures had been built from natural sandstone blocks cemented with such hydraulic lime mortar [1]. Not only that but also the ancient Medieval Aachen City walls, Germany have also been built from fine grained sandstone cemented with such type of mortars [2]. Recently, such type of mortars become week and easily weathered by the severe and aggressive weathering processes (particularly salts created from acid rains, de-icing salt …etc.) acting on all building materials [2-5]. Increasing durability of such weak mortars using some additives becomes a must. Unfortunately; a lack of experimentally supported publications and detailed information about the impact of limewater treatment on lime mortars particularly the weak ones have been found. Some previous literatures regarding hardening weak mortars presented only marginal data [6,7] or the results attained under certain limited conditions may be broadly interpreted. It may be extrapolated into conditions where no enough information is available, and so, no precise information or evidence can be found regarding this point of view [8] Consequently, the number of relevant articles is quite not enough to understand this topic i.e. it still requires several investigations to cover it for the best of archaeological conservation Angeli et al 2007 [9]. Only the most relevant experimental studies have been mentioned, theoretical works analyzing very important questions of binding mechanisms [10] and also literatures illustrating confusions in terminology (limewater against lime wash) [11] or presenting discussions against the application of limewater for consolidating mortar and/or building stone.

The efficacy of limewater applied in situ for conservation of wall paintings on lime mortar rendering has been previously studied [12]. Those researchers tested limewater treatments from the following points: the application procedure, the number of applications that are ranging from 20 – 60 cycles, dosage and maturation. They concluded that continuous "wet" applications ended with a consolidation effect, unlike applications with "drying" breaks, which do not consolidate the wall paintings. However, the observed consolidation tended to consider fixation of a released surface paint layer, for which limewater was recommended to be applied in some publications [13]. Previous literatures had not considered measuring of mechanical characteristics of the treated mortars before and after treating with limewater. On applying limewater for 40 cycles on stone as well as on crushed limestone, a very small increase in calcite content has been observed in the material, no observable change in the mechanical characteristics (particularly compressive strength), and no consolidation effect on the crushed material have been recorded [13]. Limewater effects and the use of meta-kaolin as an additive in limewater were investigated [14]. The limewater was applied for 40 cycles on stone and also on crushed limestone sand, and it has been found a very limited increase in the amount of calcite in the material, no observable change in the mechanical characteristics, and no consolidation effect on the tested crushed material [14]. Applying the limewater and limewater with meta-kaolin for consolidating old rendering with low cohesion at both of laboratory and in situ tests had been conducted [13]. It was concluded that the tested consolidates increase the mechanical resistance only of the superficial layers [14]. Based on the previous investigations in this field of render consolidation. The current study aimed to conduct an experimental program to reveal the fundamental behavior of weak lime mortars when subjected to multiple saturations and evaporation of distilled water, a saturated solution of calcium hydroxide in water ("limewater"), limewater with added meta-kaolin, and saturated solution of barium hydroxide.

Simply, the main aim of the current study is to offer an objective evaluation of the impact of adding limewater to friable mortar, and to ascertain the degree of consolidation. The consolidating effects not only of limewater but also of multiple applications of some other treatments e.g. distilled water, limewater blended with meta-kaolin, and barium water (a barium hydroxide saturated solution in water). Barium hydroxide was considered as an alternative consolidating agent to calcium hydroxide and is expected to be more effective as it is much more soluble in water than calcium hydroxide [13].

Methodology

To conduct and achieve the aims of the current study, a well performed plan of research has been structured as shown in Flow chart (1). The following sections are detailed explanation of the methods, tests and results of the measurements conducted for the control and treated mortar samples to find out which one of the suggested treating materials with which regime of applying we get the ultimate enhancement in hardness and durability of the weak lime mortar.



Flow chart 1: Presenting the protocol of conducting the current research.

Lime mortar test specimens

Surveying the previous literatures, it has been indicated a very slight effects of multiple wetting of historic mortars or stone with limewater, regarding its penetration depth and strengthening of the material under consolidation. Test specimens have been prepared in the form of short tubes for applying and testing compressive strength for these samples. The specimens were made of lime mortar prepared in the laboratory from powdered lime hydrate and sand. It is the same composition as that of the mortar composing a binding material in the walls of ancient Aachen City (Figure 1).

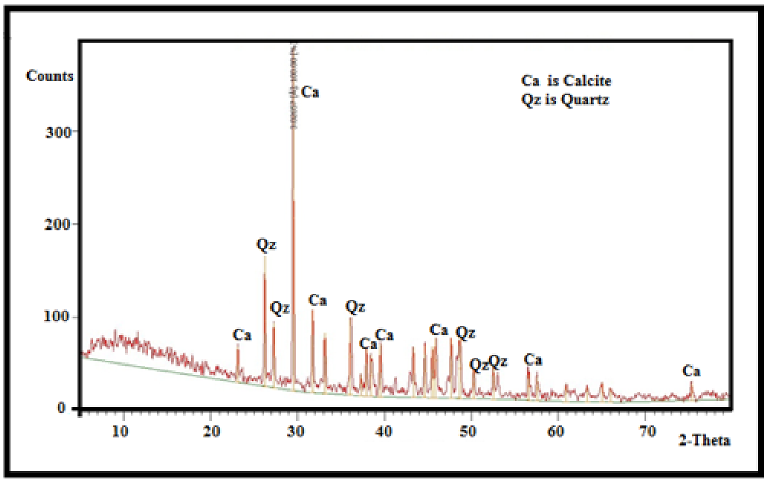


Figure 1: X-ray diffract graph presenting the mineral composition of the weak lime-mortar of the Medieval Aachen City walls.

For this purpose, the historic lime render with quartz aggregate was sampled from the medieval Aachen City walls and the sample of about 200g was dissolved by the acid dissolution. The aggregate separated from a disintegrated mortar by filtration was dried at 60 °C till reaching constant weight. In accordance with the historic render, the sand was mixed and used for preparation of the model laboratory mortar's samples in a ratio of 1:8 by volume were accurately mixed in the laboratory to prepare a weak lime mortar. The steps of mixing lime-mortar components have been listed as follows: First, water was poured into the mixing bowl then the lime hydrate was added, and the lime mixture was mixed for about 25 minutes in a laboratory mortar mixer to ensure perfect mixing of these components. After that, the sand was poured into the lime and finally, the mortar was properly mixed for about 40 minutes to ensure complete mixing and preparation of this created lime mortar. The fresh mortar was stored in a closed plastic bag to keep it away from carbonation process. The specimens were prepared by casting of the fresh mortar in a stainless-steel cast, and they were well compacted. This enabled the specimens to be safely pushed out from the cast immediately after molding and prevented the development of shrinkage defects in the prepared mortar samples. The tubular cast shape of specimens for the compressive test increased the ratio of surface/cross section area and intensified the measurable compressive strength. As the study was focused mainly on compressive strength of the consolidated mortar, Eight tubes for compressive strength testing were prepared for each mode of consolidation treatment (consolidation agent, application regime, and number of applied cycles). The specimens were cured by slight spraying of distilled water, for about one month, to support carbonation process for these samples. All specimens were kept in a conditioned room before testing at a controlled environment (i.e. temp. 20 °C, and Rh 70%). After that, the consolidation agents were applied, and on completion of the consolidation treatment, the specimens were left to mature for another 60 days, which was sufficient to allow carbonation of the calcium or barium hydroxides applied into lime mortar specimens. The other tests (Pore size distribution "PSD", microscopic examination and durability investigation) were carried out on samples prepared as a copy of that used for conducting compressive strength testing. Therefore, the tests follow a sequence from destructive to non-destructive ones.

The micro-texture of the created weak mortar can be noted, with its components, under the magnification power of the transmitting polarizing microscope (Figure 2) and for more clarification on the texture of this mortar, it has been examined under the high magnification power of scanning electron microscope (Figure 3).

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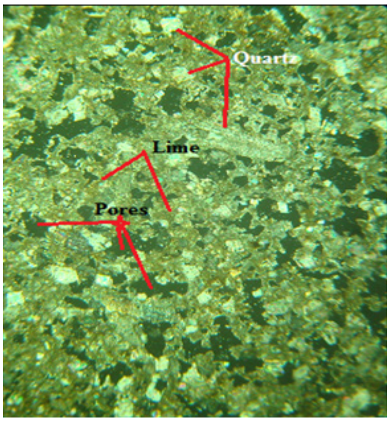

Figure 2: Thin section photomicrograph presenting components and texture of the created mortar before treatment (plane crossed nicols, 40x mag.).

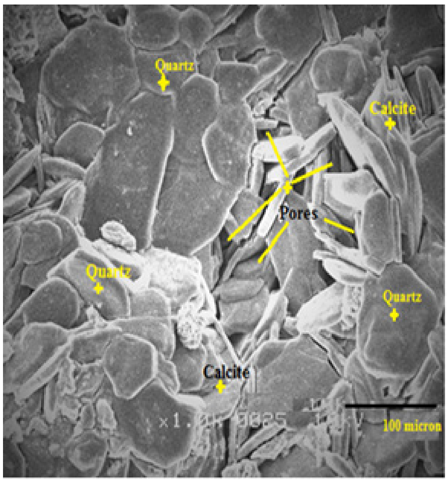

Figure 3: Scanning electron photomicrograph presenting the micro-texture of the created weak mortar before treatment.

Consolidation of mortar specimens

In the current study, four consolidating substances were applied, for the created mortars, they are namely: distilled water, calcium hydroxide saturated solution in water (known as "limewater"), limewater mixed with meta-kaolin and barium hydroxide saturated solution in water (known as "barium water"). Water solutions of calcium hydroxide and barium hydroxide were prepared, i.e., for the limewater solution 3g of Ca(OH)2 were dissolved in one liter of distilled water; while for the barium water solution, 6g of Ba(OH)2·8H2O were dissolved in one liter of distilled water. The solubility of barium hydroxide in water made it possible to prepare "barium water" with a higher concentration of barium hydroxide (6% weight) than for the limewater (0.18% weight) [15-18]. The limewater with meta-kaolin was prepared by mixing 3g of calcium hydroxide and 3g of meta-kaolin in one liter of distilled water. Meta-kaolin used in the current study for modification of the limewater was a finely ground burnt clay-stone with relatively high amount of alumina (52.5% SiO2, 43.3% Al2O3). The meta-kaolin has the particle diameter at 40% of particles equal 4µm and 60% of particles size was less than 12µm. Limewater, barium water and limewater with added meta-kaolin were prepared and stored in closed glass barrels at controlled laboratory conditions (temp. 25 °C, and 40% RH) throughout the experiment. For consolidation treatments, a solution above the solid sediment was poured off and used. Each agent was applied, on the created weak mortar, by continually dripping it from a syringe on to tubes fixed in a horizontal position on a rotating shaft (Figure 4).

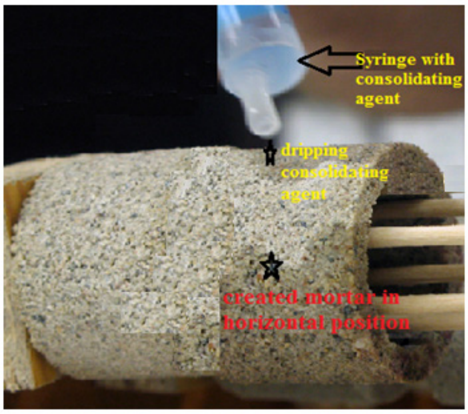

Figure 4: Presenting impregnation of created mortar with consolidating agent.

The mortar specimens were fully saturated during each application of each consolidating agent. The treatment by limewater has been conducted by means of many applied cycles of sprayed limewater into the created lime render samples. The same schedule was used for the distilled water treatment to find out the difference between effects of limewater and distilled water. In respect to other two studied agents (limewater with meta-kaolin and barium water), the applications were realized with a purpose to compare the obtained effects with limewater applied at the same condition. Two different regimes of the drying time interval between two following saturations were tested for the limewater: first regime, two applications per day were conducted, and the mortar tubes were allowed to dry completely before the following saturation (wet to dry alternative); and second regime, three applications per day were performed. The new dose of the lime or distilled water was applied to the created mortar once the mortar was capable to absorb it, but before it dried out completely (wet to wet alternative). However, the intended number of application has been precisely managed in the experimental work and actually the applied cycles of consolidating agents have slightly varied from the original schedule (60 cycles were realized for the wet to wet alternatives and 200 cycles for the wet to dry alternative). The main aim of this study is to examine the influence of lower and higher repeated applications number for the consolidating materials on the created render that imitate that of Aachen City walls.

Mechanical characteristics

The mechanical measurements for the created mortar samples have been conducted, in the current study at laboratory conditions (Rh 60%, Temp. 20 °C), the crosshead velocity movement of 0.45 mm/min. The short mortar tubes were loaded along the tube axis as shown in Figure 5.

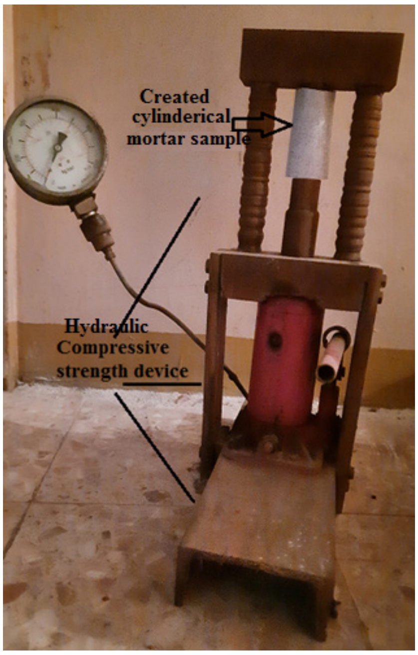

Figure 5: Tube of the created mortar under compressive strength measurement.

The attained compressive strengths had been checked for the untreated reference (control) specimens of tube shape (of dimensions 40mm diameter and 60mm length). The average compressive strength was calculated as an average value, from tests conducted, for eight samples of the created mortar at each regime of the considered consolidating material (fresh water, lime water, limewater with meta-kaolin; and barium water). The results of the mechanical tests conducted in the current study are presented in Figure 6 and listed in Table 1.

Mostly, five specimens had been tested, in few cases, the fragile mortar samples had not sustained treatment and was damaged before testing, then, only four specimens were tested. The amount of new calcite after limewater treatment is sufficient to make a slight improvement in the shear cohesion characteristics, not only that but also in the surface cohesion characteristics. Regarding data listed in Table 1 and graphically presented in Figure 6, it can be noted that barium water treatment is about three times (particularly for wet/dry regime applying it 200 cycles) as that of the control samples. Not only that but also, it is two times more efficient than limewater treatment that corresponds to a higher concentration and the high solubility of the barium hydroxide in the solution. Increasing number of applied cycles (for each of limewater and barium water) from 60 cycles (at wet/wet regime as three applications/day) to 200 cycles (at wet/dry regime as two applications/day), an increase in the compressive strength of the created mortar samples has been noted (Figure 6). The results show that there is no apparent difference in compressive strength between distilled water application and limewater application mixed with meta-kaolin (wet/wet application for 60 cycles) (Figure 6). There is a considerable increase in the compressive strength of a poor lime mortar after 200 cycles (in the case of two saturations regime, wet/dry regime either for limewater or barium water, Figure 6). The combination of limewater with meta-kaolin did not provide any noticeable input or advance in the mortar's strength (Figure 6). This indicates that the products of the pozzolanic reaction of meta-kaolin and calcium hydroxide in limewater were not water-soluble, i.e., did not penetrate throughout the mortar under investigation, and therefore did not improve its compressive strength (Figure 6). The lime presents in the lime meta-kaolin suspension was partially consumed due to a pozzolanic reaction with meta-kaolin, and the following consolidation treatment of the mortar with lime–meta-kaolin water was less effective than treatment with simple limewater. Samples undergoing the same number of treatments show a higher compressive strength when barium water was employed regarding to limewater. The observed improvement in mechanical properties is not high as it is expected considering the higher concentration of $Ba(OH)_2$ in the saturated solution. In fact, the strength after consolidation, using $Ba(OH)_2$, was three times higher than that of the untreated (control) mortar. Distilled water did not show any consolidating effect on the tested mortar with a low lime content. In this case, only compressive strength was measured, and the difference from the control specimens was insignificant (Figure 6). Probably the repeated dissolution and precipitation of the calcium carbonate presented in the treated mortar with a low content of lime, was not associated with a significant re-distribution within the volume of the specimen and no relevant micro-structural changes was occurred.

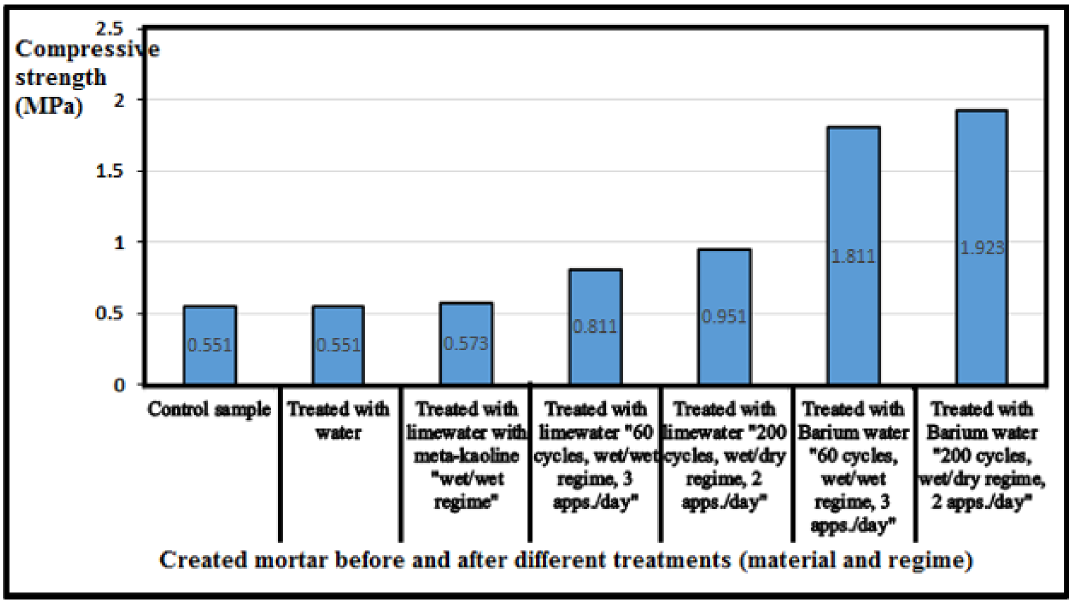

Figure 6: Compressive strength measured for control and treated mortar samples.

Table 1: Compressive strength of the control and mortar samples treated with the considered consolidating materials.

Sample State	Compressive Strength "Mpa"
Control sample	0.551

Treated with water	0.551
Treated with limewater with meta-kaoline “wet/wet regime”	0.573
Treated with limewater “60 cycles, wet/wet regime, 3 apps./day”	0.811
Treated with limewater “200 cycles, wet/dry regime, 2 apps./day”	0.951
Treated with Barium water “60 cycles, wet/wet regime, 3 apps./day”	1.811
Treated with Barium water “200 cycles, wet/dry regime, 2 apps./day”	1.923

Change in structure

Solutions with higher content of the active agents are considered as enough salt sources to a given building material e.g., brick, concrete, mortar. Such agents act as binding material for the unit components at the beginning till the whole pores and fractures are completely filled with such salt then, such agents (particularly the salts) start exerting stresses on the unit structure leading to its deformation [19-21]. Figure 7 (a-b) illustrates the basic differences between untreated (control) mortar and mortars treated with limewater and barium water, respectively, at the high power of magnification using the scanning electron microscope.

It has been noted that calcium carbonate has grown in the columnar form within the texture of the untreated mortar, together with tabular crystals. The mortar’s matrix is quite thin, with weak bridges. After 200 cycles of limewater treatment in the regime of full drying between subsequent applications, the matrix is filled with layers of newly formed discontinuous clusters of calcium carbonate. The difference between the consolidating matrices of lime and barium water can be noted (Figure 7). Barium water obviously resulted in a denser and better-connected microstructure, i.e., barium hydroxide presents higher efficiency as consolidating material compared with limewater.

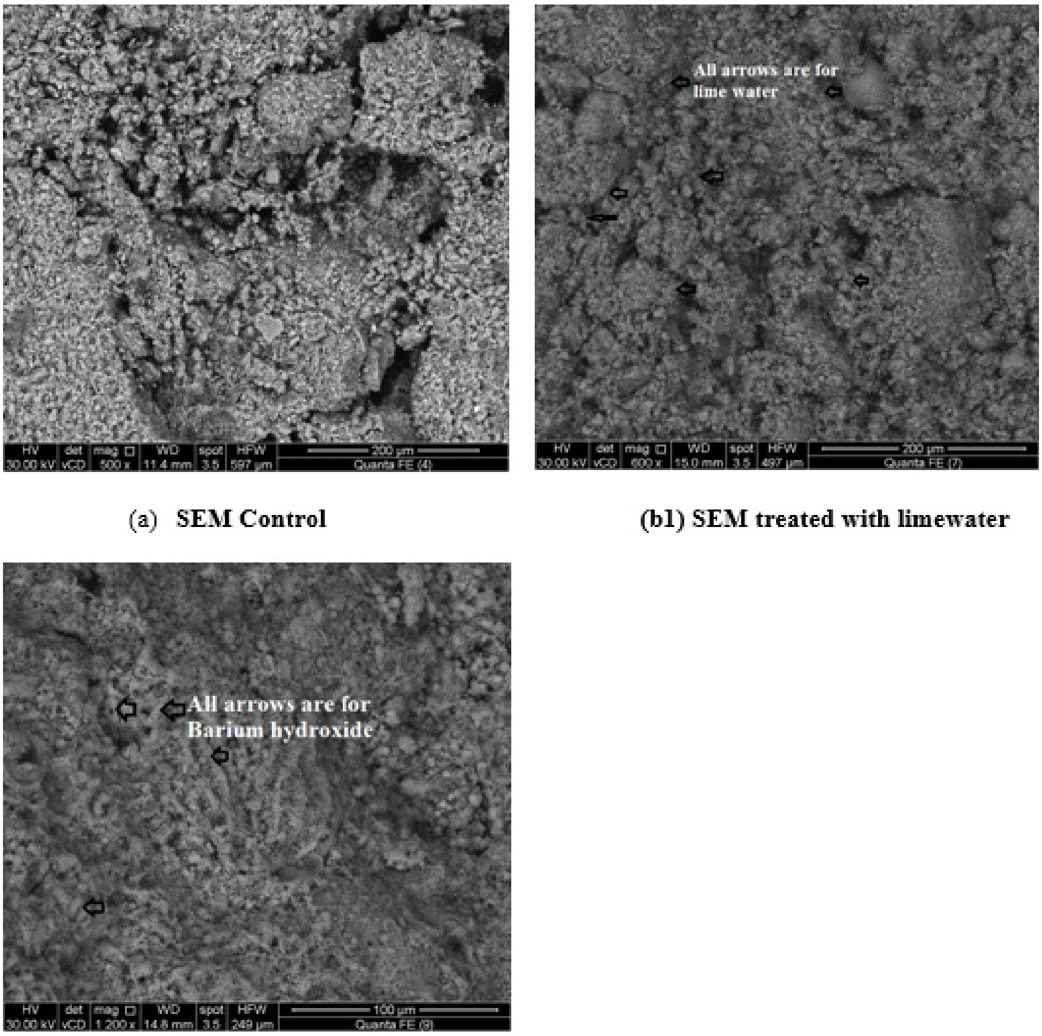

Figure 7: Presents a scanning electron microscopic investigation of the (a) control and (b) mortar samples treated with (b1) the limewater and (b2) barium water.

A microscopic study of the cross-sections conducted in the created and treated mortar samples, focused on the distribution of consolidates into the texture of the created mortar specimen through a depth profile starting from sample's surface to its deep inside. It has been noted that calcium carbonate on the surface layer of the created mortar, in the first case for the reference mortar, and in the second case for the mortar treated with 200 cycles of lime water, where a much thicker layer of calcium carbonate is visible. Barium carbonate presents dense structure on the treated mortar surface. Only the mortar samples treated with barium water presented a significantly higher deposition of barium (in the form of barium carbonate) mainly on the surface of created and treated mortar samples.

Change in porosity

The pore size distribution had examined for the reference and consolidated mortars using Mercury intrusion porosimetry (MIP AutoPore IV 9500) with pressure range of 13,000 to 30,000 MPa to achieve all pores within the examined samples. This test aims to find out the impact of different consolidating materials on the pore size distribution (PSD) of the created mortars and such PSD has been previously reported to be the main culprit behind material durability to weathering particularly by salts [22,23]. Five mortar samples copying those used for measuring each consolidation treatment (followed by calculating average values) for more data accuracy were also used for PSD measurements. The MIP results of the examined mortar samples indicated a slightly reduction for the porosity of the mortars particularly treated with limewater and barium water (Table 2a). For the lower number of consolidates (limewater or barium water) applications (60 cycles; wet/wet application; 3 apps./day), the porosity has been slightly shifted from mega-pores to meso-pores and micro-pores and the total porosity has been slightly decreased regarding its original porosity (Table 2a). While for the higher number of applications (200 cycles; wet/dry deposition; 2 apps./day), the porosity had been noticeably shifted from mega-pores to almost meso and micro-pores and the total porosity had been noticeably reduced regarding its original value (Table 2a). No significant difference, in reduction of samples' porosity, was noted for limewater with meta-kaolin compared to simple limewater consolidating materials (Table 2a). The shifting of mortars' pore size distribution at each consolidating material at each regime of application, regardless water and limewater mixed with meta-kaolin that haven't result in any progress in mortars durability, has been noted on the MIP curve (Figures 8a - 8e). The MIP enabled defining the salt susceptibility index (SSI) based on the PSD of the given mortar samples, and the interpretation of the SSI values has been based on [23] classification (Table 2b). It indicated a progress in mortars durability (by shifting SSI to salt resistance trend, Table 2a) particularly for those treated with barium water (wet/dry regime).

Table 2a: Mortar's pore properties for the control and the mortar treated with the different aimed consolid

Sample State	Porosity (%)	Salt Susceptibility Index (SSI)		Percentage of Pore Radii						
			Micro-pores		Meso-pores			Mega- pores		
		Value	Class	< 0.05μ	0.05 ~ 0.1μ	0.1 ~ 0.5μ	0.5 ~ 1.0μ	1.0 ~ 2.5μ	2.5 ~ 5.0μ	> 5.0μ
Control mortar	24.3	13.11	Very Salt Prone	0	12.9	6.7	8.05	0.23	45.6	26.52
Mortar treated with water	24.3	13.09	Very Salt Prone	1.2	8.4	9.6	7.7	3.8	47.3	23.43
Mortar treated with limewater mixed with meta-kaolin (wet/wet regime; 3 apps/day, 60 cycles)	24.1	13.02	Very Salt Prone	0.9	9.9	5.4	6.4	2.5	40.2	34.7
Mortar treated with limewater wet/wet regime, 3 apps./day, 60 cycles)	23.72	9.87	Salt prone	4.6	14.2	2.1	24.7	31.6	9.4	13.4
Mortar treated with limewater wet/dry regime, 2 apps/day, 200 cycles)	22.13	5.32	Salt prone	9.1	22.6	35.8	20.6	5.2	4.5	2.2
Mortar treated with Barium water wet/wet regime, 3 apps./day, 60 cycles)	22.01	4.51	Salt prone	2.1	9.8	19.4	23.7	21.3	12.5	11.2
Mortar treated with Barium water wet/dry regime, 2 apps/day, 200 cycles)	21.03	3.92	Salt resistant	13.8	30.2	33.7	9.3	3.2	4.6	5.2

Table 2b: Salt susceptibility index and its interpretation "Yu and Oguchi, 2010".

WSI	Interpretation
0 ≤ SSI < 1	Exceptionally salt resistant
1 ≤ SSI < 2	Very salt resistant
2 ≤ SSI < 4	Salt resistant
4 ≤ SSI < 10	Salt prone
10 ≤ SSI < 15	Very salt prone
15 ≤ SSI < 20	Exceptionally salt prone

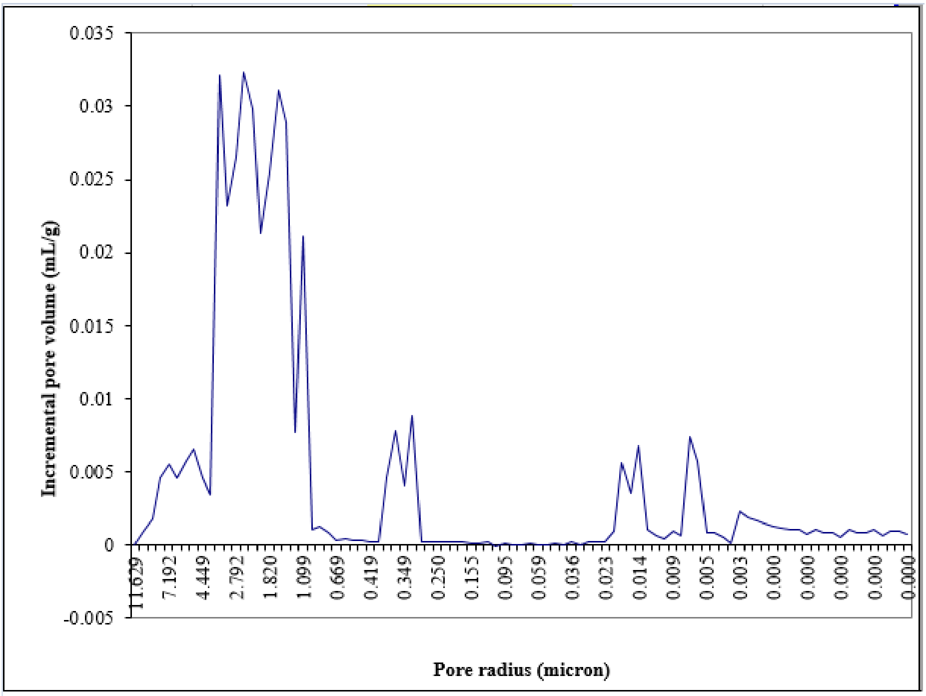

Figure 8a: Graphical relationship between Pore radius and Incremental pore volume (mL/g) for untreated mortar sample.

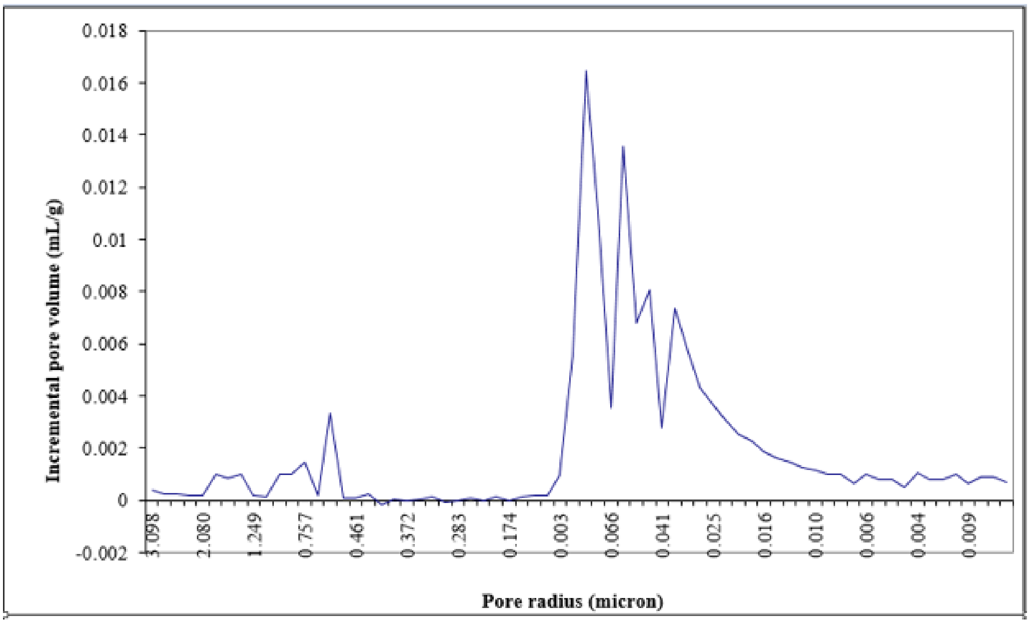

Figure 8b: Graphical relationship between Pore radius and Incremental pore volume (mL/g) for mortar sample treated with lime water (wet/wet regime, 60 cycles, 3 apps./day).

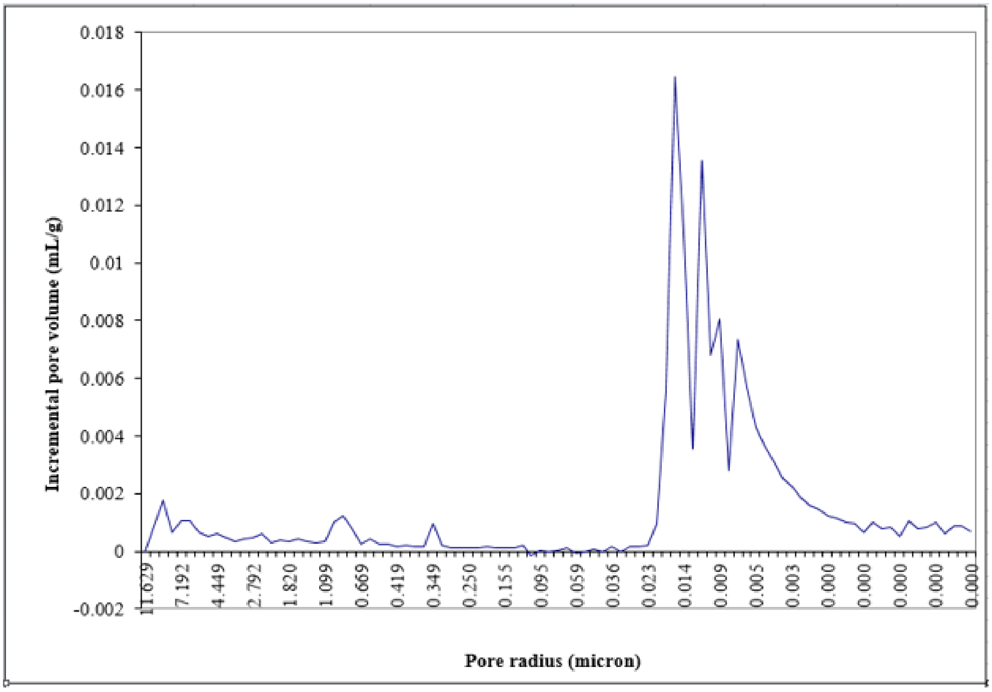

Figure 8c: Graphical relationship between Pore radius and Incremental pore volume (mL/g) for mortar sample treated with lime water (wet/dry regime, 200 cycles, 2 apps./day).

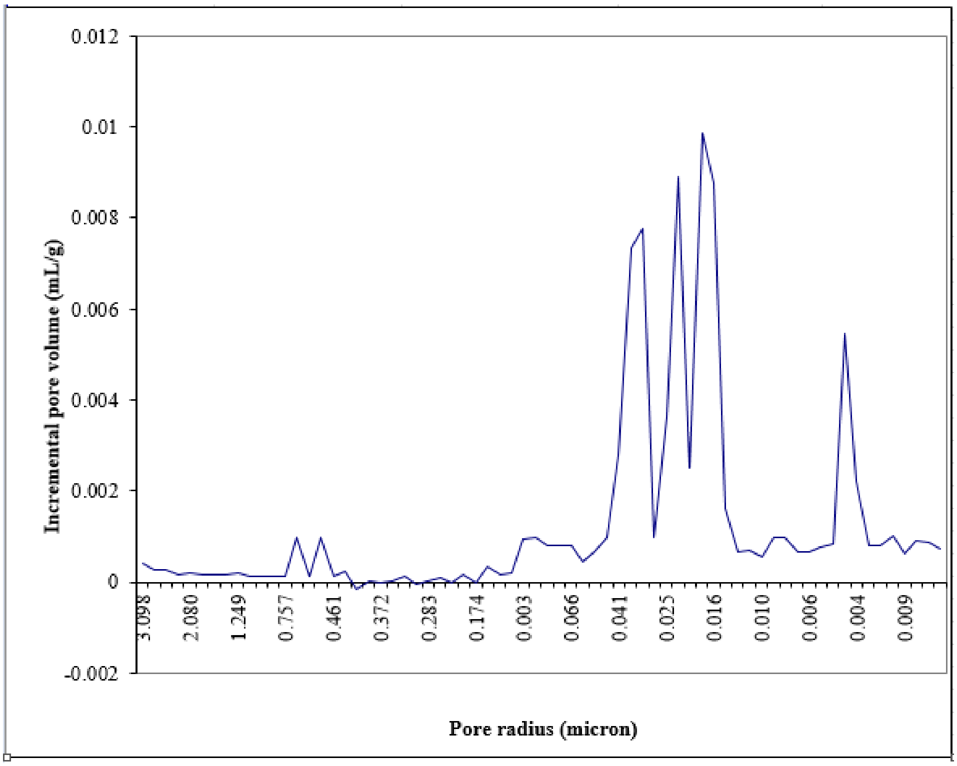

Figure 8d: Graphical relationship between Pore radius and Incremental pore volume (mL/g) for mortar sample treated with Barium water (wet/wet regime, 60 cycles, 3 apps./day).

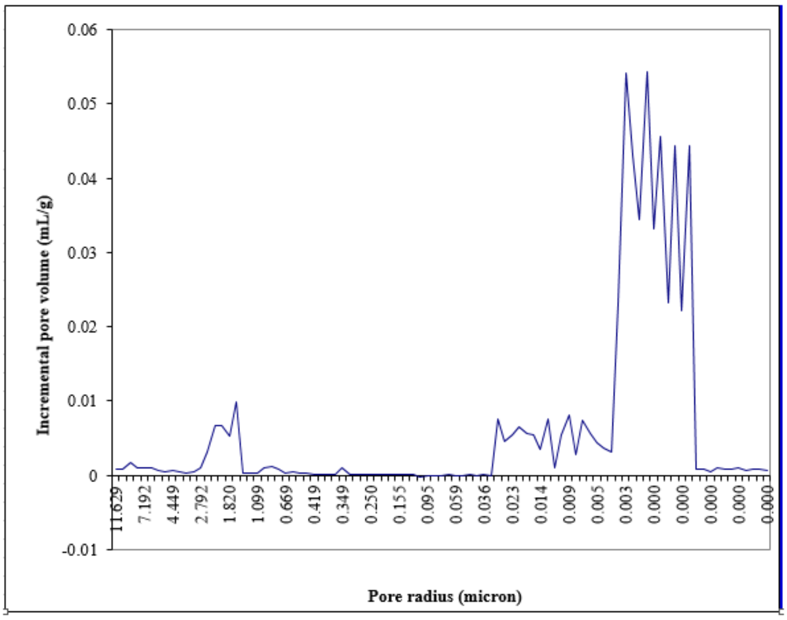

Figure 8e: Graphical relationship between Pore radius and Incremental pore volume (mL/g) for mortar sample treated with Barium water (wet/dry regime, 200 cycles, 2 apps./day).

Durability test

It is a measure of materials resistance to weathering/damage on its exposure to artificial weathering at conditions as those dominate at the study area but with condensed limits to highly reduce time from years scale to days scale [24]. The durable material is that expresses low weight loss percentage at the end of the test and vice versa. The weight loss percentage has been computed, at the end as well as every two cycles of the sixteen cycles of artificial salt weathering, for each mortar before and after treatment with each consolidating material following the equation of [25] given below:

Weight loss (%) = ((W1 – Wn) / W1)* 100 where W1 is the initial weight of a given sample, Wn is the sample's weight at the end of the test, the results are listed in Table 3, and graphically represented (Figure 9).

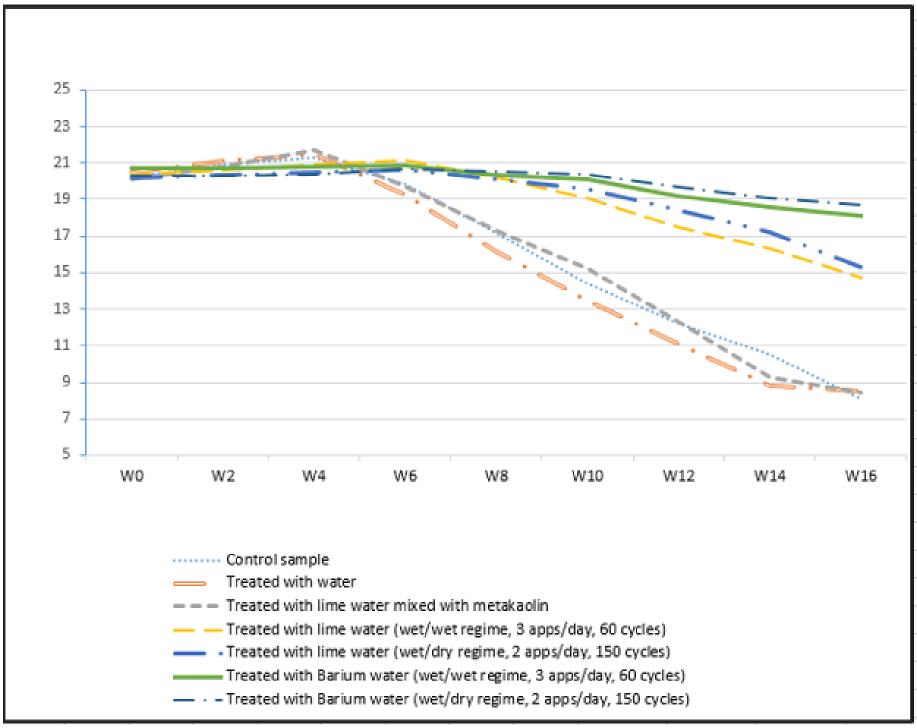

Figure 9: Presents mortar samples' weight every two artificial weathering cycles and the regime of weight loss for the control "untreated" and the other treated mortar samples.

From the graphical representation of the sample's weight through the sixteen cycles of artificial weathering (for the control and the treated mortar samples, Figure 9), it is clear that the first three cases of mortar behave nearly the same. In another words, they present slight increase in their weight as salt ingresses and fills mortars' pores in the first four cycles of durability test, then, a noticeable weight loss (decrease in samples' weight) has been reported (Figure 9 and Table 3). On the other hand, the mortar samples treated with either lime water or barium water at each of the two (wet/wet or wet/dry) regimes of application, present a noticeable withstand against weathering (particularly for barium water applied for 200 cycles, wet/dry regime) till the 12th cycle of attack. Then, slight to very slight weight loss can still be noted till the end of this test (Figure 9). This regime of weight loss is corresponding with the microscopic investigation of the treated samples that indicated noticeable ingress of barium water (more than limewater) within mortar's pore reducing pore size distribution (as indicated from MIP measurements conducted for these samples, Table 2a). This indicated the efficacy of barium water and limewater particularly limewater as well as barium water at wet/dry regime of application for that weak mortar.

By plotting the weight loss percentage of the control and treated mortar samples (Table 3) on [26] (Figure 10), the difference in durability can be noted among these cases. The three cases (control, treated with water, treated with limewater mixed with meta-kaolin) of the mortars have nearly the same durability without any impact of treating with water or limewater mixed with meta-kaolin, they are in durability class E i.e. very low durability class (Figure 10). While the mortar treated with limewater at its two regimes are falling within Class D i.e. low durability class which is better than class E [27]. Lastly, the mortar samples treated with barium water at its two regimes are within class C i.e. moderate durability class (Figure 10). This progress in cohesion/durability class of these treated mortars to the limewater and barium water trend (Table 3) is highly matching with SSI determined by MIP (Table 2a) (Figure 11).

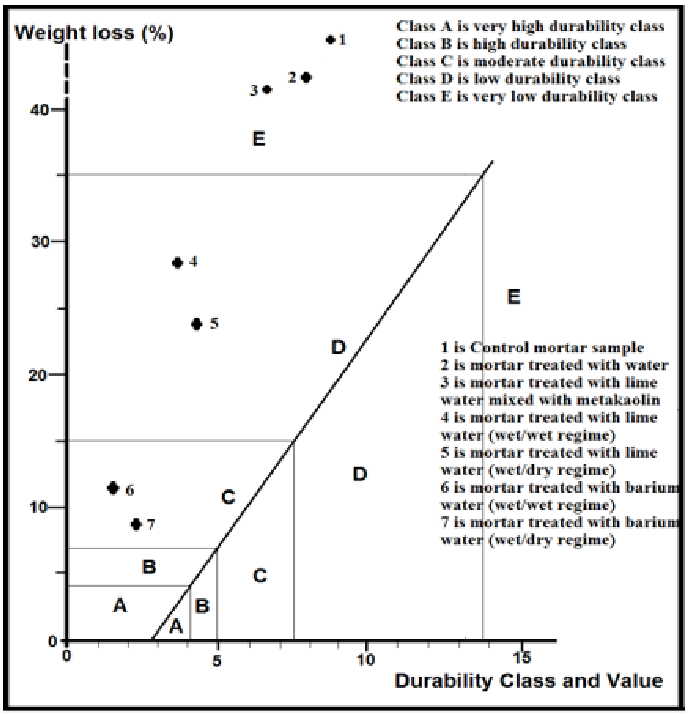

Figure 10: Barry diagram presenting weight loss against durability class for the mortar samples before and after treatment with water, limewater mixed with meta-kaolin, lime water and barium water.

Table 3: Mortar samples weight through fifteen cycles of artificial weathering using sodium sulfate salt solution.

Mortar Type	Sample's Weight Every Two Cycles through Test Progress									Weight loss%
	W0	W2	W4	W6	W8	W10	W12	W14	W16	
Control sample	20.2	20.9	21.3	19.8	17.2	14.4	12.2	10.5	8.1	59.90
Treated with water	20.5	21.1	21.5	19.3	16.1	13.5	11.1	8.8	8.5	58.54
Treated with lime water mixed with meta-kaolin	20.1	20.8	21.7	19.7	17.3	15.2	12.3	9.3	8.4	58.21
Treated with lime water (wet/wet regime, 3 apps/day, 60 cycles)	20.4	20.6	20.9	21.1	20.2	19.1	17.5	16.3	14.7	27.94
Treated with lime water (wet/dry regime, 2 apps/day, 200 cycles)	20.2	20.3	20.5	20.6	20.1	19.6	18.4	17.2	15.3	24.26

Treated with Barium water (wet/wet regime, 3 apps/day, 60 cycles)	20.7	20.7	20.8	20.9	20.3	20.1	19.2	18.6	18.1	12.56
Treated with Barium water (wet/dry regime, 2 apps/day, 200 cycles)	20.3	20.3	20.4	20.7	20.5	20.4	19.7	19.1	18.7	7.88

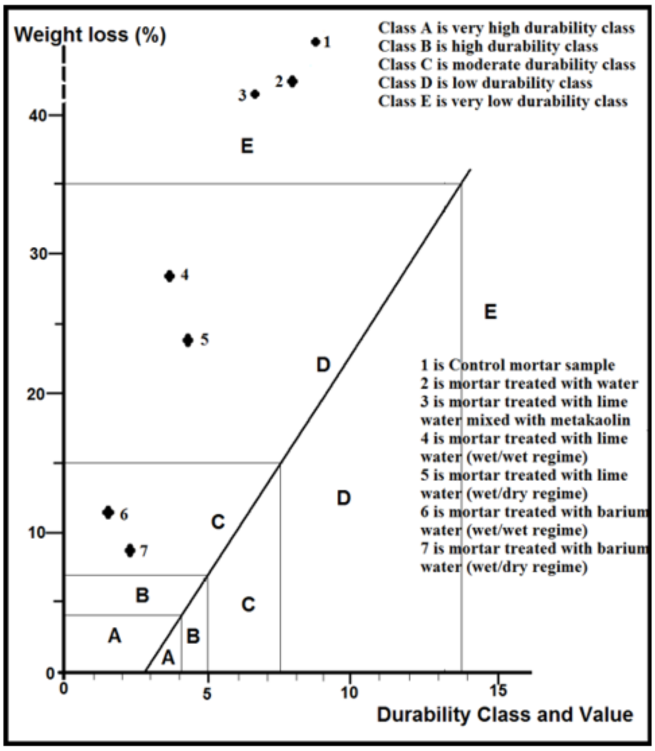

Figure 11:

Conclusion

Limewater treatment of a specific lime mortar had proved to be effective after a considerably large number of immersions (200 cycles of immersion) into a weak lime mortar. Some poor mechanical characteristics (compressive strength) were improved substantially after a large number of saturations. No consolidating effect of distilled water on the compressive strength of tested mortars with a low lime content (1:8) was observed. The higher concentration of barium hydroxide in its saturated solution resulted in higher limits of compressive strength than in specimens treated in the same mode with limewater, but the increase was not as large as would have been expected according to the concentration of the barium water. The improvement in compressive strength after consolidation was more than three times higher than the strength of the untreated (control) mortar samples. A microscopic study verified differences between the consolidating matrices of lime and barium water, where barium water clearly built a denser and better coherent substance. There was no detectable benefit of modifying limewater with meta-kaolin in terms of the mechanical characteristics of the treated mortar. The evaluated consolidating materials, in particular the barium water, reduced the porosity and pore size distribution of the investigated mortar. Concerning the distribution of the consolidates into the mortar specimens, a higher deposition of barium carbonate on the surface layer of the mortar was detected by scanning electron microscope. This finding corresponds with the results of the durability test conducted for these mortars over sixteen cycles of artificial weathering. The research reported here did not aim to optimize the application of various agents, only to make a comparison under specific conditions. This should be considered in order to avoid misinterpretation of the results.

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Conflict of Interest.

No conflict of interest.

References

1. Akin M, A Özsan (2011) Evaluation of the long-term durability of yellow travertine using accelerated weathering tests. Bull Eng Geol Environ 70: 101-114.
2. Ana PF, J Rodrigues (2012) Consolidation of carbonate stones: Influence of treatment procedures on the strengthening action of consolidants. Journal of Cultural Heritage 13(2): 154-166.
3. Angeli M, JP Bigas, D Benavente, B Menendez, R Hebrt, et.al (2007) Salt crystallization in pores: quantification and estimation of damage. Environmental Geology 52 (2): 205-213.

4. Arce R, BA Galan, JR Viguri (2010) Stabilization/solidification of an alkyl paint waste by carbonation of waste-lime based formulations. Journal of Cultural Heritage 177(1-3): 428-436.

5. Barry MK (1991) Durability factor and class attained from rock weight loss percentage after cycles of artificial weathering. Stone Conservation 17(B): 212-222.

6. Beck K, M Al-Mukhtar (2010) Evaluation of the compatibility of building limestones from salt crystallization experiments. In: Přikryl R, Török a (eds), natural stone resources for historical monuments. Geol Soc Lond Spec Publ 333: 111-118.

7. Carlos RN, D Eric, S Eduardo (2000) How does sodium sulfate crystallize? Implications for the decay and testing of building materials. Cement and Concrete Research 30(2000): 1527- 1534.

8. Clifton JR (1980) Stone consolidating materials-a status report. US Dep Commer Nat Bur Stand, NBS Tech Note 1118:46.

9. Cooke RU (1981) Salt weathering in deserts, Proc Geol Assoc London 92: 1- 16.

10. Daniele V, G Taglieri (2010) Nano-lime suspensions applied on natural lithotypes: the influence of concentration and residual water content on the carbonation process and on treatment effectiveness, J. Cult. Herit 11: 102-106.

11. Daniele V, G Taglieri (2012) Synthesis of Ca (OH)2 nanoparticles with the addition of Triton X-100. Protective treatments on natural stones: preliminary results, J Cult Herit 13: 40-46. .

12. Daniele V, G Taglieri, R Quaresima (2008) The nano-limes in cultural heritage conservation: characterisation and analysis of the carbonatation process. J Cult Herit 9: 294-301.

13. D'Armada P, E Hirst (2012) Nanolime for the consolidation of plaster and stone. J Archit Conserv 18: 63-80.

14. Fahey BD (1986) A comparative laboratory study of salt crystallization and salt hydration as potential weathering agents in deserts, Geogr Ann, Ser A: Phys Geogr 68: 107- 111.

15. Fitzner B, K Heinrichs, R Kownatzki (1995) Weathering forms, classification and mapping/ verwitterungsformen-Klassifizierung und Kartierung. Denkmalpflege und Naturwissenschaft, Naturstein-konservierung, V. 1 Berlin Ernst and Sohn 41-88.

16. Fitzner B, K Heinrichs (2002) Damage diagnosis on stone monuments-weathering forms, damage categories and damage indices. In: Prikryl R. Viles H. A. editors, Understanding and managing stone decay. Prague: the Karolinum Press 11-56.

17. Fitzner B, K Heinrichs, D La Bouchardiere (2002) Damage index for stone monuments. Protection and conservation of the cultural heritage of the Mediterranean Cities, Proc. of the 5th Int. Symposium on the Conservation of Monuments in the Mediterranean Basin, Sevilla, Spain, pp. 315-326.

18. Kamh GME (2003) Weathering processes acting on the Medieval Chester City walls, Project funded by Chester City Council, Chester City, UK.

19. Kamh GME (2011) Salt weathering, bio-deterioration and rate of weathering of dimensional sandstone in ancient buildings of Aachen City, Germany. International Journal of Water Resources and Environmental Engineering 3(5): 87-92.

20. Kramar S, A Mladenovič, M Kozamernik, B Mirtič (2010) Durability evaluation of some Slovenian building limestones. RMZ-Mater Geoenviron 57(3): 331-346.

21. Kwaad FJP (1970) Experiments on the granular disintegration of granite by salt action, Fys Geogr en Bodemkundig Lab. 67-80 (Amsterdam University).

22. Molina E, G Cultrone, E Sebastian, FJ Alonso (2013) Evaluation of stone durability using a combination of ultrasound, mechanical and accelerated aging tests. J Geophys Eng 10: 035003.

23. Moses C, D Robinson, J Barlow (2014) Methods for measuring rock surface weathering and erosion: a critical review. Earth Sci Rev 135: 141-161.

24. Price CA (1984) The consolidation of limestone using a lime poultice and lime water, in: Adhesives and Consolidants, IIC, London, pp. 160-162.

25. Wilhelm K, H Viles, O Burke, J May (2016) Surface hardness as a proxy for weathering behavior of limestone heritage: a case study on dated headstones on the Isle of Portland, UK. Environ Earth Sci 75: 931.

26. Yu S, CT Oguchi (2010) Role of pore size distribution in salt uptake, damage, and predicting salt susceptibility of eight types of Japanese building stones. Engineering Geology, Special edition, pp. 226-236.

27. Zhang J, H Deng, A Taheri (2019) Deterioration and strain energy development of sandstones under quasi- static and dynamic loading after freeze-thaw cycles. Cold Reg Sci Technol 160: 252-264.