EVALUATION OF THE WEATHERING OF STONE MASONRY DUE TO FREEZE-THAW CYCLES

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Abstract – The present study aims to contribute a better knowledge on the behavior of stone masonry subject to freeze-thaw cycles; to evaluate the wear progress on the materials, the physical and mechanical characteristics of stone masonry were determined by means of units, couplets and masonry assemblages (wallets) of granite stone and lime mortar. The freeze-thaw cycles were simulated in the laboratory; the control during various cycles was by a campaign of characterization tests. The evaluation of the mechanical properties, through flexural and compressive tests before and after being subjected to cycles, led to the prediction of wear on the units. The shear strength on masonry assemblages were obtained by means of diagonal compression tests, in addition the form of collapse was analyzed to define the wear of the mortar joints. The mortar bond strength were obtained based on tensile tests of granite and mortar couplet specimens, determined the loss of adhesion between the bonds of the mortar joints. The principals results obtained in this investigation are the variation of the physical properties like the increment of the internal porosity structure, the reduction of mechanical strength, and the loss of adherence on the joint mortars on the masonry assemblages.

Key Words – granite, lime mortar, physical and mechanical behavior.

I. INTRODUCTION

The historical monuments are mostly composed of stone materials and have many years of existence. It is important to know and understand the behavior of the material under different environment conditions, particularly when climatic changes are occurring all around the world. In particular, the focus of this paper is the analysis of the durability of stone when subjected to freeze-thaw cycles. Possible freeze-thaw cycles occur in northern region of Portugal and many other countries. Freeze-thaw cycles produce fatigue in the masonry materials and consequently cracks that induce the entrance of water Halsey *et al* [1]. The water inside the pores of the stone subjected to freeze develops internal tensions, producing tensile stresses and possible cracks and progressive degradation of the material. This leads to internal changes in the structure of the material, such as the modification of porosity and loss of cohesion. In the freezing period, the stone freezes and the water in the micro pores expands around 9% of the original volume. This expansion induces the concentration of tensile stress and damages in micro pores. The analysis of masonry materials subjected to the simulation of freeze-thaw that has been performed by different authors (mentioned in the develope of this paper) pointed out the change on physical and mechanical properties of the materials. The repetitive cycles can also lead to wear at the masonry joints, where the predominant material in historical constructions is the lime mortar. According to Lanas *et al* [2], mortars with high porosity and low resistance are more susceptible to degradation due to freeze-thaw cycles. Botas *et al* [3] points out that the capacity to resist water penetration, of losing water quickly and having an adequate porous structure that stands the strain caused by the increased volume of water as it passes between the solid and liquid state in successive, would define the evolution of weathering in the material due the cycles. This leads to the need for a better understanding of the parameters of stone masonry as a composite material influenced by the freeze-thaw cycles. This work presents an experimental campaign tests on granite stone units and lime mortar subjected to freeze-thaw cycles. Physical characterization was carried out on materials before and after submits them to freeze-thaw cycles. Properties like capillarity coefficient (C), open porosity (n), apparent volume (V_b) and ultrasonic pulse velocity (UPV) were obtained. Additionally, mechanical parameters like modulus of elasticity (E), compression strength (f_c) and flexural strength (f_f) were also determined aiming to determine the initial parameters and the control of aging through freeze-thaw cycles during different cycle intervals. Finally, it is presented the assessment of the influence of the cycles on mechanical properties like diagonal shear and tensile behavior in masonry joints.

II. MATERIALS AND METHODS

The main aim of the experimental tests is to evaluate the influence of freeze-thaw cycles on the mechanical and physical properties of materials like lime mortar and granite and masonry as a composite assemblage. For this, two procedures were used for simulation of the cycles. After the freeze-thaw cycles, mechanical tests were carried out to evaluate the influence of possible damage induced by the cycles on the mechanical properties, namely flexural and compression tests on mortar units, compression tests on granite units, diagonal compression tests on masonry assemblages (wallets) and tensile test on masonry couplets.

Characterization of materials

The most often used materials in historical and vernacular constructions in the north region of Portugal, namely in Minho region is stone masonry, the materials selected to be studied were granite stone and lime mortar. The granite selected is a yellow, two mica granite, fine to medium grain size with porphyritic trend with a high weathered degree. The lime mortar is pre-mixed mortar, dry premixed white mortar based on natural lime, a minor percentage of hydraulic binder and sand aggregate.

Equipment and testing procedure

The freeze-thaw tests were carried out following two testing methods; namely (1) the reference method used for natural stones based on the standard EN 1237 [4], (2) the reference method for the determination of the freeze-thaw resistance of brick units standard EN 772-22 [5], which was used for the assessment of the influence of freeze and thaw cycles on the shear behavior of masonry. The first testing method was used to test granites and mortar individually and the second testing method was used to carry out the freeze-thaw tests on wallets and masonry couplets. The granite cubic specimens (70x70x70 mm^3) and two types of lime mortar specimens were submitted to freeze and thaw cycles, namely 3 prismatic (160x40x40 mm^3) and 5 cubic specimens (50x50x50 mm^3). For this method, a temperature control sensor was introduced in a granite sample to validate the test and the equipment adaptation to the method stipulated in the standard. Therefore, the initial freeze cycle had a duration of 6 hours and the defrost cycle has the duration of 6 hours with the immersion of the specimens under water. To evaluate the effect of the cycles on the shear and tensile strength of granite stone masonry with lime mortar joints, 6 wallets (46x46x14 cm^3) were used for diagonal compression tests. The wallets were constructed with the same arrangement of granite units and thickness of mortar joints (1 to 1.5 cm). In order to control and evaluate the temperatures in the specimens, two sensors measured the internal temperature panel: a sensor was placed in a unit of granite and another sensor in a joint. Alike, the masonry couplet specimens were subjected to freeze-thaw cycles; 8 specimens composed of two prismatic granite pieces (150x150x50 mm^3) connected by a 10 mm of mortar joint (rough surface) were defined to evaluate the influence of the cycles of the tensile behavior of joints. The duration of the defrost phase was about 40 minutes and the duration of the freeze cycle was about 4 hours. The duration is therefore higher than the suggested by the standard but it was necessary to extend them to accomplish the temperature limits. Nevertheless, for both methods a LabView software was developed to control the acquisition system, collect and save the data for each cycle required.

Methodology to control the physical properties

As above mentioned, two types of specimens were submitted to freeze-thaw cycles, namely prismatic and cubic specimens. The prismatic specimens were subjected to 45 cycles and the cubic specimens to 40 cycles. Granite specimens were subjected to 86 cycles. During the test, a visual inspection of the specimens was performed, identifying a color dimming. The control of the physical parameters was carried out on gradually cycles, see Figure 1.

Figure 1. Test setup procedure of Method 1

The masonry wallets were immersed for 24 hours in water before the starting of the tests. As mentioned by Evans [6], the initial saturation condition influences the potential damage that can be induced by the freeze-thaw cycles. The masonry wallets were submitted to approximately 120 cycles. The smaller specimens to be tested under tensile loading were submitted to 80 cycles. Figure 2 illustrates the condition of masonry wallets and small tensile specimens inside the freezer during the freeze and thaw cycles. In diagonal test specimens measurements of UPV in granite stones were carried out before and after the freeze and thaw cycles. Both the mortar joints and the granites have a darkening of their color, like an opaque yellow.

Figure 2. Test setup procedure of Method 2

Methodology to control the mechanical properties
The diagonal compression tests were carried out following the American standard ASTM E 519-02 [7]. The specimens were tested after 28 days of construction, as indicated by the above standard. Figure 2 shows the application of a compression load along the diagonal will induce a theoretical pure shear stress distribution on the masonry wallet from which both shear and tensile strength of masonry can be obtained.
Besides, it was aimed also to evaluate the influence of freeze and thaw cycles on the tensile bod adherence of masonry mortar joints. The tensile tests were carried out under displacement control, being the control carried out in one of the LVDT's attached the mortar joint, taking as reference previous studies [8-9], see Figure 3.

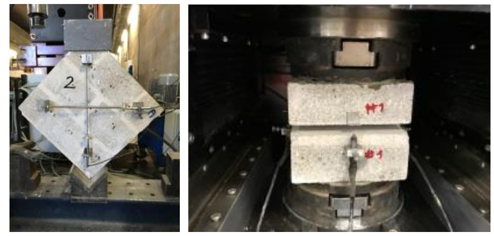

Figure 3. Details of tests on masonry assemblages: (a) Diagonal shear test; (b) Tensile test setup

III. RESULTS AND DISCUSSION

The granite units were subjected to 86 freeze-thaw cycles where: (1) mass loss and apparent volume was lesser than 1%, (2) the damage index defined by visual inspection was equal to approximately 0, (3) it was not possible to make a comparison of the modulus of elasticity (due to the heterogeneity of the material). These results mean that there was no significant damage induced on granite stone specimens according to the standard EN 12371, which indicates that up to 240 cycles should be performed to find damage on the units. Among the physical and mechanical parameters, the granites showed a slight decrease in the UPV rates due to the cycles. It was possible to identify a slight increase in the porosity values and in the capillary coefficient by water absorption. Compressive strength values failed to be comparable due to their high dispersion. However, it is identified that the porosity is a good qualitative index of the variation of the compressive strength of granites. The lime, cube and prism mortar units were subjected to 40 and 45 freeze-thaw cycles respectively, where: (1) the cubes had an average loss of dry mass of 2.8% and the prisms a mass loss of 7%, (2) the damage in the specimens was localized mainly at the surface (material detachment) and caused the decrease of its cross section. This damage could be identified by visual inspection. The values of porosity and capillarity coefficient showed a considerable increase, which is attributed to the loss of the material (Table 1).

The damage in mortar cubic specimens was localized mainly at the base of the specimens due to the superficial wearing, which influenced in the reduction of resistance under compression and flexural loading.

Table 1 Comparison of test results

Test in Units	Reference		After Cycles	
	Granite	Mortar	Granite	Mortar
C [$g/cm^2.h^{0.5}$]	0.37	0.30	0.41	-
n [%]	8.63	21.33	7.33	22.77
V_b [m^3]	345.46	128.71	347.26	126.34
UPV (m/s)	1600-2600	2768	1180-2660	2712
E (Mpa)	3669	-	4530	-
f_c [Mpa]	33.92	10.92	53.01	7.05
f_f (Mpa)	-	3.25	-	2.46

Three masonry wallets were subjected to 120 cycles of freezing and thawing, identifying: (1) visually darkening in specimens and slight loss of mortar, (2) ultrasonic velocities before and after cycles showed a 3% decrease in the wallet 1 and 15% in wallet 3, (3) reduction of the 42% of shear modulus, (4) reduction of 26% of the shear resistance. These results were also complemented with the analysis of the damage found in the comparison of the collapse patterns in the specimens tested under diagonal compression. It was observed that the freeze and thaw cycles should lead to weakness of the mortar joints and cracks developed along higher number of joints. Doing a comparison with the results of tensile bond adherence carried on couplet specimens after 80 cycles of freezing and thawing, seems to identify a reduction of the bond tensile strength.

IV. CONCLUSION

This investigation contributed to gather a better insight of the influence of freeze-thaw cycles of masonry materials and masonry assemblages. These cycles induce several damage inside the microspore structure (porosity) of the lime mortar and masonry joints. This damage resulted in the change of physical parameters and reduction of strength of materials and masonry joints.

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