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REVIEW OF HISTORIC STONE MASONRY PROPERTIES

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ABSTRACT

Selected properties of historic mortars and stone as well as mechanical properties of stone masonry under compressive, tensile and shear loadings are summarized in this paper.

INTRODUCTION

Historic stone masonry structures exist in Canada and many other parts of the world. The conservation and maintenance of these structures requires knowledge about the constituent materials of mortar and stone and about the mechanical properties of stone masonry subjected to various loadings. This paper presents a brief review firstly, of some key properties of historic mortars and stone and secondly, of mechanical properties of stone masonry subjected to compressive, tensile and shear loadings.

SELECTED PROPERTIES OF HISTORIC MORTARS

General

All too little published evidence is available about the material and mechanical properties of historic mortars. There are a number of reasons for this situation. Firstly,

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the proper study of these properties is costly and sufficient funding as well as even the full understanding of the importance of such a study by fiscal decision makers are often not present for a particular project. Secondly, where a proper study involving expertise in such areas as petrography, material science and engineering is carried out, the results typically do not get published but remain in client protected files. Thirdly, limitations such as the small size of many historic mortar joints and the low strength of mortars make it difficult to remove samples for mechanical testing in the laboratory, and fourthly, uncertainties about the exact mix proportions and mix materials of historic mortars make it difficult to reproduce these mortars for laboratory studies. In general, researchers have attempted to study small-size original mortar samples or reproduced original mortars based on their best understanding of the properties and proportions of these mortars.

Material Proportions of Historic Mortars

Historic mortars were typically lime-based, that is, lime constituted the major part or all of the binder. Also, hydraulic lime or pozzolana were used in many cases to provide hydraulic features to the mortar. The following section summarizes typical ranges of binder/aggregate ratios encountered on historic stone masonry constructions or else used in laboratory studies dealing with conservation and maintenance requirements of historic mortars.

Baronio and Binda(1991)[5] carried out a mineralogical analysis on 30 mortar samples obtained from the collapsed Civic Tower of Padua, Italy. The results indicated that the binder to aggregate ratios of the mortar varied between 1:3 and 1:5 with lime putty as the main part of the binder. No hydraulic lime was found in these tests. Gallo and Mollo(1986)[15] used reproduced mortars to construct stone masonry walls for laboratory testing. The mortar was a hydraulic lime mortar with a 1.5:1:1 lime:pozzolana:tuff stone aggregate mix; the binder to aggregate ratio therefore was a high ratio of 1:0.4. Chiostrini et al.(1989)[11] used two types of mortar in the construction of stone masonry assemblages for diagonal compression testing; the binder to aggregate ratio of both mixes was 1:3. For the binder, two ratios of hydraulic lime to Portland cement were used; these were 1:1 and 0.5:1. Calvi and Magenes(1991)[9] also employed hydraulic mortars in constructing simulated old masonry specimens; the mortars were mixed at a ratio of 1:3 by volume of hydraulic lime to sand. Mack(1977)[20] recommended a mix of white Portland cement:hydraulic lime:sand of 0.25:1:3 for lime-based old mortars. Mattioli(1986)[21] carried out compression tests on masonry specimens by using old bricks and new mortars; the new mortars were designed so that their overall properties should be similar to those of the original historic mortars. Two types of mortar were used, one with a slaked lime to sand ratio of 1:3 and the other with 7% Portland cement added to the mix.

For the conservation of Canadian historic limestone and sandstone constructions, Suter Consultants Inc.(1992)[26] carried out flexural bond tests on limestone and sandstone prisms built with four types conservation mortars; it was suggested that a mix of masonry cement:type N hydraulic lime:flyash:sand of 1.75:0.25:25%:6 was the best in terms of overall bond performance. Angotti et al.(1991)[3] designed three types of conservation mortars for the construction of stone masonry specimens for shear testing. The three mixes were Portland cement:hydraulic lime:sand = 1:2:9, lime:sand = 1:3, and hydraulic lime:sand = 1:4. Thomas(1975)[29] recommended that a good, workable repointing mortar should contain one part Portland cement to five parts of lime. Hendry(1993)[16] used two types of conservation mortars to construct limestone and sandstone masonry specimens for compression testing; the mortar mixes were Portland cement:lime:sand = 1:2:9 and 1:3:12. Angotti et al.(1988)[2] employed three types of mortar in constructing diagonal compression specimens to study the shear strength of existing masonry walls; the mixes were Portland cement:hydraulic lime:sand = 1:0.5:4, 1:2:9 and 1:0:3. ASTM C270-92a(1994)[4] lists mortar types O and N for tuck pointing; for type O, the mix should be one part Portland cement to 1.25-2.5 parts of lime, plus sand equal to 2.25-3.0 times the total of the binder.

In summary, the binder to aggregate ratio falls in the range between 1:0.4 and 1:5 with the majority of the ratios being in the 1:3 range. Concerning the binder, the ratio between Portland cement and lime is in the range between 0 and 0.5 with an average of about 0.23:1. It was found that quite a number of researchers used no Portland cement in their mixes and some researchers used hydraulic lime as part of the lime binder to give mortars some hydraulic features; it was not uncommon to employ hydraulic lime as the sole binder. It was suggested[20] that high lime mortars be used in historic masonry conservation work due to the fact that they are soft and porous and also deform little under varying climatic conditions. In addition, lime mortars are slightly soluble in water and therefore able to re-seal small cracks and voids that may develop. A certain amount of Portland cement and/or masonry cement, however, may be desirable in a mix to accelerate setting and achieve adequate freeze-thaw durability under harsh climatic conditions as exist for instance in much of Canada, the northern United States and northern Europe. Other additives may also be helpful. Suter Keller Inc.(1990)[27] reported that mortars with latex as an additive produced higher flexural bond capacities between mortar and stone units. The improved bond strength was unfortunately accompanied by a higher compressive strength which in general is not needed and not desirable in relatively massive stone masonry constructions. Biggs(1990)[7] suggested an air content of 16-18% for freeze-thaw durability of repointing mortars.

Compressive Strength of Historic Mortars

Tassions et al.(1989)[28] determined compressive strengths in the range of 3.0 and 3.5 MPa for mortars obtained from a 15th-century church. Baronio and Binda(1991)[5] reported test results on 30 mm cubes for mortar removed from historic buildings; the average strength was found to be 6.45 MPa. Tests carried out by Henzel and Karl(1987)[17] demonstrated that the compressive strength obtained from small mortar joint samples is significantly higher than that from equivalent laboratory-prepared specimens; in turn, both of those test results proved to be again higher than strengths obtained from standard-size mortar specimens. Sheppard(1985)[24] estimated a mortar strength of 3.25 MPa after performing in-situ tests on an old stone masonry wall.

Hendry(1993)[16] suggested a nominal mortar strength of 0.5-1.0 MPa be used in assessing stone masonry strength.

Peroni et al.(1981)[22] reported the results of tests on the compression strength of 476 mortar samples with varying mix ratios to model the composition of old mortars. They concluded that a 0.5-3.0 MPa compressive strength is advisable. Angotti et al.(1991)[3] designed three types of mortar, which were similar in mix to original mortars, to be used in constructing stone masonry specimens for shear testing. The average compressive strengths were 1.85, 0.94 and 0.44 MPa, respectively. Gallo and Mollo(1986)[15] carried out compression tests on 70 mm mortar cubes. The mortars were to be used in constructing shear test walls; the average compressive strength of the mortars was determined as 0.12 MPa. Calvi and Magenes(1991)[9] obtained an average compressive strength of 4.33 MPa on 15 mortar samples; these mortars were used in constructing shear specimens of old masonry. Suter Keller Inc.(1990)[27] designed five types of mortar and obtained an average compressive strength of 8.28 MPa. Suter Consultants Inc.(1992)[26] carried out tests on the physical and mechanical properties of conservation mortars, which were to be used in constructing sandstone and limestone masonry prisms for flexural bond testing. Eight types of mortar were used with a total of 24 mortar samples. The average compressive strength was 10.6 MPa. Hendry(1993)[16] used two types of conservation mortars to construct stone masonry specimens; an average compressive strength of 1.86 MPa was obtained from 18 mortar samples. Faella et al.(1991)[14] tested 10 tuffstone masonry walls under compression loading; the average compressive strength of mortars was 2.87 MPa..

In summary, for the compressive strength of original mortars, the available information reveals that it lies in the range of 0.1 and 3.5 MPa. For the reproduced conservation mortars, however, some researchers obtained higher strengths. Nevertheless, the majority of the reproduced mortars were reported to have a compressive strength in the range of 0.5 and 4.5 MPa. Based on the above discussions, in the case where no information is available concerning the original lime-based mortars, the assumption of a compressive mortar strength between 1.0 and 3.5 MPa is advisable.

Other Properties of Historic Mortars

Test results reported by many researchers indicate that the ratio between tensile and compressive strengths of historic mortars can be much higher than that of modern mortars, where the latter has a ratio around 10 to 20%. Angotti et al.(1991)[3] reported values of 71% and 63% for two groups of mortars. Tension tests performed by Gallo and Mollo(1986)[15] on 30 mm thick specimens indicated that the tensile strength was 10% of the compressive strength. Calvi and Magenes(1991)[9] obtained an average tensile splitting strength of 0.66 MPa for 14 mortar samples; the average modulus of rupture and splitting tensile strength represented 36.7% and 15.2% of the compressive strength, respectively. Suter Consultants Inc.(1992)[26] carried out tensile splitting tests on 24 mortar cylinders representing modern restoration mortars; the average result was 1.63 MPa which constituted about 16% of the compressive strength. In summary, for historic lime-based mortars, an average value of 36% was found for the ratio of tensile to compressive strength.

Baronio and Binda(1991)[5] reported test results for the modulus of elasticity of historic mortars; they obtained an average value of 905 MPa measured at 20-60% of ultimate strengths. Peroni et al.(1981)[22] reported modulus values for 70 conservation mortar samples; they determined average values of 4670 MPa and 2980 MPa for the initial tangent modulus and the final secant modulus, respectively.

PROPERTIES OF BUILDING STONES

Rocks used in buildings and monuments are called stones. The commonly used building stones are limestone, sandstone, marble, slate and shale. They belong to one of the following three genetic groups of rocks: igneous rocks, sedimentary rocks and metamorphic rocks, differentiated by the process of formation, which leads to varying properties for different rocks. Limestone and sandstone are sedimentary rocks. Granite and diabase are igneous rocks. Marble, slate and gneiss are metamorphic rocks. Sandstone and limestone are the most commonly used building stones. Compressive strength, density, modulus of rupture and modulus of elasticity are the major properties of building stones. It is found that the compressive strength of stones is closely related to their densities[30]. For most types of stones, the compressive strength is directly proportional to the density when the stone's strength is below 100 MPa[10].

Tests carried out by Colback(1965)[13] on sandstone samples showed that the strength of quartzitic sandstone at 98% relative humidity is only about 63% of the strength at dry condition. This percentage was about 57% for samples submerged in water before testing. The density of building stones varies in the range of 1800 and 2770 kg/m^3. In the province of Ontario, Canada, the average density of limestone and sandstone is 2620 and 2420 kg/m^3, respectively, and the average porosity is 4.6% and 11.1% for limestone and sandstone, respectively[18, 19].

The compressive strength of stones really depends on the specific material. For the strength of limestones and sandstones, a wide range between 20 and 250 MPa is reported by different authors[3, 24, 7, 25, 16]. Hewitt[18, 19] obtained an average compressive strength of 134 and 117 MPa for limestones and sandstones, respectively, from quarries in the province of Ontario. The compressive strength of limestones and sandstones lies in the wide ranges of 47-204 and 75-219 MPa, respectively.

The modulus of rupture of stones is about 10-30% of the compressive strength[23]. Biggs(1990)[7] reported a tensile strength of 20.7 MPa for limestones from an 1891 building; the tensile strength was 21% of the compressive strength of the stones, which was 99.6 MPa. Hewitt(1964)[18] reported an average tensile strength of 15.4 MPa for limestones from 15 Ontario quarries; the average compressive strength was 134 MPa. Hewitt(1964)[19] also reported an average tensile strength of 8.72 MPa for sandstones from 22 Ontario quarries; the average compressive strength was 134 MPa.

Robertson(1982)[23] reported an average modulus of rupture of 20.5 and 30 MPa for sandstone and limestone samples, respectively.

UNIAXIAL PROPERTIES OF STONE MASONRY

Under Compression

Walls in historic buildings often consist of more than one wythe with possibly different materials such as stone, brick and rubble making up the wythes. As a rule, these stone walls are usually very thick and the stresses in the walls are low. On the other hand, the strength of these walls can be very low due to the presence of weak mortars, the method of construction and the deteriorated state of the walls. Old masonry constructions are at times characterized by a high degree of deformability and considerable inelastic deformations[21].

Baronio and Binda(1991)[5] reported test results on thick brick-stone walls extracted from original buildings; the average compressive strength of masonry was determined as 2.8 MPa. Based on in-situ test results, Žarnić(1990)[31] suggested a compressive strength of 1.60 MPa, an elastic modulus of 2000 MPa and a shear modulus of 100 MPa for old masonry. Beolchini(1992)[6] carried out compression tests on 15 stone masonry specimens which were obtained from an 18th-century building; the average compressive strength was 1.12 MPa, with a strain of 0.013 corresponding to the maximum stress. Chiosterini and Vignoli(1994)[12] reported in-situ compression test results of old brick-stone masonry walls; the typical compressive strength for brick-stone and stone masonry was determined as 1.28 and 3.21 MPa, respectively.

Sheppard(1985)[24] carried out compression tests on two stone-and-brick walls, which were built by employing similar materials as used in the original building; the average compressive strength for stones and mortar were 55 MPa and 3.25 MPa respectively. The compressive strength for both walls was found to be 1.1 MPa and a design value of 0.9 MPa was suggested for compressive strength. Faella et al.(1991)[14] carried out compression tests on 10 tuffstone masonry panels. The test results indicated an average compressive strength of 1.34 MPa.

Hendry(1993)[16] carried out a series of compression tests on stone masonry piers; an average value of 8.31 MPa was obtained. Based on the expression given by Eurocode 6, see Equation 1, and on the test results, the K value was obtained as 0.55 for ashlar masonry and 0.45 for squared rubble, for a stone strength of up to 120 MPa.

$$f_k = K\,(\delta f_b)^{0.65}\,f_m^{0.25} \qquad (1)$$

where K is a constant related to the type of construction; f_k is the masonry compressive strength; f_m is the compressive strength of mortar; f_b is the compressive strength of the unit and δ represents a shape factor for the unit which is given by δ

$= (h/\sqrt{A})^{0.37}$, where h is the height of the unit and A is the loaded area of the unit.

BS 5628(1978)[8] deals in some detail with the compressive strength of stone masonry. For natural stone masonry built with large carefully shaped units and with relatively thin cement mortar joints, the compressive strength of stone masonry is more related to the compressive strength of the stone units than of the mortar, and the masonry compressive strength should be taken similar to that of solid concrete block masonry as given by the same code. For randomly laid rubble stone masonry, its masonry compressive strength may be taken as 75% of that of regular stone masonry. If lime mortar is used, 50% of that value should be used.

From the available sources, the compressive strength of stone or stone-brick masonry falls in the range of about 0.9 to 8.0 MPa; an average value of 1.3 MPa is obtained if the two extreme values are excluded. The average modulus of elasticity is 1465 MPa which is close to 1100 times the masonry's average compressive strength.

Under Tension
Suter Keller Inc.(1990)[27] carried out standard flexural bond tests by means of a bond wrench apparatus with 5 types of mortar and three types of historic masonry units, for a total of 75 specimens. The units were brick, limestone and sandstone. The test results revealed that the bond strength was significantly influenced by the type of unit. The mortars had an average compressive strength of 8.8 MPa and an average splitting tensile strength of 0.85 MPa. The average flexural bond strength for brick, sandstone and limestone prisms was 0.412, 0.268 and 0.704 MPa, respectively. The average bond strength of sandstone and limestone samples was 0.65 and 1.71 times that of brick prisms, respectively; since the bond strength of limestone prisms was 2.63 times that of sandstone prisms, the results added to the reasoning that bond strength is significantly influenced by the physical properties of units. Suter Consultants Inc.(1992)[26] carried out flexural bond strength tests on 40 prisms built with the same three types of historic masonry units as the 1990 work just discussed; mortar mix proportions, however, varied from the earlier work. The average ratio between bond and mortar compressive strength was found to be 8.1%. While the average bond strength of sandstone prisms was 4.8% of the mortar's compressive strength, this ratio was 11.4% for limestone. This test work showed very poor bond for sandstone as compared to limestone prisms. Based on in-situ test results, Žarnić(1990)(1990)[31] suggested a tensile strength of 0.12 MPa for old masonries. Sheppard(1985)[5] obtained a tensile strength of 0.131 MPa for old stone(and brick) masonry walls. A design value of 0.08 MPa was suggested.

PROPERTIES OF SHEAR LOADED WALLS

Beolchini(1992)[6] carried out cyclic diagonal compression tests on 15 prototype old stone masonry specimens with irregularly arranged round stones. The shear strength was found to vary between 0.09 and 0.685 MPa, with an average of 0.23 MPa. Angotti et al.(1991)[3] carried out in-situ destructive shear tests on two original walls. The average shear strength was determined as 0.17 MPa, corresponding to an average strain of 0.00363. The average shear stiffness was found to be 58.42 MPa, which fell into the same range as stiffnesses obtained from rebuilt walls. Sheppard(1985)[24] carried out in-situ destructive shear tests on a stone-and-brick masonry wall. The masonry compressive strength was 1.1 MPa. The maximum shear stress obtained was 0.20 MPa(at a strain of 0.014) and the initial shear stiffness was found to be 40 MPa. There was no obvious elastic limit since the stress-strain relationship was a smooth curve(no radical change of stiffness) from initial loading to the maximum stress.

Angotti et al.(1991)[3] carried out diagonal compression tests on seven newly-built stone masonry walls but using materials similar to those occurring in historic buildings. Two types of mortar were used and the average shear strengths were determined as 0.293 and 0.041 MPa, respectively. The average principal tensile strengths at the panel center were found to be 0.21 and 0.03 MPa, respectively. An average shear stiffness of 77 MPa was determined for the wall exhibiting the higher shear capacity.

Beolchini(1992)[6] analyzed the results of 15 diagonal compression tests on stone masonry walls which were extracted from a building built in the 18th century. He concluded that a bi-linear elasto-plastic relation gives the best fitting for the shear stress-shear strain curves. The ratio between γ_m(the strain corresponding to the maximum shear stress, τ_{max}) and γ_1(elastic strain) was found to be between 2 and 4, which can be taken as a measure of the ductility of the wall. An almost linear relationship was found between τ_1 and τ_{max}. In-situ destructive tests conducted by Angotti et al.(1991)[3] on two walls in an old building revealed firstly, that the shear stress-shear strain curve was parabolic before a yield level(the point after which the stiffness decreases dramatically) and flat thereafter, and secondly, that the deformational capacity after yield was very low as compared to the results obtained from tests on newly built walls. The newly built walls tested under diagonal compression exhibited a fairly good parabolic response with a large descending portion. The cause for this was not clear but the difference in testing equipment might have contributed to it. The shear strain at ultimate shear strength was 0.00350 and 0.00375 for the two walls, respectively, with an average value of 0.00363.

In-situ destructive shear tests carried out by Sheppard(1985)[24] on an old stone-and-brick masonry wall indicated that the stress-strain curve is parabolic before maximum stress and there was no obvious elastic limit, that is, the curve was smooth from initial loading to maximum stress. The shear strain at ultimate shear stress was about 0.014. Abrams(1992)[1] found, through experimental tests, that unreinforced masonry walls need not be considered brittle as usually assumed, and the ultimate shear capacity may as high as 3 times their initial cracking strength. Four brick walls were extracted from an old building and then tested. The results showed that the walls demonstrated substantial deformational capacity after initial cracking. Chiostrini and Vignoli(1994)[12] reported in-situ shear tests on stone masonry walls in an old building. Unlike the classical setup of the in-situ shear test, where the top edge of the wall is still connected to the rest of the structure, their test walls were cut along the two sides and the top edge. In this way the value of the normal compressive stress exerted on the top edge of the wall can be controlled. Chiostrini and Vignoli(1994)[12] also reported in-situ shear tests on five stone masonry walls in an old building by using the classical in-situ test setup. Horizontal load was applied at mid-height of each wall where the top and the bottom of the wall were still connected to the structure. The ultimate shear strength of three typical panels were found to be 0.15, 0.19 and 0.25 MPa with a normal compressive stress of 0.23, 0.43 and 0.12 MPa, respectively. Angotti et al.(1991)[3] tested 7 walls under diagonal compression. The resultant shear stress-shear strain curves were parabolic in shape with a long descending portion; this behaviour indicated significant ductility.

In summary, the ultimate shear strength of stone masonry ranges between about 0.09 and 0.69 MPa. Strengths were obtained from diagonal compression or direct shear tests. It was found in general that the deformability of stone masonry after so-called yield was very low. Parabolic curves for shear stress versus deformation were obtained by a number of researchers.

CONCLUDING REMARKS

Overall, relative little research has been carried out in the field of historic stone masonry. The brief review dealt with in this paper indicates that historic mortars are mostly lime-based and that their proportions of binder to aggregate vary greatly. In turn, key physical properties for both mortar and masonry such as compressive strength, bond strength, modulus of elasticity and shear strength also vary greatly.

For important stone masonry conservation and restoration projects, it is recommended to perform relevant testing rather than rely on the wide and therefore uncertain strength and property ranges available in publications. More of the project-oriented research should be published in order to help establish a broader, yet better defined, basis for historic stone masonry analysis and design as part of conservation and strengthening measures.

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