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Mechanical behavior of masonry assemblages manufactured with recycled-aggregate mortars

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ABSTRACT

Mortars containing recycled aggregate, instead of quartz sand, were characterized to find an alternative application for the fine recycled-aggregate fraction coming from building debris processing. Tests on bond strength of mortar to masonry units were carried out, as well as tests on compressive and shear strengths of masonry assemblages. The results obtained were related to the mechanical properties of mortars and brick. On the basis of the characterization results and performance evaluations, recycled-aggregate mortar appears to be superior to ordinary mortars in terms of mortar–brick bond strength and shear strength of masonry assemblages. This improved performance is of particular interest for the masonry structures in zones of seismic activity. In addition, the use of fine recycled aggregate is in accordance with the sustainable development concept, where recycling of building rubble plays a key role in ending the building life cycle.

1. Introduction

In the context of increasing waste production and growing public awareness of environmental problems, recycled materials from demolished concrete or masonry can be profitably used in different ways within the building industry. In Italy, at present these materials are mainly used untreated as obtained from demolition for excavation filling, roadbeds or floor foundation.

If suitably selected, ground, cleaned and sieved in suitable industrial crushing plants, rubble from building demolition could become useful for applications with higher performance standards.

Several authors [1–3] have studied the possibility of using recycled aggregates to prepare structural concretes and a Technical Committee (CEN/TC 154) in 2003 has drawn a European Standard (EN 12620 – "Aggregates for concrete including those for use in roads and pavements") in which artificial or recycled aggregates are considered for use in concrete. These studies showed that, in recycled-aggregate concrete, the fine recycled-aggregate fraction is particularly detrimental to both mechanical performances and durability of concrete. Evangelista and de Brito [4] found that the use of fine recycled concrete aggregates does not jeopardize the mechanical properties of concrete, for replacement ratios up to 30%. The author in previous works [5–7] studied mortars containing recycled aggregate, instead of quartz sand, to find an alternative application for the fine recycled-aggregate fraction.

Certainly, from a mechanical performance point of view, recycled-aggregate mortars are weaker than mortars prepared with quartz sand, but the same might not be true when comparing the behavior of masonry walls made of these mortars. In fact, the masonry mechanical behavior depends much more on the bond strength between brick and mortar than on the intrinsic mechanical properties of the mortar itself; and bond strength is related to the quality of the adhesion of fresh mortar to the brick [8–10], and thus to the rheological properties of the mortar [6].

In this work, some tests on recycled-aggregate mortars were carried out by comparing their behavior to that of traditional mortars made of quartz sand. The attention was focused on bond strength of mortar to masonry units, as well as on compressive and shear strengths of masonry assemblages. Results obtained were related to both elastic and mechanical properties of mortars and brick and, finally, to the quality of their interface.

2. Materials and procedures

2.1. Materials

A commercial portland-limestone blended cement type CEM II/A-L 42.5 R according to EN-197/1 [11] with Blaine fineness of 0.415 m^2/g was used. Also a hydraulic lime was used in order to compare the behavior of recycled-aggregate and virgin-aggregate mortars in the presence of a weaker binder. Actually, in Italy hydraulic lime is the most widely employed binder for mortars in ancient masonry. The chemical compositions of both cement and hydraulic lime are reported in Table 1.

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Table 1
Chemical composition of binders.

Oxide	Cement (%)	Hydraulic lime (%)
SiO_2	27.33	20.85
Al_2O_3	3.45	2.63
Fe_2O_3	1.66	1.27
TiO_2	0.08	0.06
CaO	62.46	71.36
MgO	1.06	0.81
SO_3	2.99	2.28
K_2O	0.73	0.56
Na_2O	0.24	0.18
LOI[a]	24.75	61.20

[a] Loss on ignition.

Either quartz sand or a fine fraction of recycled aggregate were used to manufacture mortars. The fine recycled-aggregate fraction was directly supplied by an industrial crushing plant in Villa Musone, Italy, where rubble from buildings demolition are suitably selected, ground, cleaned and sieved. The mean composition of this recycled-aggregate fraction was 72% old concrete, 25% bricks and tiles, and 3% miscellaneous (asphalt, glass, wood, paper, and other similar construction debris). Coherently with the indications reported in UNI EN 13139 [12], the content in the recycled-aggregate fraction of chlorides, sulphates, organic materials were evaluated according to the methods recommended by UNI EN 1744-1 (part 7, 11, 12, 14 and 15) [13] and the presence of alkali–silica reactive materials according to the method recommended by UNI EN 8520-22 [14]. No evidence of organic or alkali–silica reactive materials was detected; concerning the amount of chlorides and sulphates they were under 0.04 wt% and 0.15 wt%, respectively.

Recycled aggregates coming from the same plant were previously used to make concretes with encouraging results, as described in [15–17]. On the other hand, quartz sand was obtained from quarry by crushing process.

The particle size distribution of both virgin and recycled aggregates, with maximum size of 6 mm, determined according to EN 933-1 [18], are shown in Fig. 1. The specific gravities in saturated-surface-dried conditions, determined according to EN 1097-6 [19], were 2620 kg/m^3 and 2150 kg/m^3 for the quartz sand and the fine recycled fraction, respectively; the water absorptions were about 3% and 10%, respectively.

2.2. Mortar mixture proportions

The mixture proportions of the mortars are given in Table 2. The cement to sand ratio was 1:3 (by mass); the water content of each mortar was set to achieve the same consistence (120 ± 10 mm),

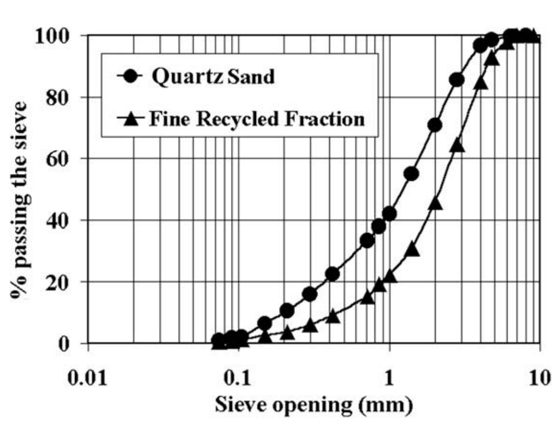

Fig. 1. Grain size distribution curves of the aggregate fractions.

Table 2
Mortar mixture proportions.

Mixture	W/CM	Mixture proportions (kg/m^3)				
		Water	Cement	Hydraulic lime	Natural sand	Recycled aggregate
Cem + REF	0.52	235	450	–	1350	–
Cem + REC	0.71	320	450	–	–	1350
HL + REF	0.56	250	–	450	1350	–
HL + REC	0.67	300	–	450	–	1350

Table 3
Absorption, porosity and mechanical characteristics of the brick.

Water absorption after 24 h immersion (wt%)	20.6
IRA[a] (kg/m^2/min)	2.35
Total Open Porosity[b] (%)	44
average pore Diameter[b] (μm)	1.98
compressive strength (MPa)	22.11
Flexural strength (MPa)	3.33
Shear strength (MPa)	4.72
Tensile strength (MPa)	2.52
Elastic modulus, E[c] (GPa)	13.70
Poisson coefficient, vv[c]	0.231
Elastic shear modulus, G (GPa)	5.56

[a] IRA: Initial Rate of Absorption.
[b] Determined by mercury intrusion porosimetry.
[c] Measured by means of strain gauges.

evaluated according to EN 1015-3 [20]. When fine recycled aggregate was added, a higher water dosage was necessary with respect to virgin-aggregate mortar to achieve the same consistency, because of the higher water absorption of the fine recycled aggregate with respect to the quartz sand.

2.3. Brick

A red high-burnt brick (980 °C) was employed to prepare masonry specimens; some absorption and porosity characteristics of the brick are reported in Table 3, together with some data on the physical and elastic behavior of the brick. The Initial Rate of Absorption (IRA) represents the mass of water absorbed per unit area in 1 min by the brick face in contact with the mortar when immersed to a depth of 3 mm in water; generally the IRA is expressed in kg/m^2/min. In this case, a brick with an Initial Rate of Absorption value very close to 2 kg/m^2/min was chosen, in correspondence to the recommended value [21] for obtaining the maximum bond strength value. The pore size distribution for the red brick is shifted towards large pores (average pore diameter of about 2 μm, see Table 3); it allows mortar to penetrate the brick surface well, to permit the water flow caused by the suction of brick pores, and to ensure a suitable water to cement ratio in the interfacial zone, as expected from capillary pressure theories [21].

3. Results and discussion

3.1. Chemical characterization of mortars

The presence of calcium hydroxide and calcium carbonate in the mortars was determined by differential thermal analysis; the results are reported in Figs. 2 and 3, respectively, as a function of curing time up to 90 days. The carbonation effect on the relative amount of calcium carbonate and calcium hydroxide was kept into account for each curing time. The different nature of the aggregates is quite evident in Fig. 3 the calcium carbonate content in recycled-aggregate mortars is 25–35% whereas for the virgin-aggregate

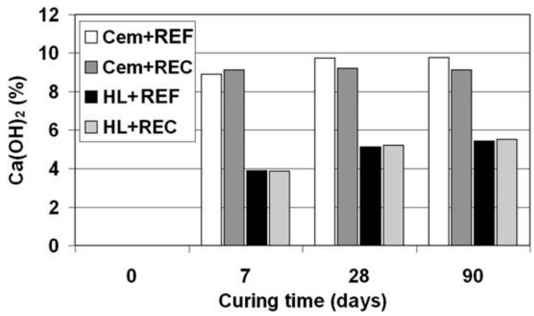

Fig. 2. Calcium hydroxide content of mortars as a function of time up to 90 days of curing.

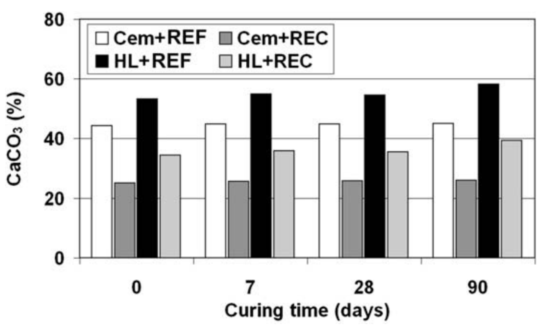

Fig. 3. Calcium carbonate content of mortars as a function of time up to 90 days of curing.

mortars it is 45–55% (the first percentage is relative to cement and the second percentage to hydraulic lime).

3.2. Pore structure characterization of mortars

Three samples were picked up from each mortar specimen after 70 days of wet curing, for testing them by means of the Mercury Intrusion Porosimetry. The mean results are shown in Fig. 4, where not only the total open porosity is reported but also its division into micropores (<0.1 μm), mesopores (0.1–1 μm) and macropores (>1 μm). Mortars prepared with the recycled aggregate showed higher total open porosity owing to a more porous aggregate but their content of macropores is lower.

3.3. Mechanical strengths of mortars

Prismatic specimens (40 × 40 × 160 mm) were manufactured, cast and wet cured at 20 °C up to 28 days. The compressive and

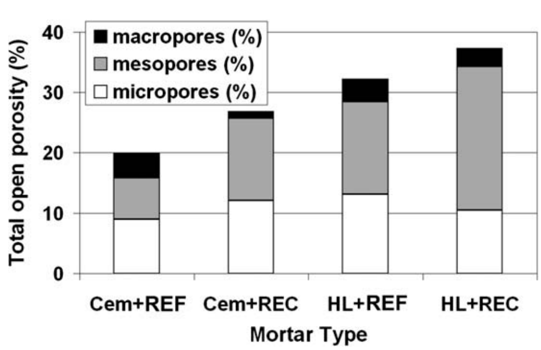

Fig. 4. Pore structure of mortars after 70 days of curing.

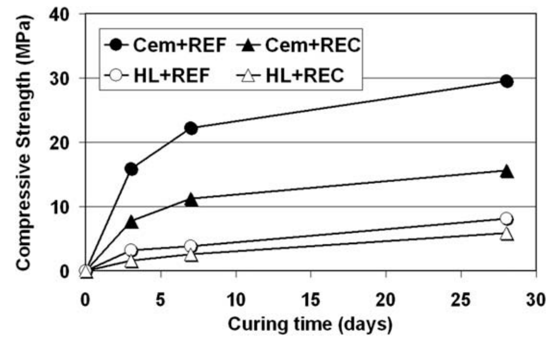

Fig. 5. Compressive strength of mortars vs. curing time.

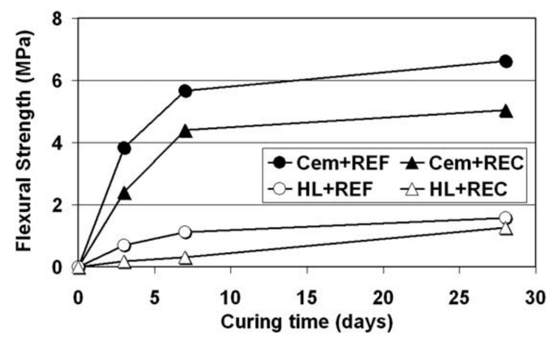

Fig. 6. Flexural strength of mortars vs. curing time.

flexural strengths were evaluated according to EN 1015-11 [22]. The results are reported in Figs. 5 and 6, respectively. Tensile strength was evaluated by means of splitting test. The results are reported in Fig. 7.

3.4. Elastic properties of mortars

Elastic modulus of elasticity (E) and poisson coefficient (v) were measured by means of strain gauges glued on cylindrical specimens (height of 180 mm and diameter of 60 mm). In order to avoid the temperature effect on the measurements, a dummy gauge was placed on an unloaded specimen (see Fig. 8). Results obtained are reported in Table 4.

The two mortar mixtures prepared with recycled aggregates, owing to the presence of a less stiff inert fraction, showed lower values of all the elastic properties with respect to the mortars prepared with quartz sand. The same effect was obtained in the presence of hydraulic lime instead of cement; in this case the reason lies in the weaker binding matrix surrounding the aggregate particles.

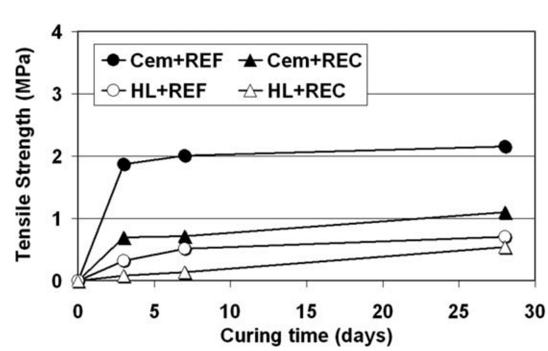

Fig. 7. Tensile strength of mortars vs. curing time.

Table 4
Elastic properties of the mortars after 28 days of curing.

Mortar type	Tangent elastic modulus, E (GPa)	Poisson ratio, $\nu\nu$	Elastic shear modulus,[a] G (GPa)
Cem + REF	36.84	0.222	15.07
Cem + REC	13.66	0.137	6.01
HL + REF	16.84	0.190	7.08
HL + REC	8.87	0.179	3.76

[a] Calculated as $G = E/2(1 + \nu\nu)$.

Table 5
Results obtained after 28 days by means of triplet tests, compression and diagonal tension tests on masonry assemblages.

Mortar type	Cem + REF	Cem + REC	HL + REF	HL + REC
Triplet test				
Mortar–brick bond strength (MPa)	0.89	1.14	0.23	0.26
Compression test				
First-cracking compressive strength (MPa)	6.34	6.09	4.09	4.01
Ultimate compressive strength (MPa)	11.31	11.15	9.09	9.74
Diagonal tension test				
Ultimate shear strength (MPa)	2.79	2.98	0.76	0.95
Elastic shear modulus (GPa)	3.875	5.260	2.460	4.850

The elastic properties of the brick reported in Table 3 were also measured and/or calculated according to the above described procedure.

3.5. Bond strength of mortars to bricks

In this work a test method, derived from UNI EN 1052-3 [23], was adopted in order to evaluate the bond strength developed between brick and a mortar layer 10 mm thick. In this way the masonry behavior in the absence of normal stress was investigated, corresponding to the constant term in the Mohr–Coulomb friction law.

The tested model, shown in Fig. 9, is composed of three bricks; it has a symmetric structure thus avoiding eccentric loads. For this purpose the geometry of the model was always kept under careful control. The configuration of the model was chosen to avoid the influence of the lateral deformation of the brick portions emerging from the joined portion. The applied load (L) was measured and at the same time the vertical displacement of the central brick (δ) was also monitored.

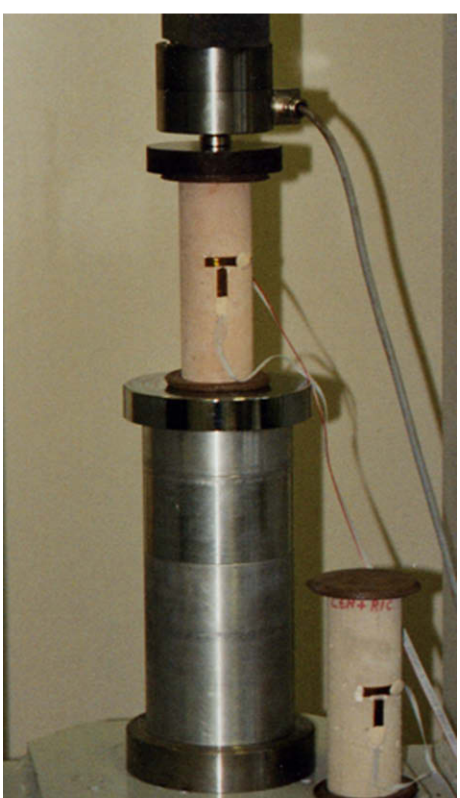

Fig. 8. Experimental apparatus for the measurement of elastic modulus (E) and poisson coefficient ($\nu\nu$) of mortars.

Usually at the end of the test only one joint was cracked, so the bond strength was calculated dividing the maximum load by twice and by the fracture area where brick and mortar were in contact (approximately 120 × 200 mm); test results are included in Table 5.

A good mortar–brick adhesion depends mainly on the quality of the interfacial zone; in fact, as shown in Table 5, the recycled-aggregate mortars, in spite of a worse mechanical behavior (see Figs. 5–7), showed better mortar–brick bond strengths with respect to virgin-aggregate mortars, whichever the kind of binder used; in particular an excellent result was obtained for the cementitious recycled-aggregate mortar (Cem + REC).

In fact, as shown in a previous work [6], the presence of recycled material influences the rheological behavior of mortars by lowering the yield stress value and by keeping it low for longer times; in this way the mortar could better permeate the brick surface assuring a physical interlock and, as a consequence, an improved bond. Also the lower stiffness of recycled-aggregate mortars, as shown in Table 4, could play a role in improving mortar behavior when submitted to bond strength test. Finally, on the basis of the results obtained by Poon and Lam [24], which showed the water absorption of the blocks to be closely related to the water absorbability of the aggregate particles, a positive effect on bond strength could be also ascribed to the higher tendency to retain water of the recycled-aggregate mortars.

3.6. Compressive strength of masonry assemblages

First-cracking compressive strength and ultimate compressive strength of masonry assemblages such as that reported in Fig. 10

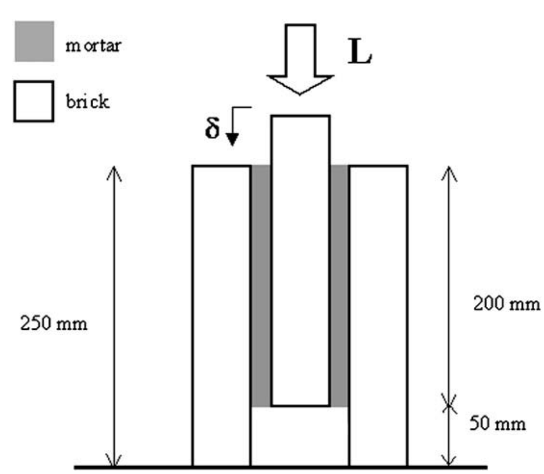

Fig. 9. Masonry model for triplet test.

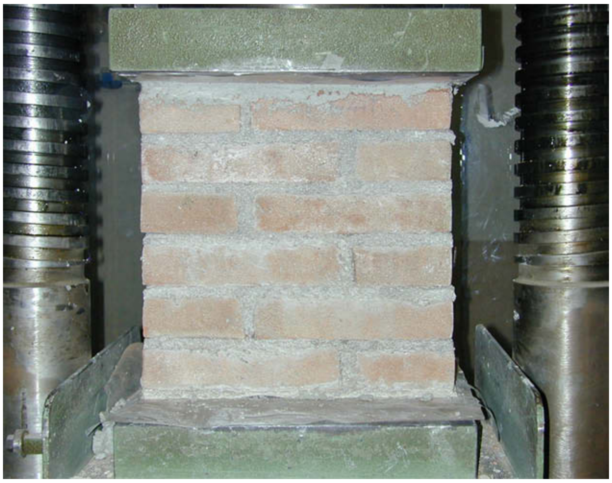

Fig. 10. Masonry assemblage for compression test.

were evaluated following a procedure similar to that described by ASTM C 1314-03b "Standard Test Method for Compressive Strength of Masonry Prisms" [25].

Three masonry prisms (120-mm thick, 390-mm long and 375-mm high) were prepared for each kind of mortar and cured in laboratory air at a temperature of 24 ± 4 °C, with a relative humidity of 70% for a period of 28 days. Proper capping of the prisms was carried out according to procedures prescribed in ASTM C 140 [26], so that the bearing surfaces were reasonably parallel and the bearing planes were smooth. The brick masonry prisms had a height-to-thickness ratio $h/t = 3.125$, consequently their compressive strengths were multiplied by a factor equal to 0.89 for keeping into account the slenderness effects [25].

The results obtained are reported in Table 5. In terms of both first-cracking and ultimate compressive strength, the masonry assemblages prepared with the two type of aggregate performed similarly, since a slightly higher performance was obtained in the presence of virgin aggregate when cement was used as a binder, while the opposite seemed to be valid for mortars prepared with hydraulic lime. In any case, the mechanism of failure involved the bricks, which broke for the tensile stresses induced on them by the transversal dilatation of the surrounding mortar. In this mechanism, the mortar mechanical properties are less important than other factors such as the quality of the mortar–brick interface, the value of the mortar elastic modulus and, in particular, of the mortar poisson coefficient in relation to that of the brick. In fact, a lower value of the mortar poisson coefficient with respect to that of the brick (as in the case of REC mortars) means a lower transversal dilatation of the mortar when stressed and, consequently, a positive restraint effect on the brick.

However, on average, 50% higher compressive strength was obtained in the presence of cement instead of hydraulic lime.

3.7. Shear strength of masonry assemblages

In order to achieve the proper structural design of a masonry building to resist wind or seismic actions, the strength and rigidity of the structural elements used in the shear wall construction must by accurately known. For this purpose, 'Diagonal tension tests' were carried out with a procedure similar to that described in ASTM E 519-02 "Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages" [27], which provides an accurate means to measure the diagonal tensile (shear) strength of masonry assemblages. In fact, the masonry assemblages are loaded in compression along one diagonal of the specimen. This results in a diagonal tension failure with the specimen splitting apart in a direction parallel to the load application. In fact, the specimens were placed into the testing machine with diagonal axis positioned as shown in Fig. 11. The load on the specimen was increased until failure of the specimen occurred. The failure pattern of each specimen was registered and ultimate shear strength as well as shear elastic modulus (modulus of rigidity) were calculated. Three masonry prisms (120-mm thick, 660-mm long and 660-mm high) were prepared for each kind of mortar and cured in laboratory air at a temperature of 24 ± 4 °C, with a relative humidity of 70% for a period of 28 days.

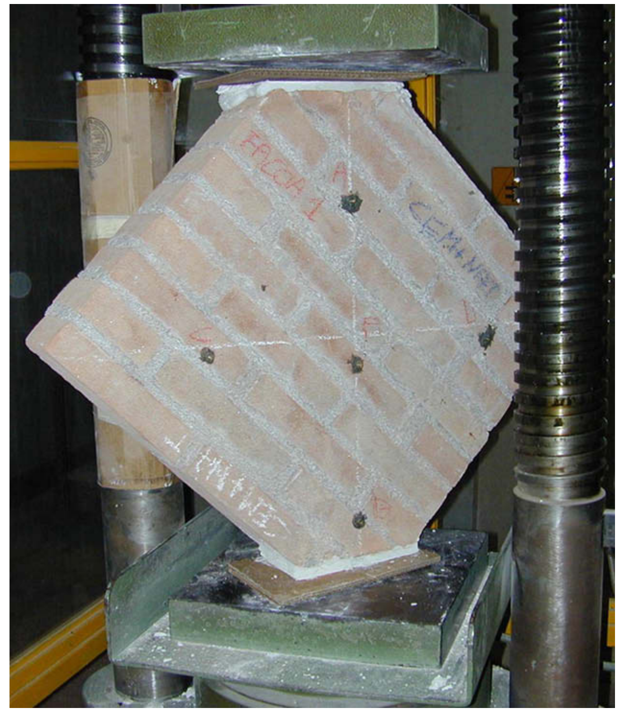

Fig. 11. Masonry assemblage for diagonal tension test.

The ultimate shear stress was calculated as follows:

$$\tau = \frac{0.707 \cdot L}{A} \tag{1}$$

where τ is the ultimate shear stress (MPa); L the applied load (N); and A is the average of the areas of the two contiguous upper sides of the specimen (mm^2). The shear strain was calculated as follows:

$$\gamma = \frac{\Delta V + \Delta H}{g} \tag{2}$$

where γ is the shearing strain (mm/mm); ΔV the vertical shortening (mm); ΔH the horizontal lengthening (mm); and g is the vertical gage length (mm). ΔH and ΔV were referred to the same gage length, g, equal to 500 mm, and they were measured by means of mechanical strain gage.

The elastic shear modulus, G (MPa), was calculated for predetermined stress levels, at approximately 20% and 50% of ultimate load, as follows:

$$G = \frac{\tau}{\gamma} \tag{3}$$

The results obtained are reported in Table 5. The failure pattern of the two specimens prepared with cementitious mortars (Cem + REF and Cem + REC) was produced by brick failure rather than by the separation along the interface between mortar and bricks. As confirmed by the high level of ultimate shear stresses measured for these mortar assemblages, when the mechanism of failure mostly involves the bricks higher shear stress is reached. On the other hand, the failure pattern of the two specimens prepared with hydraulic lime mortars (HL + REF and HL + REC) was a mix of the two kinds of failure previously described: through the bricks and along the interface between mortar and bricks.

By comparing the values of elastic shear modulus of brick, mortars and masonry assemblages (reported in Tables 3–5, respectively) it should be noticed that the masonry specimens prepared with recycled-aggregate mortars were more stiff than the related specimen prepared with virgin-aggregate mortar, whatever the kind of binder used although the recycled-aggregate mortars themselves were less stiff. The reason probably lies in the higher bond strength developed at the interface between recycled-aggregate mortar and brick (Table 5), which leads to lower wall deformability.

4. Conclusions

The recycled-aggregate mortars, in spite of poorer mechanical properties, show excellent bond strength with bricks due to what is likely a higher quality of the interfacial zone. Concerning the mechanical performance of masonry assemblages under vertical loads only, virgin- or recycled-aggregate mortars can be indifferently used; on the other hand, the use of cementitious mortars instead of hydraulic lime mortars can be recommended for achieving higher strength. Finally, the cementitious recycled-aggregate mortar performed well within masonry assemblages under shear-type loading, which would be important in seismic regions.

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