Mechanical Characterization of a Polyurethane-Cement Hybrid Foam in Compression, Tension, and Shear

Orsola Coppola, Ph.D.[1]; Gennaro Magliulo, Ph.D.[2]; and Ernesto Di Maio, Ph.D.[3]

Abstract: The mechanical properties of a polyurethane-cement hybrid foam are investigated. The hybrid foam, based on the combined, synergic use of rigid polyurethane foam and portland cement, was introduced for application in the building field. Thermal and acoustic insulation properties, water vapor permeability, and the fire resistance of the material have been reported in previous works. Here, a broad mechanical characterization including compressive, tensile, and shear tests is conducted according to ASTM standard methods for cellular plastic materials. The compressive tests show a brittle behavior of the hybrid foam, with the maximum strength achieved at large values of strain, compared to concrete. The material exhibits more strength under tension than under compression. The shear resistance values are similar to those of other building materials generally used for nonstructural components, i.e., cellular concrete and bricks. Finally, by comparing the physical properties of the hybrid foam with those of bricks and cellular concrete it is possible to highlight that the lightweight features of the former, associated with appreciable mechanical properties, make it suitable for building nonstructural components, also in seismic zones. **DOI: 10.1061/(ASCE)MT.1943-5533.0001738.** *© 2016 American Society of Civil Engineers.*

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Introduction

The functional and mechanical performances of building architectural nonstructural components, such as internal partitions, infills, cladding panels, and ceilings, are recognized to be a key issue in the field of energy saving (Papadopoulos and Giama 2007; Kilar et al. 2014; Pacheco-Torgal 2014) and in the framework of performance-based earthquake engineering (PBEE) (Bertero and Bertero 2002; Filiatrault et al. 2013).

On the one hand, the partitions and the infills are required to have good properties in terms of thermal and acoustic insulation, permeability to water vapor and, in some specific cases, fire resistance. On the other hand, the seismic performance of architectural nonstructural components is also a crucial aspect: the buildings' seismic response is generally influenced by the presence of partitions and infills (Tanganelli et al. 2013; Petrone et al. 2014); and, even in the case of low return period earthquakes (less intense than the reference earthquake for structural design), the damage of such secondary structures can cause a threat to life, the inoperability of the building, and large economic losses (Taghavi and Miranda 2003; Miranda et al. 2012). An example is provided by the damages observed after the 2009 L'Aquila earthquake in Italy [Fig. 1(a)]. In this case, the failure of brick partitions and infills (Braga et al. 2011) resulted in heavy socioeconomic consequences, including human casualties and loss of building functionality. Another example is provided by the 2012 earthquake in Italy's Emilia region, where the collapse of cladding panels caused the most widespread damage [Fig. 1(b)] and was the main cause of injury. In this case, the lack of seismic design in cladding panel-to-structural element connection devices, which allows accommodating the structure deformations during the seismic excitation, was the main cause of their collapse (Magliulo et al. 2014a).

For these reasons, in the last years, the selection of suitable internal partitions, infills and cladding panels, capable of accommodating the deformations of the main structure during an earthquake without exhibiting significant damage, has represented a critical aspect. Modern plasterboard partition systems are currently developed. They are usually designed in order not to interfere with the hosting structure, up to moderate levels of interstory drifts (<0.5%). Many studies refer to this nonstructural component typology, both in terms of experimental tests (Landolfo et al. 2006; Lee et al. 2007; Restrepo and Bersofsky 2011; Magliulo et al. 2014b; Petrone et al. 2015a), and numerical models representative of their seismic behavior (Fülöp and Dubina 2004; Kanvinde and Deierlein 2006). However, this typology is largely used in commercial and industrial buildings rather than in civil applications.

Moreover, new bricks are nowadays available for civil applications. For instance, cellular concrete blocks (Grinfeldl et al. 2014) are becoming popular both for internal partitions and for external infills because of their lightweight and appreciable mechanical properties (Tam et al. 1987). The light weight of the material is, indeed, largely considered the key issue in order to reduce the inertial forces acting on the nonstructural component during an earthquake. Actually, this aspect is related to the out-of-plane behavior because a reduced mass simply implies less intense inertial forces acting in the out-of-plane direction, which can cause the partition to overturn (Petrone et al. 2015b). However, the deformability of cellular concrete blocks, i.e., the ability to accommodate the in-plane deformation of the main structure during the seismic excitation, is not sufficiently supported in the literature.

Recently, a new hybrid material based on the combined, synergic use of polyurethane and cement was developed (Iannace et al. 2008)

[1]Postdoctoral Fellow, Dept. of Structures for Engineering and Architecture, Univ. of Naples Federico II, Via Claudio 21, 80125 Naples, Italy.

[2]Assistant Professor, Dept. of Structures for Engineering and Architecture, Univ. of Naples Federico II, Via Claudio 21, 80125 Naples, Italy (corresponding author). E-mail: gmagliul@unina.it

[3]Associate Professor, Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Univ. of Naples Federico II, P.le Tecchio 80, 80125 Naples, Italy; Hypucem S.r.l., P.le E. Fermi 1, Portici, 80055 Naples, Italy.

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(a) (b)

Fig. 1. Failure of (a) infills after the L'Aquila earthquake in 2009 (image by Gennaro Magliulo); (b) cladding panels in a precast building after the Emilia earthquake in 2012 (image by Orsola Coppola)

in order to obtain a new material able to meet the requirements for architectural nonstructural components in seismic areas, such as low density, strength and ductility, combined with thermal and acoustic features.

Polyurethane foams are widely used in the construction industry for their thermal and acoustic insulation properties, although they are characterized by low strength and stiffness. Common methods for increasing the foam stiffness consist of filling the polymeric matrix with a rigid phase; glass fiber, nylon fiber, silicon dioxide powder, and aluminum powder are examples of fillers. Despite the stiffening effect, several studies pointed out the problem of adhesion between the polymeric matrix and the filler, resulting in a brittle and weak overall behavior. For this reason, usually polyurea products are used in combination with masonry or concrete elements as reinforcement systems (Silva et al. 2008), rather than polyurethane foams.

Cement represents the most widely used structural material, but the high specific weight, low ultimate strain, low acoustic and thermal properties, and susceptibility to frost damage make this material unsuitable for architectural nonstructural components in seismic zones.

The new polyurethane-cement hybrid foam optimizes the properties of these two components and, at the same time, provides a lightweight material. The hybrid foam is conceived so that the inorganic and organic phases are cocontinuous throughout the material and the phases are intimately dispersed within each other. In this way, the system is designed to meet both the advantages of the polyurethane foam and the inorganic binder.

Previous studies (Verdolotti et al. 2008, 2010, 2013) reported the thermal and acoustic insulation properties of the material, the water vapor permeability, and the fire resistance. All of these properties proved the material suitable for infills or partition systems applications. Furthermore, the hybrid foam shows good compressive properties and adhesion to concrete and mortar typical of inorganic cementitious binders.

In this study, a broad mechanical characterization of the hybrid foam is presented to investigate the possible application in the civil building field for the seismic protection of nonstructural components, extending the previous characterization to the tensile and shear behavior.

Material

Polyurethane comprises a wide range of materials sharing the urethane functional group. In the common meaning it is the thermosetting form, obtained after the reaction of two oily liquids—polyol and isocyanate—reacting together to form a solid material and, as a side product of the reaction, a gas, responsible for the foam formation. In this case, the polyurethane-cement hybrid is formed by adding the cement to the polyol and then isocyanate was added. After mixing all the components, the mixture was poured in a wood closed mold ($50 \times 50 \times 5$ cm^3) and the foam was allowed to expand/cure for 20 min at room temperature [more details can be found in Verdolotti et al. (2008)]. Finally, hydration of the cement is achieved in water for 72 h at 60°C. It is this final hydration step that gives the hybrid label to the polyurethane-cement mixture. In fact, hybrid refers to a cocontinuous material in which both the polyurethane and the cement are continuous (both are matrixes and not a matrix and a filler). This peculiar and performing structure is achieved by a careful selection of the polyurethane and the cement and of their ratio, fixed at 2:3, as reported in Verdolotti et al. (2010). To clarify the hybrid definition, Fig. 2 reports scanning electron micrographs at different magnification of the fracture surface of the hybrid foam, evidencing both the coarse foam morphology and, within the solid foam walls, the hydrated cement forming a continuous network.

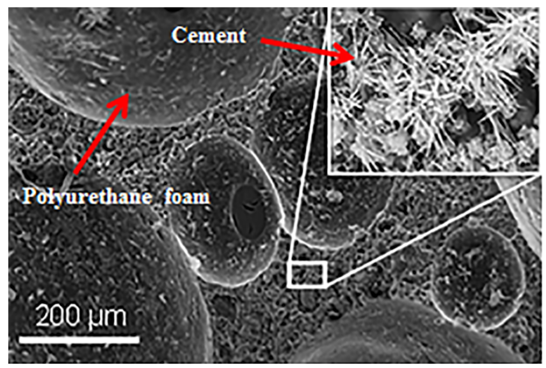


Fig. 2. Scanning electron micrographs of the fracture surface of the hybrid foam; inset: magnification of the hybrid foam formed by the polyurethane and the embedded hydrated cement phases (image by Ernesto Di Maio)

Experimental Program

Samples were prepared by mixing at room temperature the cement powder to the polyol with catalysts, silicone surfactant, chain

(a) (b) (c)

Fig. 3. (a) Cubic specimen cut from (b and c) a 60-mm-thick panel of the hybrid foam (images by Orsola Coppola)

extenders, and water as blowing agent. This mixture is stirred mechanically for 2 min and then MDI was added and mixed for 40 s. Mixing is performed according to ASTM C305 (ASTM 2014) by a Hobart mixer (model N50, Hobart, North York, Ontario, Canada). According to Iannace et al. (2008), the polyurethane-to-cement weight ratio was fixed to 2:3. After mixing all the components, the mixture is poured in a wood closed mold ($50 \times 50 \times 5$ cm^3) and the foam is allowed to expand/cure for 20 min at room temperature. The sample is then removed from the mold. Samples are then cured in water, for 72 h at 60°C, to allow for the hydration of the cement powder.

The chemical, physical, and morphological characterization of hydrated samples was reported in a previous publication (Verdolotti et al. 2012). Here, the authors focus on specific mechanical properties, namely, compression, tension and shear, which were determined according to ASTM international standards.

The standards were selected on the basis of the material chemical composition and structure. Particular attention was paid to cut the specimens so that all the surfaces were free from large visible imperfections: a milling machine was used to obtain the desired shapes according to the standard specifications.

Compressive Tests

The compressive properties of the polyurethane-cement hybrid foam were evaluated by testing the material according to ASTM D1621-00 (ASTM 2003a) (standard test method for compressive properties of rigid cellular plastics). To perform the tests, five cubical specimens with a 50 mm edge [Fig. 3(a)] were carefully cut from a rectangular panel of the hybrid material [Figs. 3(b and c)]. Before testing, each sample was gauged and weighted to measure the initial thickness and calculate the density.

A universal electromechanical machine (Alpha Technologies Tensometer 2020) was used as testing system with an automatic acquisition system [Fig. 4(a)]. The tests were performed in displacement control, with a displacement rate equal to 2.5 mm/min.

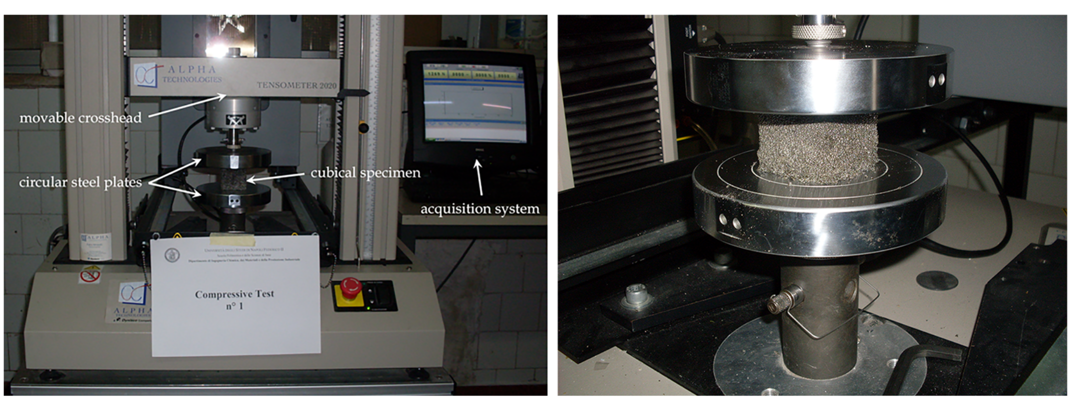
Some cracks and drop of dust characterized the specimen compression failure, as evidenced in Fig. 4(b). The test can be considered concluded when a 13% compression strain of the specimen original thickness is reached, i.e., a 6.5 mm crosshead displacement.

On the basis of the experimental stress-strain curves, the maximum strength for each specimen was evaluated, as well as the elastic modulus in compression (Young's modulus).

Tensile Tests

The ASTM D1623-03 (ASTM 2003b) (standard test method for tensile and tensile cohesion properties of rigid cellular plastics) was used as the reference method. According to this method, seven specimens were shaped as shown in Fig. 5. The two external conical parts of each specimen are conceived in order to connect the specimen to the testing machine, while the central cylindrical portion represents the length to test.

The test setup is conceived so that the external grips are fixed to the testing machine [Fig. 6(a)], while the internal parts are used to



(a) (b)

Fig. 4. (a) General view of the compressive test setup; (b) specimen configuration at the test end (images by Orsola Coppola)

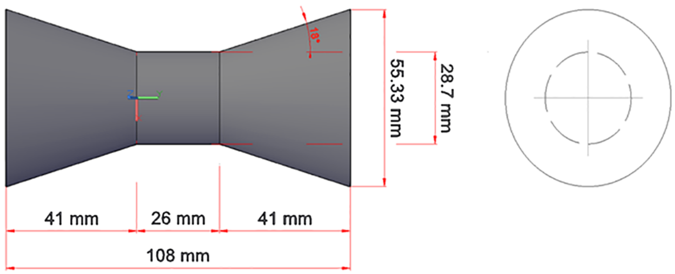


Fig. 5. Configuration of the specimen for tensile tests

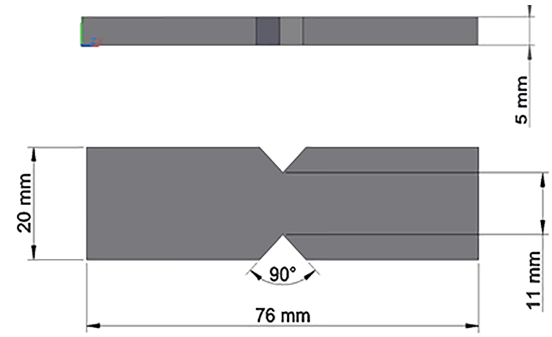


Fig. 7. Specimen configuration for shear tests

accommodate the specimen [Fig. 6(b)] and then are inserted in the external grip for testing [Fig. 6(c)]. At the beginning of the test, the external grips were approached and the acquisition system was set to zero. When the test started, the external grips were distanced with a 1.3 mm/min rate, up to the specimen failure [Fig. 6(d)]. The experimental stress-strain curves were obtained by dividing the recorded force by the cross section area of the specimen in the central portion and the recorded grip moving by the height of the central portion. The tensile elastic modulus is also evaluated, as in compression, by considering the slope of the first branch of the experimental stress-strain curve.

Shear Tests

The shear properties of the material were evaluated according to the ASTM D5379 (ASTM 2012) (standard test method for shear properties of composite materials by V-notched beam method). Even if this method is conceived for composite materials reinforced by high-modulus fibers, the V-notch shear test was originally proposed by Iosipescu (1967) for determining the shear properties of isotropic materials such as metals. In 1983, Walrath and Adams (1983) used it to test a wide variety of composite materials and even materials such as wood and foam. In all of these applications, the method worked well, providing well reproducible results.

According to the test method, five rectangular flat strip specimens, with symmetric centrally located V-notches (Fig. 7), were loaded by a special fixture, schematically shown in Fig. 8.

The specimens were inserted into the fixture with the V-cut located along the loading axis. During the test, the relative displacement between the two fixture halves, loaded the notched specimens.

The shear strength, recorded in the middle section of the specimen, was evaluated according to the following Eq. (1):

$$\tau_{\max} = \frac{F_{\max}}{t \cdot l} \tag{1}$$

where $F_{\max}$ = peak force of each experimental curve; t = thickness of the specimen at the V-notch (Fig. 7); and l = specimen width at the V-notch (Fig. 7).

Results and Discussion

Fig. 9 reports typical tensile (gray) and compressive (black) stress-strain curves of the hybrid foam. The compressive curve shows an initial elastic behavior, rather linear, up to the maximum strength of 1.46 (mean value) ± 0.21 (standard deviation) N/mm^2 (Table 1), beyond which a steep strength reduction of about 40% occurs, followed by a plastic behavior, with the stress almost constant while the strain increases. According to the utilized standard, the test was stopped at a strain of 13%, before the occurrence of the densification, which is a steep increase of the stress, typically observed in polyurethane foams at strain values of 70–80%. The maximum strength is reached for a 1% strain. This value is larger than the strain corresponding to the maximum concrete stress (i.e., 0.20%), proving a good deformability of this material at the maximum strength. The stress drop observed at 1% strain is due to the fragile fracture of the hybrid material forming the foam walls/struts. After the fracture of a first (weakest) horizontal section, there is a new stress buildup caused by the loading of the other sections, up to the

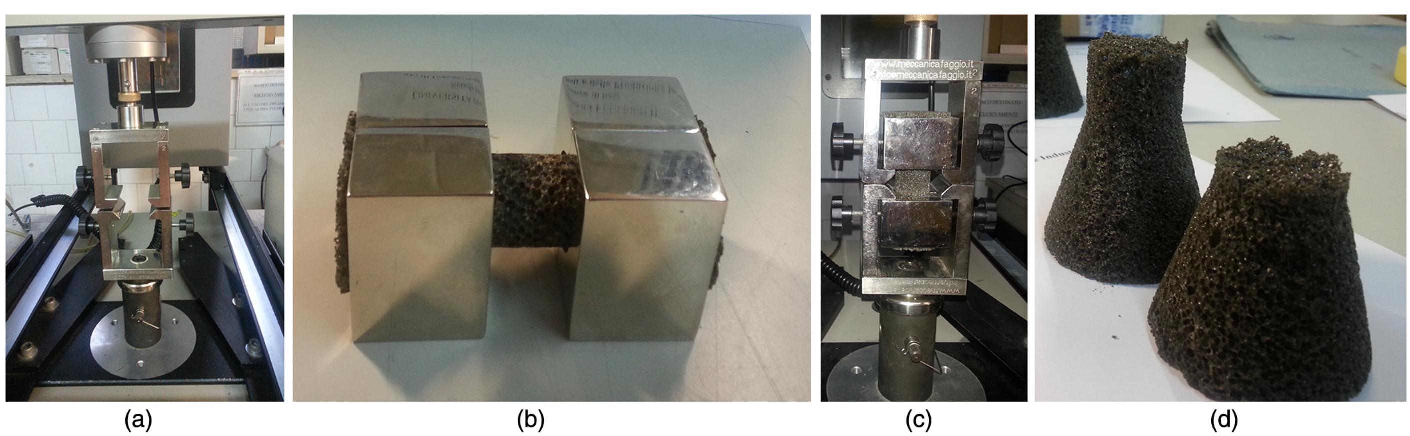


Fig. 6. (a) External grip connected to the testing machine; (b) specimen inside the testing equipment; (c) complete tensile test setup; (d) failed specimen at the end of the test (images by Orsola Coppola)

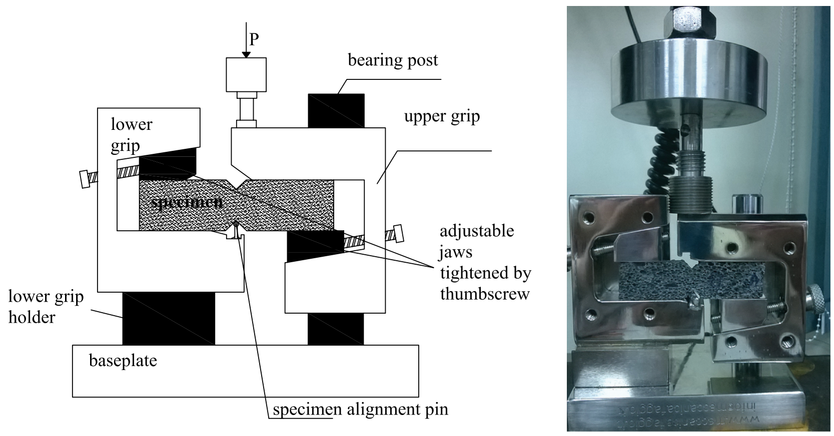


Fig. 8. (a) Scheme of the shear test fixture with the specimen; (b) view of the complete setup during the shear test (images by Orsola Coppola)

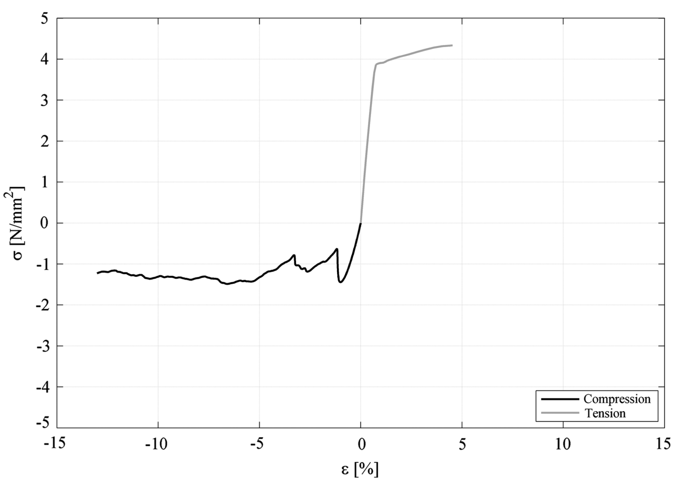


Fig. 9. Representative compressive (black) and tensile (gray) stress-strain curves of the hybrid foam

Table 1. Hybrid Foam Mechanical Properties in Compression, Tension, and Shear, Listed in Terms of Mean and Standard Deviation of the Test Results

Material	Unit	Hybrid foam
Density	kg/m^3	270
Compressive strength	N/mm^2	1.46 ± 0.21
Compressive Young's modulus	N/mm^2	144.23 ± 37.73
Tensile strength	N/mm^2	4.23 ± 0.23
Tensile Young's modulus	N/mm^2	612.05 ± 18.27
Shear strength	N/mm^2	0.66 ± 0.09

next fracture. A typical response of a compressive test of a foam is the attainment, after an initial elastic linear section, of a nearly horizontal plateau in the stress-strain curve, after which a sudden rise due to densification occurs. Along this plateau, cell edges buckle at constant Euler load, if morphology is regular, and progressively more and more cells are involved in buckling, at constant stress and in a large range of strain. This is true for flexible foams. If the material forming the foam is brittle, cell edges break, instead, with a continuous rise and fall of the stress-strain curve. This compressive behavior should be classified as microscopically brittle and macroscopically ductile, as the overall strength remains constant.

The results herein achieved in compression (Table 1) are in accordance with previous results, as evidenced in Fig. 10, both in terms of compressive strength and Young's modulus. Considering a linear trend in case of both density versus compressive strength and density versus Young's modulus in compression, the black circle, from the present investigation, is consistent with the ones in Verdolotti et al. (2008, 2010); namely, both the strength and the stiffness of the hybrid foam in compression increase linearly with the increase of foam density.

In the tensile region (gray line in Fig. 9) of the stress-strain curve, an elastic-plastic behavior is evidenced. Larger maximum strength and elastic modulus are recorded in tension, as evidenced in Table 1, than in compression. The presence of the polyurethane phase provides the hybrid foam with good tensile strength and an appreciable ductility in comparison with a standard or cellular concrete.

In terms of shear behavior, it was not possible according to the standard specifications for shear tests to glue the strain gauges on the specimens surface in order to measure the shear strains. In fact, in some preliminary tests, it was noted that the adhesive paste, penetrating into the hybrid materials cavities, modified the test response by changing the expected failure mechanism. So, the results listed here are related to new tests performed without strain gauges, in order to have, at least, information on the shear strength. The experimental force-displacement curve, shown in Fig. 11, highlights a linear trend up to the maximum force (66 N), beyond which a brittle behavior is recognizable. The value of shear strength, i.e., 0.66 ± 0.09 N/mm^2, is lower with respect to the values of compression and tension strength.

The mechanical properties, in compression, tension, and shear achieved by the presented tests allow making a comparison between the hybrid foam of interest here and other materials, nowadays widespread in the building market and generally used in the field of architectural nonstructural components.

In Table 2, a comparison in terms of mechanical and physical properties between the hybrid material and other two materials for architectural nonstructural component use, i.e., brick, widely studied (Decanini et al. 2004; Dolšek and Fajfar 2008b, a) and largely used in civil applications for infills and internal partitions, and cellular concrete, is reported. The choice of these two materials for comparison is not fortuitous, since the hybrid foam could be

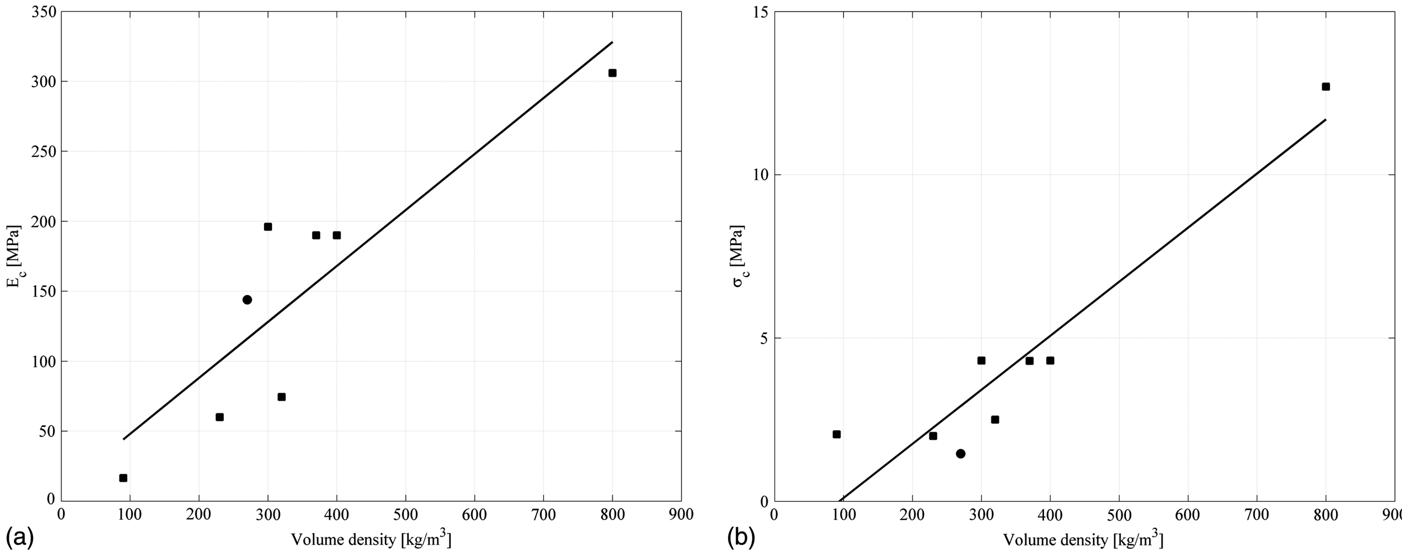


Fig. 10. Effect of the hybrid foam density on (a) compressive strength; (b) compressive Young's modulus and fitting line with corresponding value of coefficient of determination [black squares indicate data from Verdolotti et al. (2008) and Verdolotti et al. (2013); black circles indicate data from the present work]

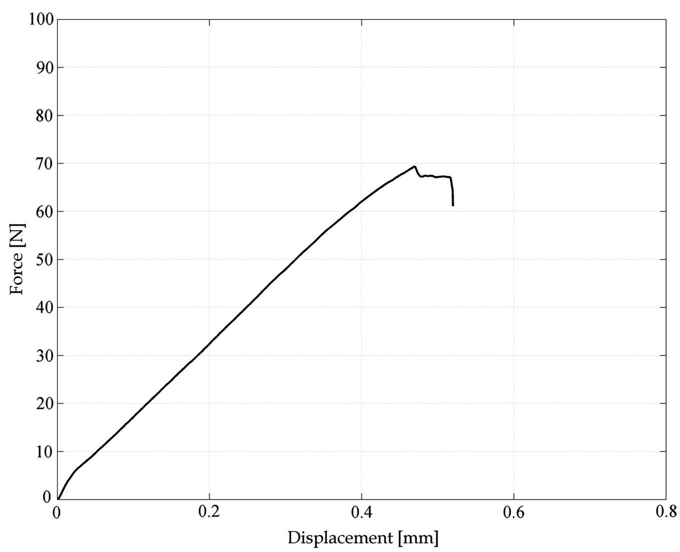


Fig. 11. Representative shear force-displacement curve of the hybrid foam

used in the same field, i.e., for infills and internal partitions of reinforced concrete structures, due to its good cohesion properties to mortars. In the case of the hybrid foam, indeed, the high concentration of hydrated cement, distributed within the material and on the surface, allows a good cohesion to the mortar. In comparison with bricks and cellular concrete, furthermore, the hybrid foam has the lowest specific weight, which is a suitable aspect in seismic field due to the reduction of mass and, consequently, of inertial forces. The lowest Young's modulus in compression proves the hybrid foam to be a more deformable material, which could accommodate the deformations of the hosting structure during an earthquake.

The hybrid foam shows a lower compression strength in comparison with the brick and the cellular concrete; however, as shown in Fig. 10, strength and stiffness increments could be obtained by a density increase. On the contrary, good behavior in terms of tension strength was found for the hybrid polyurethane cement foam, even though a direct comparison is not shown in Table 2 because brick and cellular concrete tension behavior was not found in the literature. In terms of shear strength, the observed values for the hybrid foam are close to the average value for brick and larger than the cellular concrete shear strength. This aspect is attractive if applications for internal partitions or external infills are considered for the hybrid material: the capacity of accommodating the in-plane deformation of the structure, due to the seismic excitation, increases with the shear strength.

With regard to the physical characteristics, the fire reaction Euroclass of the hybrid material (B2) highlights lower fire resistance features, due to the presence of the polyurethane phase, than the brick and the cellular concrete, which are classified as not combustible materials (A1). The properties of sound insulation are comparable between the analyzed materials, even though the polyurethane-cement foam has the lowest value. This hybrid foam typically shows a microstructure characterized by both closed cell walls and microcavities; for this reason, it does not perform as well in sound insulation as the open-celled foams, such as the flexible polyurethane foams. The hybrid foam shows very low values of thermal conductivity, lower than those of the traditional lightweight concrete commonly used as insulator (i.e., 0.12 W/m K). Generally, a decrease of the insulating performances was observed with the increase of the density. This result is reasonable in view of the relative higher amount of conducting solid phase in higher density hybrid foams. The introduction of the cement in the hybrid foam improves the permeability property of the material: as the amount of cement in the hybrid material increases, the water vapor transmission resistance decreases (Verdolotti et al. 2012). This relevant decrease of the water vapor transmission resistance has been ascribed to the formation of the cocontinuous cement phase within the polyurethane matrix, as a consequence of the hydration reaction. The cocontinuity, in turn, determines the occurrence of a path, accessible to water molecules, percolating throughout the hybrid foam.

Table 2. Mechanical and Physical Properties Comparison between Brick, Cellular Concrete, and Hybrid Foam

Material	Unit	Brick[a]	Cellular concrete[a]	Hybrid foam
Volume density	kg/m^3	660	575	270
Compressive strength	N/mm^2	5.00	2.81	1.44
Compressive Young's modulus	N/mm^2	1,600	2,125	144
Tensile strength	N/mm^2	N/A	N/A	4.23
Tensile Young's modulus	N/mm^2	N/A	N/A	612.05
Shear strength	N/mm^2	0.20–1.40	0.20–0.30	0.66
Fire reaction (UNI EN 13501-1:2009)	Euroclass	A1	A1	B2
Sound insulation (UNI ISO 140-1 and 717)	dB	45	50	34
Thermal conductivity (l)	W/m K	0.13–0.21	0.13	0.036–0.046
Water vapor permeability	kg/m s Pa	2×10^{-13}	3.8×10^{-8}	6×10^{-11}

Note: Some data concerning the hybrid foam are from Verdolotti et al. (2012).
[a]Typical values.

Conclusions

The present paper investigates the mechanical properties of a polyurethane-cement hybrid foam. Compressive, tensile, and shear tests are conducted according to ASTM standard methods for cellular plastic materials to understand the potential use of such a material in the building field for the seismic protection of architectural nonstructural components.

The test results show a compressive strength of 1.4 N/mm^2 and an elastic modulus of 144 N/mm^2, whereas the tensile strength and the Young's modulus in tension are larger than the compressive ones, also evidencing a pseudo elastic-plastic behavior in the tensile region of the stress-strain curve. Furthermore, a maximum shear strength of 0.6 N/mm^2 is evaluated.

These values, if compared with the corresponding properties of two other materials generally used for architectural nonstructural components, i.e., bricks and cellular concrete, both characterized by a much larger specific weight, show that the hybrid foam is less resistant and stiff in compression, while showing good resistance under tension. Furthermore, the hybrid foam shear strength is greater than the corresponding value of the cellular concrete and comparable to bricks.

In view of the functional properties, such as fire resistance, sound insulation and absorption, thermal conductivity, and water vapor permeability, the results gathered in the present work make the hybrid foam suitable for applications in the building field, with particular reference to architectural nonstructural components in seismic prone areas. Dynamic tests on a subassembly, representing an application of the hybrid material for an internal partition and/or external infill, could represent the next research step for this hybrid material.

Acknowledgments

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