1874-1495/20

Send Orders for Reprints to reprints@benthamscience.net

The Open Civil Engineering Journal

Content list available at: https://opencivilengineeringjournal.com

RESEARCH ARTICLE

Thermo-mechanical Characterization of Insulating Bio-plasters Containing Recycled Volcanic Pyroclasts

Loredana Contrafatto[1], Salvatore Gazzo[2], Antonio Purrazzo[3] and Antonio Gagliano[4,*]

[1]*Department of Civil Engineering and Architecture, University of Catania, Catania, Italy*
[2]*Department of Civil Engineering and Architecture, University of Catania, Catania, Italy*
[3]*Material Testing Laboratory collaborator, University of Catania, Catania, Italy*
[4]*Department of Electrical, Electronics and Computer Engineering, University of Catania, Catania, Italy*

Abstract:

Aim:

The research proposes the reuse of volcanic wastes in the production of lightened and insulating bio-plasters.

Introduction:

The goal is the production of a novel sustainable construction material that reduces the environmental impact.

Methods:

Four mixtures were designed. The recycled Volcanic Ash was used in combination with two bio-compatible binders; basically Natural Hydraulic Lime (NHL) or calcium hydroxide blended with a commercial Portland cement (CH-CEM). To improve thermal properties, CH-CEM mixtures were treated with an Air Entraining Agent (AEA) in two different percentages and a breathable resin (R). The main physical, mechanical and thermal properties were experimentally determined.

Results:

The results of such analysis indicate that the mixture NHL, realized using hydraulic lime as a binder, do not satisfy the threshold of the water absorption coefficient, exceeding the limit established by UNI EN 998-1 standard.

Conclusion:

On the contrary, one of the mixtures CH-CEM, containing both AEA and R, is suitable for use as lightweight plastering mortar and also satisfies the requirements for insulating mortars.

Keywords: Volcanic ash, Bio-composite, Thermal insulating plaster, Insulating panels, Etna, Eco-design, Bio-plasters, Volcanic pyroclsts.

Article History	Received: December 12, 2019	Revised: March 10, 2020	Accepted: March 27, 2020

1. INTRODUCTION

Eco-design and energy-efficiency are current concepts of fundamental importance that highlight the need to find new building materials that are environmentally friendly and lead to save non-renewable resources of energy consumption [1]. In recent years, the idea of "sustainability" applied to the building design has encouraged many researchers to propose novel sustainable construction materials characterized by a reduced environmental impact, especially in terms of the amount of greenhouse gas emissions [2]. In particular, the development of new thermal and acoustic insulating products by using natural or recycled waste materials reduced the energy demand for space heating, the installed power of air-conditioning systems and consequently, the total energy cost [3]. The current European legislation pertaining to waste materials, which is the Directive 2008/98/EC on waste (Waste Framework Directive), obliges the member states to recycle at least 70% of their nonhazardous construction and demolition wastes as raw materials by 2020. Waste legislation and policy of the EU member states shall apply following the waste management hierarchy [4] shown in (Fig. **1**).

Taking into account that the quantity of the waste being derived from construction and demolition is the highest in EU, estimated to be 25-30% of all produced wastes [4], and that the

* Address correspondence to this author at the Department of Electrical, Electronics and Computer Engineering, University of Catania, Catania, Italy; Tel: 3204332228; E-mail: antonio.gagliano@dieei.unict.it

DOI: 10.2174/1874149502014010066, 2020, *14*, 66-77

current recycling rate is approximately 46% [6, 7], it is imperative to identify new ways to use demolitions wastes as recycled products [8]. Petri Sormunen proposed a literature review concerning the opportunities of using recycled construction and demolition waste in composite manufacturing. Recycled wood, paper, cardboard, metal, glass, and ceramics were investigated as raw components for composite materials [9]. Some studies focus on thermal and acoustic insulation properties of mixtures and insulating panels with the purpose of limiting the environmental impact [10, 11]. Recycled concrete aggregates and coal bottom ash aggregates have been used in partial replacement of natural crushed limestone aggregate on the pervious concrete [12]. The mechanical properties, thermal conductivity and sound absorption feature, were significantly improved compared to those of pervious concretes containing only natural aggregates.

In recent years, the recycling policies have also prompted the scientific community to study the recycling possibilities of many other types of waste. Buratti *et al*. [13], investigated the thermal, acoustic, and environmental performances of recycled waste panels consisting of rice husk produced by gluing and pressing the raw material. The recycling of synthetic post-industrial textiles waste, constituted by a mixture of nylon, spandex and polyurethane in the production of novel thermal insulation panels, is the topic of the paper [14]. An innovative mineral fiber panel for building insulation has been proposed by Moretti *et al*. [15], with a very low thermal conductivity, within the range of 0.031-0.034 W/mK, depending on the density. In rubber granules from used tires, high-density fiberboard flooring sawdust and fresh high-density polyethylene pellets were blended to produce perforated composite panels having sound-absorbing properties [16]. Lightweight tiles were developed by Cetin *et al*. [17], starting from mining tailings, like the waste generated by the mining of boron-rich minerals and basalt rock, and recycled glasses like common soda-lime glass and pharmaceutical boro-silicate glass. In recycled printing circuit boards, plastic materials have been used for producing thermo-insulating panels [18]. The physical-mechanical properties of a lightweight construction material composed of plaster, dune sand and Expanded Polystyrene Beads (EPS) are investigated [19]. A considerable number of studies about the possibility of incorporating waste from the most varied sources in concrete and pavement mixtures have been conducted in the past decade by Siddique and coauthors (see for instance the latest papers) [20 - 24]. Volcanic Ash (VA) is another material frequently used in concrete-like composites. The use of VA as a pozzolanic material has caught the attention of the scientific community because it allows to produce green and economical mortar, reducing environmental pollution and decreasing the used quantity of Ordinary Portland Cement (OPC) [25 - 28]. Many research works on blended cements containing VA are focused on the description of specific properties of cement paste, mortar, and concrete [29 - 32]. Bahadori presented an experimental study where three types of natural pozzolans (VA), available in Iran, were used for the stabilization of marl soil. Another study investigated the potential of using natural and [33], artificial pozzolans for the stabilisation of Urmia Lake peat [34].

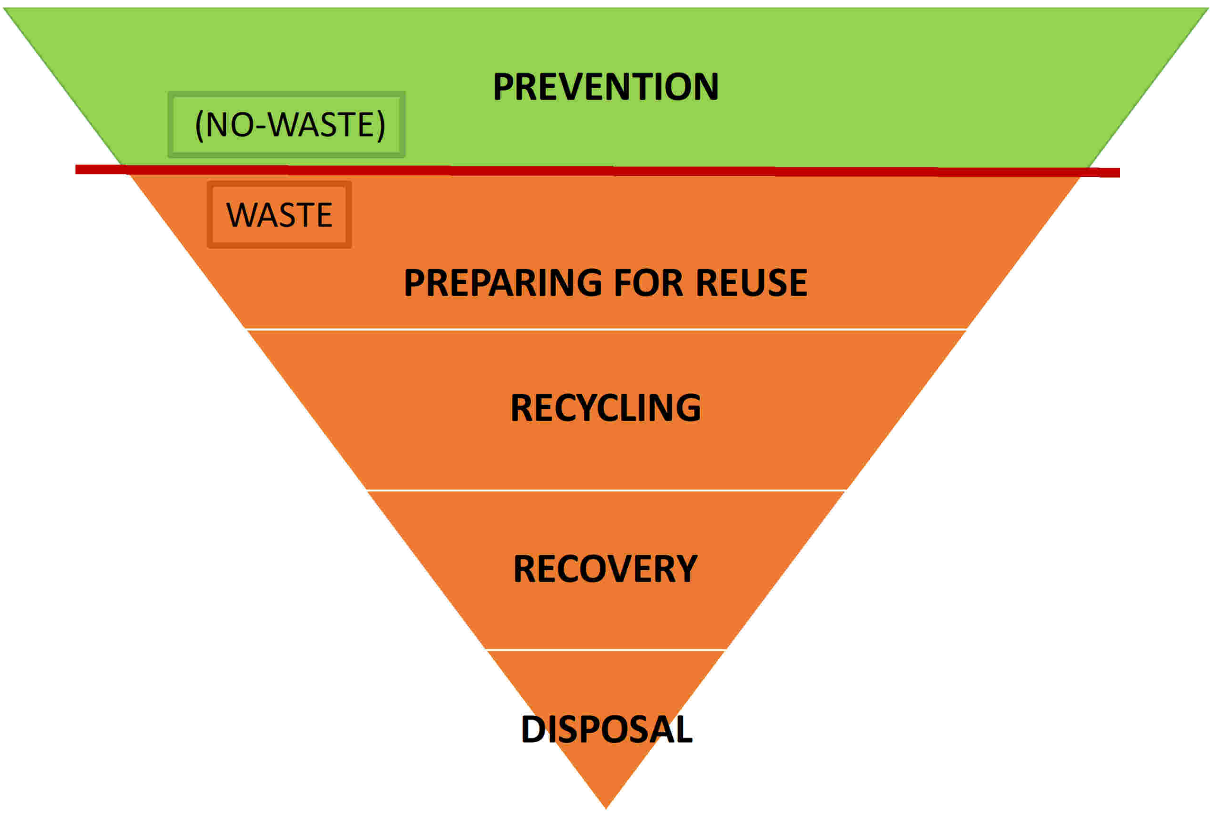


Fig. (1). Waste management hierarchy (rearranged by the Authors) [5].

However, the pozzolanic property varies with the origin of the VA, the mode of formation, the geographical region and the source [35]. In this context, studies regarding the opportunities to reutilize VA coming from the Etna volcano are of great interest. Indeed, a huge amount of ash repeatedly cover the surrounding area causing serious road and air traffic accidents, difficulties in the agricultural sector as well as human health problems. Subsequent to the eruptions, the pyroclastic products are removed by the local municipalities from public spaces. Thus, they, being classified as urban waste, have to be disposed of. The persistence and duration of the eruptive phenomena have become a challenging problem over the years, because it implies high costs; and from the environmental point of view, the occupation of huge landfill spaces. So, it is very important to prove that the waste code can be permanently modified, placing the material in a not-hazardous category so that it can be reused like recycled resources. In fact, the physical and mechanical properties of this recycled volcanic product remain substantially unchanged with respect to the virgin material.

Some recent studies are focused on the characterization of the rock [36, 37] and on the reuse of Etna eruptive products in the field of mortar and concrete production [38 - 40]. Thus an ongoing challenge for marketers of recyclable VA is to expand end-user products and material markets in different areas of civil engineering [41].

This study investigates the possibility of using the eruptive products of volcano Etna in the production of bio plasters, as an alternative to their disposal as waste. The goal is therefore the realization of a sustainable product accompanied by a reduction of the environmental impact. Indeed, the use of recycled material does not only allow to reduce the depletion of natural resources but also diminishes the amount of the energy necessary to extract, transform and transport the material to the point of use or application, that is, the so-called Embodied Energy (EE). In particular, the attention is focused on the thermal properties of the final product obtained, due to the porous structure of the pyroclasts. The requirements in order to classify the plastering mortar as an insulating, or simply, a lightened material was carried out through experimental measurements of strength and thermal conductivity.

2. MATERIALS AND METHODS

The experimental research studies two different types of bio-plasters, obtained by combining a natural binder with recycled aggregates derived from the volcanic pyroclastic waste produced during the eruptions of volcano Etna, being the highest and the most active volcano of Europe.

The first type of mixture, denoted as NHL, is characterized by a natural hydraulic lime I.PRO Calix NHL 3.5 by Italcementi S.p.A.; the binder of the second type of mixture, denoted as CH-CEM, is calcium hydroxide CL90-S by SACED S.p.A. combined with a commercial Portland-limestone blended cement, type CEM II/B-LL 32.5 R by Colacem S.p.A. An Air Entraining Agent (AEA) in two different volume ratio with respect to the dry mixture (0.05% 0.1%) was added to the mixture CH-CEM to increase the porosity. Moreover, a breathable resin (R) in the ratio of 1% of the binder was added in the mixture containing 0.1% of AEA. Based on the content of the additives AEA and R, the designed CH-CEM mixtures were labelled as CH-CEM-0.05-0, CH-CEM-0.1-0, CH-CEM-0.1-1. In the case of the NHL mixture, no additive was used since the binder has intrinsically very low mechanical strength.

The aggregates, taken from landfill depots, were used as they stand, with-out any treatment or grain size reduction, to maintain the virgin porosity. The pyroclastic waste can be classified as an insulator of mineral origin, according to the UNI EN ISO 10456. The density was between 0.57 kg/m^3 and 1.81 kg/m^3, for the material passing the sieve 4.76 mm and 0.001 mm, respectively.

2.1. Mix Design

In order to obtain a composite with good mechanical strength, the pro-portion of the constituents and an adequate particle size distribution are of fundamental importance. The Fuller-Thompson ideal gradation curve is usually used to achieve high-density composites. However, the main purpose of this study is the design of a porous medium, showing thermal insulating properties. Therefore, the mix design was made by choosing a grain size assortment which increases the intergranular voids, and then the porosity, due to a higher percentage of coarse aggregates with respect to the theoretical fuller value (Fig. **2**).

Fig. (**3**) shows the grain assortment of the raw material after the particle size analysis.

the left to the right, the fractions passing the sieve are 0.25, 0.5, 1.0, and 2.0 mm, respectively.

All the blends have the same volume ratio among the aggregates, so that all are characterised by the same granulometric composition given in Fig. (**2**)

Consequently, all the mixtures contain:

• Coarse volcanic pyroclastic aggregates, with a diameter $2 \leq d < 9.5$ mm

• Fine volcanic pyroclastic aggregates, with a diameter $0.25 \leq d < 2$ mm;

• Very fine aggregates, consisting of aggregates such as carbonate and pozzolan with a diameter $d < 0.25$ mm.

The finer fraction was added to facilitate the sliding at the interface between the larger grains and, therefore, to confer greater workability. From preliminary tests, in fact, in the absence of the very fine fraction, the workability of the mixture was not acceptable. The aggregates were used in the dry state. The water content also includes the part needed to wet the aggregates.

Table **1** reports the composition of NHL mixture per liter of the mixture. The binders, fine aggregates and the coarse aggregate are in the ratio of 1:1.97:1.8.

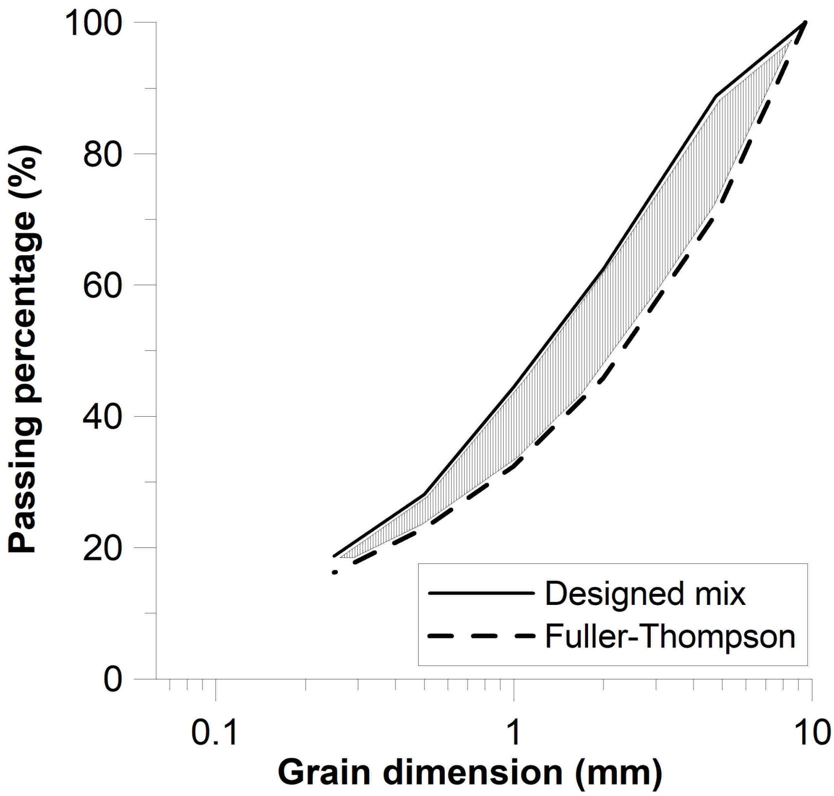


Fig. (2). Grain size assortment for the NHL and CH-CEM mixtures.

Table 1. Composition of a unit volume of mixture NHL.

Mixture NHL	-
constituent	(g)
I.PRO Calix NHL 3.5	232.9
coarse aggregate	450.7
fine aggregate	525.8
very fine aggregates	225.3
water	375.6

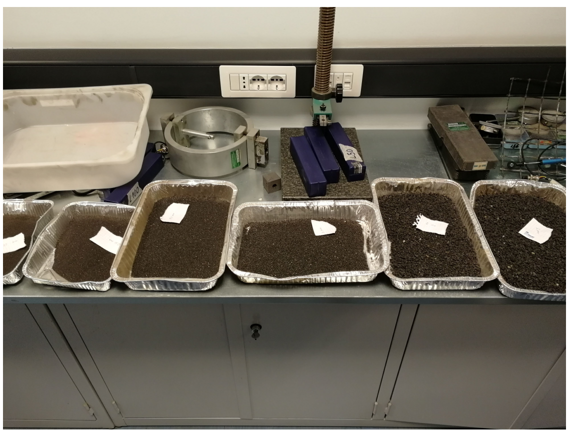


Fig. (3). Raw pyroclastic material.

Mixture CH-CEM contains binders, fine aggregates, and coarse aggregates in the ratio 1:2.25:2.05. Table **2** shows the composition per liter of mixture CH-CEM .

3. MECHANICAL CHARACTERIZATION

3.1. Laboratory Setup and Measurements

In order to determine the main physical and mechanical characteristics of the above mentioned mixtures, different experimental tests have been carried out at the Official Materials Testing Laboratory of the Department of Civil Engineering and Architecture of the University of Catania. The tests were carried out both on fresh mortar and on hardened mortar after 28 days of curing. For each type of mixture, 6 prismatic samples of 160 mm x 40 mm x 40 mm size were packaged.

Table 2. Composition of a unit volume of mixture CH-CEM.

Mixture CH-CEM	-
constituent	(g)
Calcium Hydroxide CL90-S	131.5
CEM II/B-LL 32.5 R	124.2
coarse aggregate	438.5
fine aggregate	511.6
very fine aggregate	219.3
water	365.4

The average flexural strength was obtained by three points bending test on 3 prismatic specimens. From the bending breakage, 6 half prismatic bars were obtained, subsequently used to measure the compressive strength. Finally, 3 half prisms were used to measure the water absorption coefficient, while the remaining 3 half prisms were used to measure the open porosity. The curing method and the time for removing the specimens from the molds were specified by the standard UNI EN 1015-11.

3.1.1. Consistency of Fresh Mortar

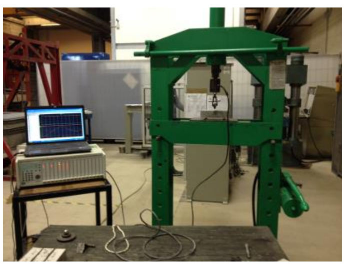
Consistency tests on fresh mortar were conducted according to the standard UNI EN 1015-3 through the use of a flow table. The mortar was mixed after the addition of the required amount of water to the dry mixture and introduced into a truncated cone mold, positioned in the middle of the table, in two layers compacted with 10 short strokes of the pestle. The excess mortar was removed with a spatula and the mold was slowly removed. The flow table was then lifted up 40 mm and then dropped 15 times, resulting in the spread of the mortar on the table. The expansion diameter measured the consistency of the mix. The test results are reported in Table **3**.

Table 3. Consistency of fresh mortar.

Sample	Water Content (g)	Spread (mm)
CH-CEM	500	100
NHL	500	120

3.1.2. Flexural Strength

The test aims to assess the flexural strength of prismatic specimens, compliant to the requirements of UNI EN 1015-11 standard, by means of three points bending. The machine used to carry out the test was a frame containing a plate with two support rollers spaced 10 cm apart, on which the sample was positioned and centred (Fig. **4a**). At the centerline, a third roller transferred the loading pressure, manually controlled by means of a hydraulic system, through a 20 kN load cell connected to an HBM data acquisition unit. The load was applied to the specimen at a constant speed of 10 N/s and respecting the test duration time required by the standard, ranging from 30 s to 90 s. From the maximum value at break F_f, the maximum strength R_f was obtained according to the simply supported beam scheme:



(a)

(b)

Fig. (4). (**a**) Three points bending test. (**b**) Uniaxial compression test.

$$R_f = (1.5 \cdot F_f \cdot l)/d^3 \quad (1)$$

Where d is the dimension of the cross-section side and l the distance between the supports.

3.1.3. Compressive Strength

The uniaxial compressive strength R_c was obtained, as prescribed by the standard UNI EN 1015-11, by applying the load at a constant rate on the half prism obtained by the bending failure. The instrumental test apparatus was identical to that of the flexural test, as it is shown in Fig. (**4b**). The compressive strength value was obtained from the maximum applied load F_c as:

$$R_c = F_c/A \quad (2)$$

Where A is the area of the rigid plate of side d used to distribute the load.

3.1.4. Volumetric Mass Density

The volumetric mass density ρ indicates the weight per unit volume in dry conditions. It is given by the ratio of the dry weight m_{dry} of the porous solid and the total volume V, including the voids:

$$\rho = m_{dry}/V \quad (3)$$

The test procedure was conducted according to the standard UNI EN 1015-10. The prismatic bars were inserted in an oven at a temperature of 100C°. The bars were weighed every 2 hours until the difference between two successive weightings was less than 0.2%.

3.1.5. Water Absorption Coefficient

The determination of the water absorption coefficient by capillarity of hardened mortars (C) provides information on the open porosity of the composite. Procedure and methods were set out in the standard UNI EN 1015-18. The standard provides the packaging of three prismatic specimens. Once the prepared specimens reached the proper curing stage, they were removed from the molds, broken in half and dried in a ventilated oven. Three half prisms were immersed in a tub containing water with the part of the broken surface in contact with water. The four longitudinal faces of the half prisms were sealed with a water-repellent material in order to ensure the rise of the water only along the vertical direction during the test. The height of the immersed portion varied from 5 to 10 mm. The water level was kept constant throughout the test, also preventing evaporation from the wet specimens. After 10 minutes, the specimens were removed and dried quickly with a cloth, weighed, registering the weight M1, and placed back in the tub. The same procedure was repeated after 90 min, recording the M2 value. The coefficient of water absorption by capillarity was obtained from the relation:

$$C = 0.1 \cdot (M_2 - M_1) \quad (4)$$

3.1.6. Porosity

The open porosity is the ratio of the volume of open voids that communicates with the outside, and the apparent volume of the sample. To carry out this test, the remaining half prisms of the previous test were used, whose dry weight m_{dry} was known. The next stage of the test consisted of totally immersing the three specimens in the tub for a time to make them completely saturated. At the end of the test, the specimens were patted with a cloth to eliminate the excess water and weighed for measuring the saturated mass m_{sat}. The saturation of the specimens involves a complete filling of the open voids with water, with a consequent increase in mass. From the difference between the mass of the saturated specimen and the mass of the dry specimen, it is possible to derive the mass of water that fills the volume of the voids of the specimen. Therefore, with the density of water, we can derive the volume of water which is, as previously stated, equal to the volume of open voids. From the relationship between the volume of the voids V_v and the apparent volume V_a, the porosity of the sample was obtained:

$$p = (V_v/V_a) \cdot 100 \quad \textbf{(5)}$$

4. RESULTS OF THE MECHANICAL CHARACTERIZATION

Following the test procedures described in the previous sections, the mechanical and physical properties of the individual mixtures were evaluated.

4.1. Mechanical Characterization of the Mortar Specimens

Table **4** shows the average values of density, flexural strength, compressive strength, capillary absorption coefficient, open porosity of the mixtures under examination. For the CH-CEM mixtures, (Figs. **5** and **6**) depict the variation in the mechanical strength, density, porosity and water absorption as a function of the percentage of AEA, from 0 to 0.1%.

In case of CH-CEM mixtures, it is possible to observe that the compressive and flexural strength diminish, increasing the percentage of AEA with a linear gradient. Both the types of mechanical strength show a decrease in the gradient in correspondence with the percentage of AEA being 0.05%.

The compressive strength R_c shows a decrease from 2.82 to about 0.57 MPa, for AEA ranging from 0 to 0.05%, so with a reduction of about 80% and a gradient of 45%. R_c is about 0.33 MPa for AEA of 0.1% with a reduction of 42% with respect to the case of AEA equal to 0.05% and a gradient of 4.4% for AEA higher than 0.05%. The flexural strength R_f shows a decrease from 0.81 to about 0.4 MPa, for AEA ranging from 0 to 0.05%, so with a reduction of about 50% and a gradient of 8%. R_f is about 0.16 MPa for AEA of 0.1% with a reduction of 60% with respect to the case of AEA equal to 0.05% and a gradient of 5% for AEA higher than 0.05.

Table 4. Flexural strength, compressive strength, capillary water absorption coefficient, open porosity, density.

Mixture	R_f	R_c	C	p	ρ
-	*(MPa)*	*(MPa)*	*(kg/(m²min⁵))*	%	*(g/l)*
NHL	0.41	0.99	1.27	20.93	1361.98
CH-CEM	0.81	2.82	1.13	21.04	1351.56
CH-CEM-0.05-0	0.40	0.57	0.80	21.89	1221.35
CH-CEM-0.1-0	0.16	0.33	0.40	22.18	1085.94
CH-CEM-0.1-1	0.41	0.56	0.20	20.05	1171.88

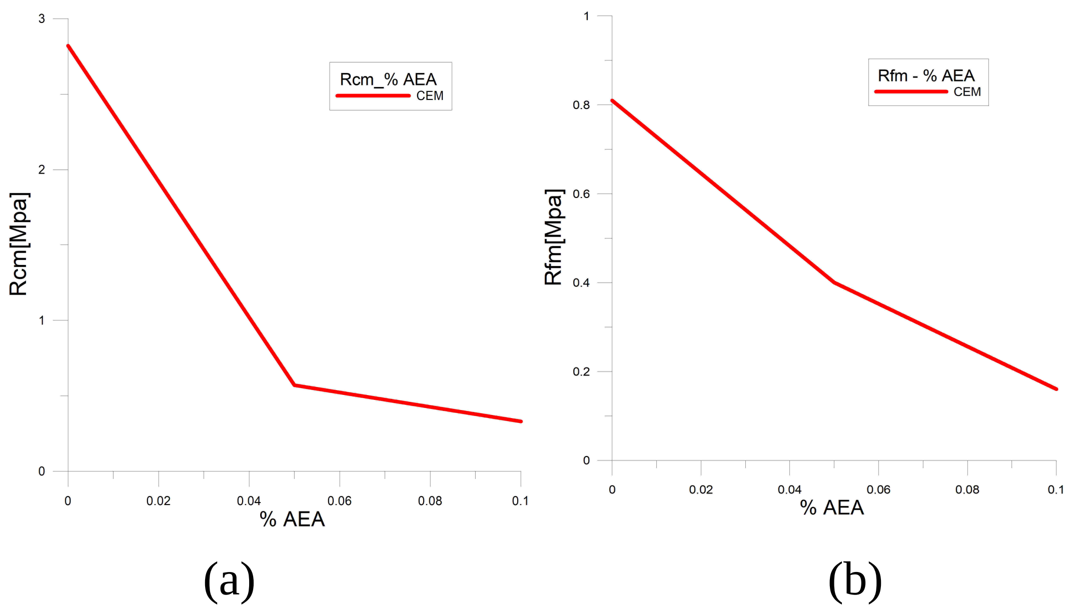


Fig (5). Compressive strength **(a)** and flexural strength **(b)** of mixtures CH-CEM to varying the AEA content.

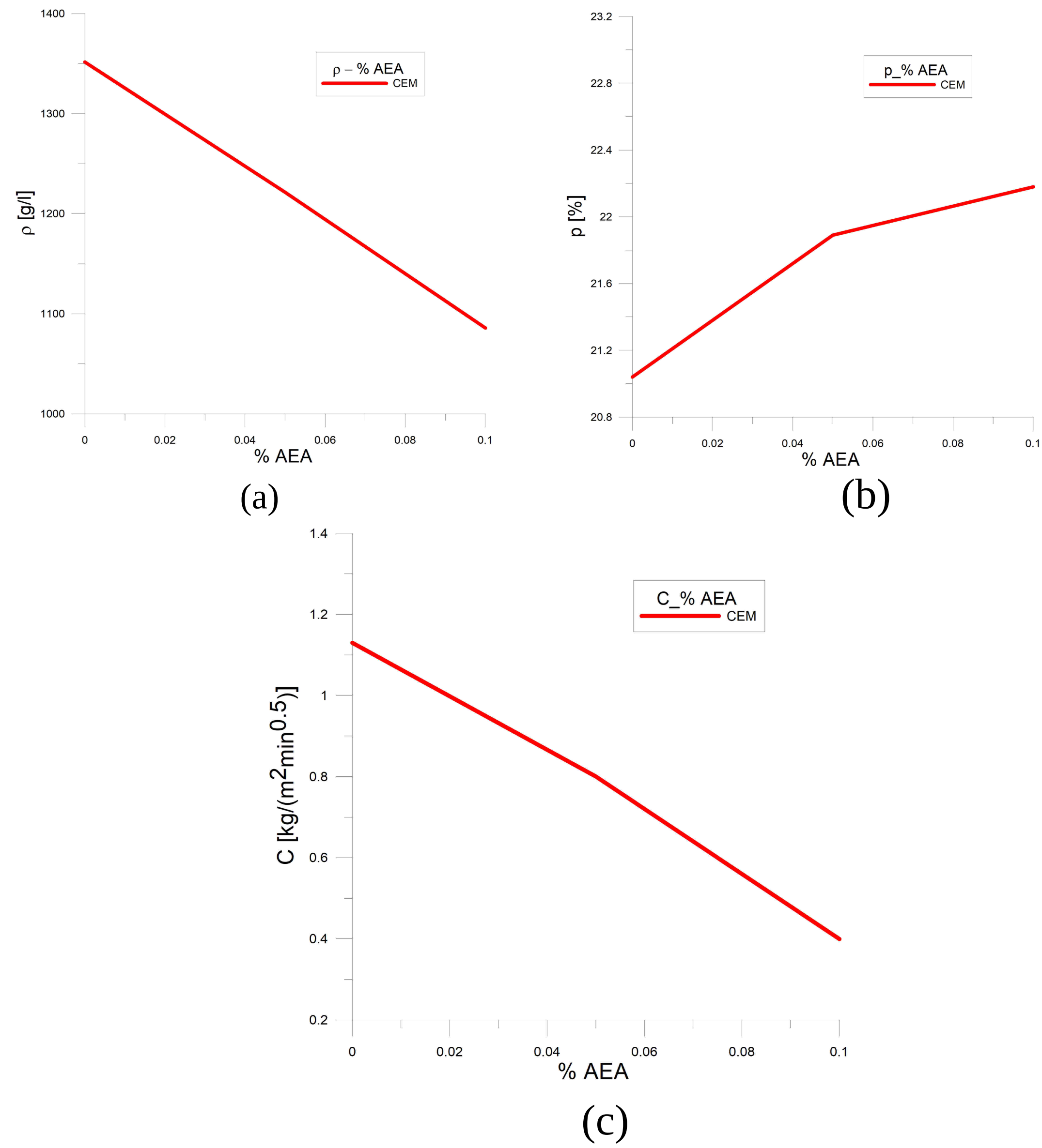


Fig (6). Density (**a**), porosity (**b**) and water absorption coefficient (**c**) of mixtures CH- CEM to varying the AEA content.

With regard to the density, a continuous linear decrease was observed as the AEA increases. A similar behavior shows the water absorption, which shows a smooth variation in the gradient in correspondence with the percentage of AEA being 0.05%. Otherwise, as expected, the porosity increases with the increase of the AEA; once again a variation in the gradient is observed for AEA of 0.05%.

The presence of R in mixture CH-CEM-0.1-1 brings the value of R_c and R_f back to the values of the mixture without resin and with 0.05% of AEA (comparing CH-CEM-0.1-1 and CH-CEM-0.05-0). The mixture CH-CEM-0.1-1 presents the lowest value of the capillary water absorption coefficient, of open porosity and density.

These results can be compared with the research by Laoubi *et al*. [19], who determined the compressive and flexural strengths of a lightweight construction material composed of plaster as a binder and dune sand and Expanded Polystyrene Beads (EPS) as aggregates. According to the proportion and sizes of particles of EPS, the authors found a mean compressive and flexural strength of about 2.8 and 1.5 MPa respectively, in correspondence with the percentage of EPS content of 50%. Moreover, the overall results show a trend of the physical mechanical quantities in line with the framework of this research. Similar results are also reported in other studies [42, 43].

5. THERMO-PHYSICAL CHARACTERIZATION

5.1. Laboratory Setup

Different methods to measure the thermal conductivity of materials exist. Their accuracy is essential to determine which applications are suitable for, in addition to more practical considerations such as the measurement length and ease of test set up. In this study, the thermal conductivity of the different mixtures was determined through the measurements carried out using two different types of equipment: the heat flow meter NETZSCH HFM 436 Lambda and the Thermal Conductivity Meter Sensor TLS-100 produced by THERMTEST instruments. The two types of equipment were placed in a conditioned laboratory at a temperature of ±23 2°*C* and relative humidity of 50.5%, according to the test conditions required by the standard EN 12664:2002.

5.1.1. NETZSCH HFM 436 Lambda

The equipment consists of two plates that are heated and cooled through the thermoelectric effect. The temperature difference generates a heat flux between the top and bottom plate until a steady-state condition is observed. Thus, the thermal conductivity is calculated according to Fourier's Law. The overall accuracy of the instrument is within 3% that remains stable for several days, thus providing excellent repeatability. The Heat Flow Meter HFM 436 Lambda is able to hold specimens with a maximum size of 300 x 300 mm and a maximum thickness of 10 cm, so the samples have to comply with this constraint. Fig. (**7**) shows the operation scheme and a picture of the HFM with one of the samples studied.

5.1.2. TLS-100

The Transient Line Source (TLS) meter follows the ASTM Standard D5334-14. The thermal conductivity (k) is determined using a needle probe that consists of a thin heating wire and temperature sensor sealed in a 100 or 50 mm steel tube. Thus, it has a considerable length to diameter ratio to simulate a condition of an infinitely long specimen, according to the transient line source test method. The probe is completely inserted into the sample to be tested. The power is delivered to the sample using a constant current source (q). As a consequence, the temperature rises with time. This set up results in minimal damage to the sample and allows thermal conductivity tests over a range of 0.1 to 5 W/mK. The reproducibility of the measurements is of 2% and the accuracy of 5%, with temperature within the range of -40 to 100C°. The thermal conductivity is obtained from an analysis of the approximately linear portion of the quasi-steady-state temperature-time response. In the calculation, the slope of the plot of the temperature versus the logarithm of time is used.

The value of k is calculated according to equation 6:

$$k = \frac{2.30q}{4\pi(T_2 - T_1)} Log_{10}(t_2/t_1) = \frac{q}{\pi(T_2 - T_1)} ln(t_2/t_1)$$

$$q = \frac{RI^2}{L} \tag{6}$$

Where T_1 and T_2 are the temperatures of the plates and t_1 and t_2 two different instant times.

Fig. (**8**) shows the picture of the TLS 100 heat flow meter. It is important to highlight that such equipment allows determining the thermal conductivity in almost 10 min. Therefore, a very large set of measurements can be executed in a very short time.

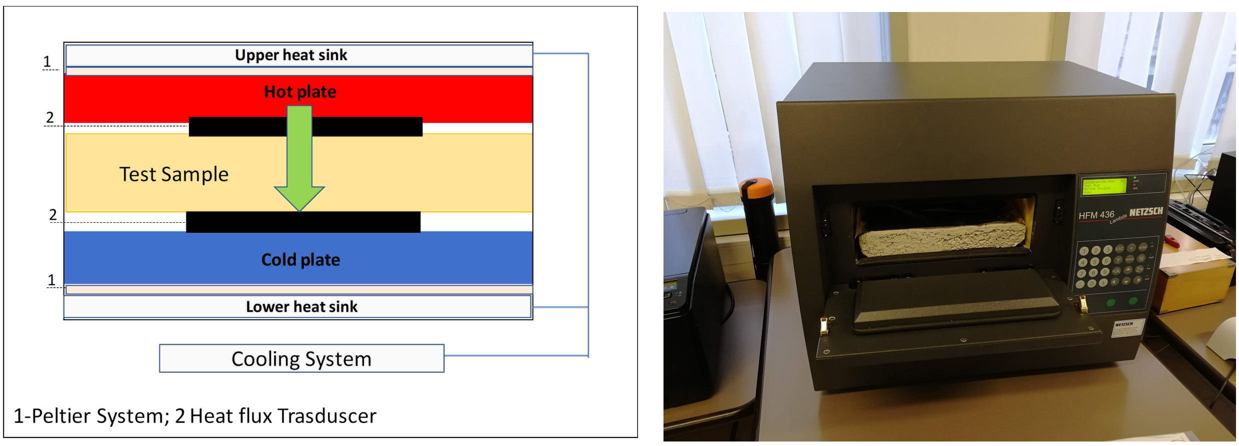
The requirements for obtaining right measurements are:

The probe has to be placed at the center of the sample and in a vertical position;

The test must be started 10 min later that the probe is inserted into the sample, in such a way to reach a thermal equilibrium condition;

• Absence of thermal gradient into the ambient room.

Thus, in accordance with this last recommendation, the samples were placed within a cardboard box.



(a) Operation scheme of the HFM **(b)** Picture of the HFM with one

Fig. (7). Operation scheme and picture of the NETZSCH HFM Lambda heat flow meter.

(a) TLS 100 heat flow meter **(b)** Measure of conductivity

Fig. (8). The TLS 100 heat flow meter.

5.2. Measurements and Results

As previously mentioned, the aggregate utilized in the mortar is constituted by a volcanic product that may be classified as a thermal insulating material . The thermal conductivity of a sample of this material, constituted by grain with diameters ranging between 9.5 to 2 mm, was measured through the TLS 100 equipment. The low value of the thermal conductivity of the VA, that is 0.056 W/mK, confirmed the potential thermal insulation properties of such a material.

After being prepared, the samples were dried in an oven at 100C$^{\circ}$ until a constant mass was attained. Before and after each drying cycle, the samples were weighed on a laboratory balance. Thus, the difference between the wet and dry weight, the initial water content and the density of each sample were determined. The measurements of thermal conductivity accomplished by the HFM lambda were conducted by varying the temperatures of the two plates in the heat flow meter while keeping a constant gradient of temperature ΔT = 20C$^{\circ}$ between them. The thermal conductivity was measured for two different values of the cold plate temperature that were 10 and 15C$^{\circ}$. The dimensions of the specimens were 300 x 300 x 50 mm. The thermal conductivity of each specimen was determined by executing three different sets of measures through the TLS 100 equipment. The mean value of the three measurements was calculated.

5.2.1. Thermal Characterization of the Mortar Specimens

Preliminarily, it has to be highlighted that among the prepared specimens, the specimens NHL were seriously damaged due to their very low mechanical strength, so it was not possible to execute the measurements with the HFM. The tiles CH-CEM-0.1-0 and CH-CEM-0.1-1 also experienced other defects that did not allow to carry out the measurements with the TLS 100. Table **5** reports the density, the two values of thermal conductivity measured with the HFM at 10C$^{\circ}$ and 15C$^{\circ}$, namely HFM.1 and HFM.2 respectively, the average value of the thermal conductivity measured with the TLS 100 (TLS.av), and the mean value of thermal conductivity derived by the average of the three sets of measurements (mean).

It is worth noting that the measurements carried out through the two equipment did not show substantial differences.

Table 5. Thermal conductivity measured by the heat flow meter.

Specimen	Density *kg/m*^{3}	HFM.1 *W/mK*	HFM.2 *W/mK*	TLS.av *W/mK*	Mean *W/mK*
NHL	1361.98	-	-	0.159	0.159
CH-CEM	1351.96	0.241	0.218	0.221	0.227
CH-CEM-0.05-0	1221.25	0.195	0.188	0.194	0.192
CH-CEM-0.1-0	1085.94	0.157	0.150	-	0.154
CH-CEM-0.1-1	1171.88	0.18	0.177	-	0.179

The specimens realized with NHL achieved a thermal conductivity of 0.159 W/mk; however, the mechanical strength did not satisfy the requirements of standard UNI EN 998-1. The group of specimens constituted with CH-CEM achieved values of thermal conductance both higher and lower than 0.20 W/mK, (which is the threshold value of standard UNI EN 998-1 for classifying a mortar as thermal mortar). In particular, the specimens CH-CEM had a value of thermal conductance of 0.226, while specimens CH-CEM-0.05- 0 and CH-CEM-0.1-0 achieved values of thermal conductance lower than 0.20 W/mK, with average values of 0.192 and 0.174 W/mK respectively. These results reflect the effects on the thermal properties of the addition of AEA for increasing the mortar porosity. Moreover, further addition of the resin R did not improve the thermal insulating property of the mortar, as can be observed from the results of specimens CH-CEM-0.

These results are in line with those reported by Laoubi *et al*. [19], with

regard to the thermal conductivity of plaster composite containing Expanded Polystyrene (EPS) and dune sand as aggregates. The authors found the values of thermal conductivity ranging from 0.75 to 0.2 W/mK as the content of EPS increased from 0 to 50% (Fig. **9**).

6. DISCUSSION

The results reported in the paper are part of a wider research activity carried out at the University of Catania about the reuse of the pyroclastic products of the volcano Etna. In the present paper, the physical, mechanical and thermal properties of plastering mortars containing recycled volcanic aggregates are illustrated. Although one of the objectives was to obtain a very porous material, the maximum grain diameter used in the design of the mixtures was 9.5 mm. Higher diameter fractions were not considered because in that case, the aggregates are extremely brittle, causing a strong reduction of the mechanical properties of the composite. Additives were used, aiming to improve the insulating property without significantly affecting the mechanical strength. The main results can be summarized as follows.

Mixture NHL, realized using only hydraulic lime as a binder, neither satisfies the requirements of lightened mortars nor of the insulating mortar because the value of the water absorption coefficient exceeds the limit established in standard UNI EN 998-1.

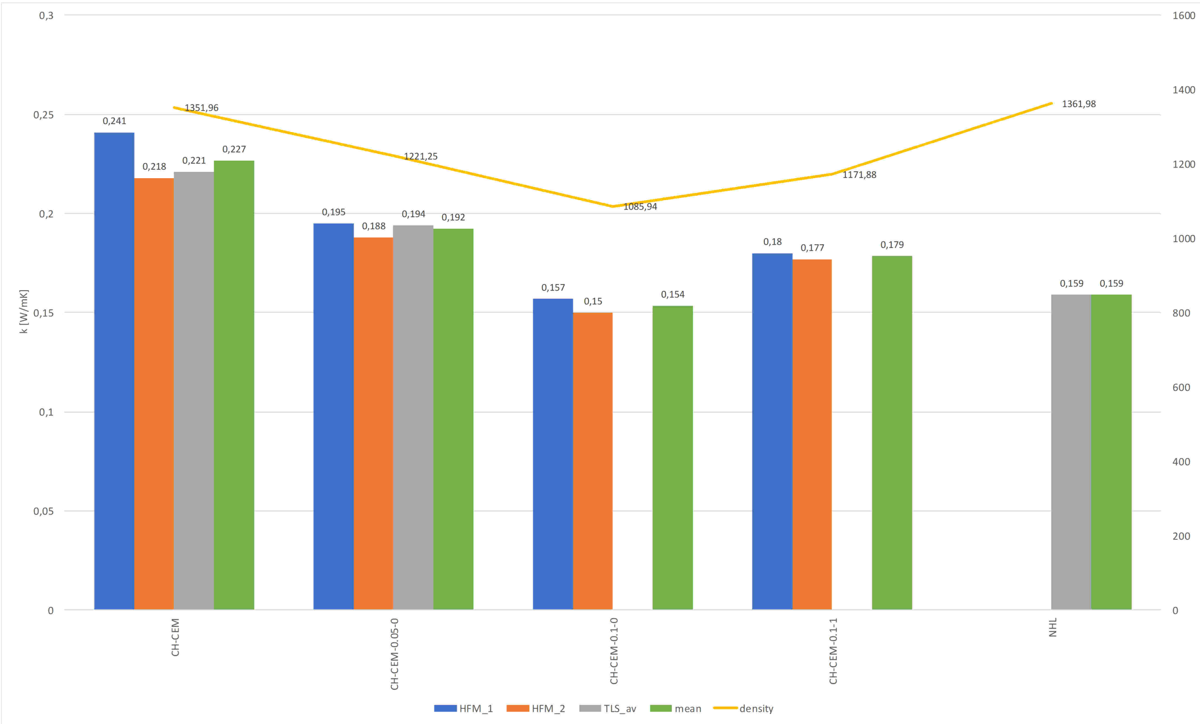


Fig. (9). Thermal conductivity and density of the mixtures.

The mixtures containing Calcium Hydroxide, commercial Portland cement (CH-CEM) and an Air Entraining Agent (AEA) present a density lower than 1300 kg/m^3. Then, according to standard UNI EN 998-1, they were suitable for use as lightweight plastering mortars. The mixture containing 0.1% of AEA and 1% of breathable resin (R) also satisfies the requirements for insulating mortars.

CONCLUSION

On the whole, this study is a contribution to the environmental sustainability, highlighting the possibility to produce plastering mortars by using recycled volcanic aggregates. In this way, two fundamental outcomes are achieved: the reduction in the amount of waste disposal and the application of the main pillar of the circular economy, which is the idea of recycling waste. In this context, it is very important to evaluate the Energy Embodied (EE) of the mortar containing VA compared with the traditional ones. Indeed, EE of building materials is meaningfully influenced by the kind of the constituent used, manufacturing efficiency, transportation, the durability of the materials and construction methods implemented. Future developments will be oriented to the search of new mixtures to further increase both mechanical and thermal properties, in order to recognize thermal bio/plasters as new mixtures containing recycled volcanic ashes.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The authors confirm that the data supporting the findings of this study are available within the article.

FUNDING

This study was funded by the Italian Ministry for the Environment and the Protection of Natural and Marine Resources, Project REUCET, 2017-2019, Grant Number 59725022097/18/ 21042215 UNICT.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

The authors are grateful to Dott. Antonio Lo Presti for his decisive assistance in the design of the mixtures and Eng. Carmelo Lazzaro Danzuso for his collaboration in the execution of the experimental tests.

REFERENCES

[1] A. La Rosa, A. Recca, A. Gagliano, J. Summerscales, A. Latteri, and G. Cozzo, "Environmental impacts and thermal insulation performance of innovative composite solutions for building applications", *Constr. Build. Mater.*, vol. 55, pp. 406-414, 2014. [http://dx.doi.org/10.1016/j.conbuildmat.2014.01.054]

[2] D.L. Distefano, A. Gagliano, E. Naboni, V. Sapienza, and N. Timpanaro, "Thermophysical characterization of a cardboard emergency kit-house", *Mathemat. Modell. Engineer. Probl.*, vol. 5, no. 3, pp. 168-174, 2018. [http://dx.doi.org/10.18280/mmep.050306]

[3] T. Cardinale, G. Arleo, F. Bernardo, A. Feo, and P. De Fazio, "Investigations on thermal and mechanical properties of cement mortar with reed and straw fibers", *Int. J. Heat. Technol.,* vol. 35, pp. S375-S382, 2017.
[http://dx.doi.org/10.18280/ijht.35Sp0151]

[4] Construction and Demolition Waste (CDW), *European-Commission,* 2019.

[5] "F. O¨ zalp, H. Yilmaz, M. Kara, O¨. Kaya, A. S¸ahin, "Effects of recy cled aggregates from construction and demolition wastes on mechanical and permeability properties of paving stone, kerb and concrete pipes", *Constr. Build. Mater.,* vol. 110, pp. 17-23, 2016.
[http://dx.doi.org/10.1016/j.conbuildmat.2016.01.030]

[6] "F. O¨ zalp, H. Yilmaz, M. Kara, O¨. Kaya, A. S¸ahin, "Effects of recy cled aggregates from construction and demolition wastes on mechanical and permeability properties of paving stone, kerb and concrete pipes", *Constr. Build. Mater.,* vol. 110, pp. 17-23, 2016.
[http://dx.doi.org/10.1016/j.conbuildmat.2016.01.030]

[7] EU Construction and Demolition Waste Protocol and Guidelines, *European-Commission,* 2018.

[8] L. Contrafatto, R. Cosenza, R. Barbagallo, and S. Ognibene, "Use of recycled aggregates in road sub-base construction and concrete manufacturing", *Ann. Geophys.,* vol. 61, no. 2, p. SE223, 2018.
[http://dx.doi.org/10.4401/ag-7785]

[9] P. Sormunen, and T. K¨arki, "Recycled construction and demolition waste as a possible source of materials for composite manufacturing", *J. Build. Eng.,* vol. 24, 2019.100742
[http://dx.doi.org/10.1016/j.jobe.2019.100742]

[10] P. Ricciardi, E. Belloni, and F. Cotana, "Innovative panels with recycled materials: Thermal and acoustic performance and life cycle assessment", *Appl. Energy,* vol. 134, pp. 150-162, 2014.
[http://dx.doi.org/10.1016/j.apenergy.2014.07.112]

[11] A. Ucar, and F. Balo, "Determination of the energy savings and the opti- mum insulation thickness in the four different insulated exterior walls", *Renew. Energy,* vol. 35, pp. 88-94, 2010.
[http://dx.doi.org/10.1016/j.renene.2009.07.009]

[12] C. Ngohpok, V. Sata, T. Satiennam, P. Klungboonkrong, and P.S. Chin-daprasirt, Mechanical properties, thermal conductivity, and sound absorption of pervious concrete containing recycled concrete and bottom ash aggregates*Proceedings of the 71st Conference of the Italian Thermal Machines Engineering Association,* vol. 22. 2018, pp. 1369-1376.Turin, Italy
[http://dx.doi.org/10.1007/s12205-017-0144-6]

[13] C. Buratti, E. Belloni, E.F.M. Lascaro, and P. Ricciardi, Srice husk panels for building applications: Thermal, acoustic and environmental characterization and comparison with other innovative recycled waste materials. *Construct. Build. Materials,* vol. 171. 2018, pp. 338-349.Proceedings of the 71st Conference of the Italian Thermal Machines En- gineering Association, Turin, Italy.

[14] D.G.K. Dissanayake, D.U. Weerasinghe, K.A.P. Wijesinghe, and K.M.D.M.P. Kalpage, "Developing a compression moulded thermal insulation panel using postindustrial textile waste", *Waste Manag.,* vol. 79, pp. 356-361, 2018.
[http://dx.doi.org/10.1016/j.wasman.2018.08.001] [PMID: 30343764]

[15] E. Moretti, E. Belloni, and F. Agosti, "Innovative mineral fiber insulation panels for buildings: Thermal and acoustic char- acterization", *Appl. Energy,* vol. 169, pp. 421-432, 2016.
[http://dx.doi.org/10.1016/j.apenergy.2016.02.048]

[16] X. Xu, H. Wang, Y. Sun, J. Han, and R. Huang, "Sound absorbing properties of perforated composite panels of recycled rubber, fiberboard sawdust, and high density polyethylene", *J. Clean. Prod.,* vol. 187, pp. 215-221, 2018.
[http://dx.doi.org/10.1016/j.jclepro.2018.03.174]

[17] S. Cetin, M. Marangoni, and E. Bernardo, "Lightweight glass-ceramic tiles from the sintering of mining tailings", *Ceram. Int.,* vol. 41, pp. 5294-5300, 2015.
[http://dx.doi.org/10.1016/j.ceramint.2014.12.049]

[18] D. Janacova, H. Charvatova, P. Mokrejs, V. Vasek, A. Blaha, and K. Kolomaznık, "Using of cross-linking protein hydrolysates for preparing of thermoinsulating panels from printed circuit boards waste", *Int. J. Mathemat. Model. Method. Appl. Sci.,* vol. 6, no. 7, pp. 837-844, 2012.

[19] H. Laoubi, M. Bederina, A. Djoudi, A. Goullieux, R.M. Dheilly, and M. Queneudec, "Study of a new plaster composite based on dune sand and expanded polystyrene as aggregates", *Open Civ. Eng. J.,* vol. 12, pp. 401-412, 2018.
[http://dx.doi.org/10.2174/1874149501812010401]

[20] K. Vardhan, R. Siddique, and S. Goyal, "Influence of marble waste as partial replacement of fine aggregates on strength and drying shrinkage of concrete", *Constr. Build. Mater.,* vol. 228, 2019.116730
[http://dx.doi.org/10.1016/j.conbuildmat.2019.116730]

[21] H. Kaur, R. Siddique, and A. Rajor, "Influence of incinerated biomedical waste ash on the properties of concrete", *Constr. Build. Mater.,* vol. 226, pp. 428-441, 2019.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.07.239]

[22] R.K. Sandhu, and R. Siddique, "Strength properties and microstructural analysis of self-compacting concrete incorporating waste foundry sand", *Constr. Build. Mater.,* vol. 225, pp. 371-383, 2019.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.07.216]

[23] S. Goyal, R. Siddique, S. Jha, and D. Sharma, "Utilization of textile sludge in cement mortar and paste", *Constr. Build. Mater.,* vol. 214, pp. 169-177, 2019.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.04.023]

[24] P.N. Pham, Y. Zhuge, A. Turatsinze, A. Toumi, and R. Siddique, "Application of rubberized cement-based composites in pavements: Suitability and considerations", *Constr. Build. Mater.,* vol. 223, pp. 1182-1195, 2019.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.08.007]

[25] K.M.A. Hossain, "Performance of volcanic ash based precast and in situ blended cement concretes in marine environment", *J. Mater. Civ. Eng.,* vol. 17, no. 6, pp. 694-702, 2005.
[http://dx.doi.org/10.1061/(ASCE)0899-1561(2005)17:6(694)]

[26] A. Elahi, Q.U.Z. Khan, S.A. Barbhuiya, P.A.M. Basheer, and M.I. Russel, "Hydration characteristics of cement paste containing supplementary cementitious materials", *Arab. J. Sci. Eng.,* vol. 37, no. 3, pp. 535-544, 2012.
[http://dx.doi.org/10.1007/s13369-012-0193-6]

[27] S. Al-Bahar, J. Chakkamalayath, A. Joseph, M. Abdulsalam, S. Al-Otaibi, and A. Al-Aibani, "Effect of volcanic ash incorporation on the mechanical properties and surface morphology of hydrated cement paste", *J. Mater. Civ. Eng.,* vol. 29, no. 8, 2017.04017052
[http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001886]

[28] O. Onikeku, S.M. Shitote, J. Mwero, A.A. Adedeji, and C. Kanali, "Compressive strength and slump prediction of two blended agro waste materials concretes", *Open Civ. Eng. J.,* vol. 13, no. 1, pp. 118-128, 2019.
[http://dx.doi.org/10.2174/1874149501913010118]

[29] K.M.A. Hossain, "Blended cement using volcanic ash and pumice", *Cement Concr. Res.,* vol. 33, pp. 1601-1605, 2003.
[http://dx.doi.org/10.1016/S0008-8846(03)00127-3]

[30] K.M.A. Hossain, and M. Lachemi, "Fresh, mechanical, and durability characteristics of self-consolidating concrete incorporating volcanic ash", *J. Mater. Civ. Eng.,* vol. 22, no. 7, pp. 651-657, 2010.
[http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000063]

[31] R. Siddique, "Effect of volcanic ash on the properties of cement paste and mortar", *Resour. Conserv. Recycling,* vol. 56, no. 1, pp. 66-70, 2011.
[http://dx.doi.org/10.1016/j.resconrec.2011.09.005]

[32] R. Siddique, "Review-properties of concrete made with volcanic ash", *Resour. Conserv. Recycling,* vol. 66, no. 1, pp. 40-44, 2012.
[http://dx.doi.org/10.1016/j.resconrec.2012.06.010]

[33] H. Bahadori, A. Hasheminezhad, and F. Taghizadeh, "Experimental study on marl soil stabilization using natural pozzolans", *J. Mater. Civ. Eng.,* vol. 31, no. 2, 2019.04018363
[http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0002577]

[34] H. Bahadori, A. Hasheminezhad, and S. Mohamadiasl, Stabilisation of urmia lake peat using natural and artificial pozzolans*Proceedings of the Institution of Civil Engineers-Ground Improvement,* 2019, pp. 1-10.
[http://dx.doi.org/10.1680/jgrim.19.00024]

[35] N. Deardorff, and K. Cashman, "Rapid crystallization during recycling of basaltic andesite tephra: timescales determined by reheating experiments", *Sci. Rep.,* vol. 7, p. 46364, 2017.
[http://dx.doi.org/10.1038/srep46364] [PMID: 28402339]

[36] G. Pappalardo, and S. Mineo, "Investigation on the mechanical attitude of basaltic rocks from Mount Etna through infrared thermography and laboratory tests", *Constr. Build. Mater.,* vol. 134, pp. 228-235, 2017.
[http://dx.doi.org/10.1016/j.conbuildmat.2016.12.146]

[37] S. Mineo, and G. Pappalardo, "Infrared thermography presented as an innovative and non-destructive solution to quantify rock porosity in lab- oratory", *Int. J. Rock Mech. Min. Sci.,* vol. 115, pp. 99-110, 2019.
[http://dx.doi.org/10.1016/j.ijrmms.2019.01.012]

[38] L. Contrafatto, "Recycled Etna volcanic ash for cement, mortar and concrete manufacturing", *Constr. Build. Mater.,* vol. 151, pp. 704-713,

2017.
[http://dx.doi.org/10.1016/j.conbuildmat.2017.06.125]

[39] L. Contrafatto, and S. Gazzo, Re-use of Mt Etna pyroclasts in mortar and concrete manufacturing*AIMETA 2017- Proceedings of the 23rd Conference of the Italian Association of Theoretical and Applied Mechanics,* vol. 3. 2017, pp. 2059-2066.

[40] L. Contrafatto, C. Lazzaro Danzuso, S. Gazzo, and L. Greco, "Physical, mechanical and thermal properties of lightweight insulating mortar with recycled Etna volcanic aggregates", *Constr. Build. Mater.,* vol. 240, 2020.117917
[http://dx.doi.org/10.1016/j.conbuildmat.2019.117917]

[41] G. Banna, P. Capilleri, M. Massimino, and E. Motta, Geotechnical characterization of Mount Etna ash for its reuse preserving human health.*Volcanic Rocks and Soils.,* CRC Press: London, 2016.

[42] R. Tene Fongang, J. Pemndje, P. Lemougna, U. Chinje Melo, C. Nanseu, and B. Nait-Ali, "Cleaner production of the lightweight insulating composites: Microstructure, pore network and thermal conductivity", *Energy Build.,* vol. 107, pp. 113-122, 2015.
[http://dx.doi.org/10.1016/j.enbuild.2015.08.009]

[43] P. Chindaprasirt, P. Nuaklong, Y. Zaetang, P. Sujumnongtokul, and V. Sata, "Mechanical and thermal properties of recycling lightweight pervious concrete", *Arab. J. Sci. Eng.,* vol. 40, pp. 443-450, 2015.
[http://dx.doi.org/10.1007/s13369-014-1563-z]