Recycled plastic aggregates in manufacturing of insulating mortars

Barbara Liguori
Department of Chemical, Materials and Industrial Productions Engineering, University of Napoli, Federico II, Italy
barbara.liguori@unina.it

Fabio Iucolano
Department of Chemical, Materials and Industrial Productions Engineering, University of Napoli, Federico II, Italy
fabio.iucolano@unina.it

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Abstract

In this paper artificial aggregates based on recycled plastic materials, mostly polyolefin and polyethylene terephthalate waste, were used as partial replacement of natural aggregates for manufacturing hydraulic mortars. In particular, different amounts (10 to 50% by weight) of siliceous sand were substituted by the same weight of the above plastic waste, to obtain six mortars with different composition. The influence of plastic addition on physical properties (density, porosity, water vapour permeability) was studied. Moreover the thermal conductivity of the obtained mortars were evaluated.
Recycled plastic substitution enhances the open porosity with an increase in water vapour permeability. Nevertheless, the presence of plastic aggregate leads to a significant reduction in thermal conductivity, which improves the thermal insulation performances of the mortar. For this reason the addition of recycled plastic aggregate in the manufacturing of hydraulic mortars can be considered a way to reduce the growing environmental impact of polymers and, at the same time, it allows the development of increasingly eco-sustainable building materials.

1. Introduction

The energy performance of a building is becoming increasingly important, because of environmental restrictions and rising costs of fuel and energy. These issues have led to the development of appropriate solutions, creating a fast growing sector in modern construction. To obtain buildings with good thermal insulation performances, the use of new materials of suitable thermal insulation properties should be held into consideration. Recent studies have reported the promising use of polymers in manufacturing of concrete, as part of the binder or as aggregate substitute (Yazoghli Marzouk et al., 2007; Saikia and de Brito, 2012). Polypropylene (PP) (Mesbah and Buyle-Bodin, 2008), polyethylene (PE) (Zoorob and Suparma, 2000), polyethylene terephthalate (PET) (Frigione, 2010) and other materials (Sivakumar and Santhanam, 2007) are some of the polymers used in the building industry either in fiber or sand shape.
In particular, the large growth in the use of plastic materials has generated a growing interest worldwide in reusing the various types of recycled polymers (Ahmadinia et al., 2011). Many authors have already studied the suitability of plastic waste, such as PET (Frigione, 2010) and polystyrene (Eskander and Tawfik, 2011) in cement and/or concrete manufacturing. The use of this type of waste in the construction field may represent an effective solution both to the problem of reducing the environmental impact of plastics and to the development of an increasingly sustainable building industry.
It is well known that manufacturing and use of increased amounts of Portland cement is a source of environmental concern, due to exceeding CO_2 production and the related greenhouse effect. To overcome the above problems, a renewed interest in use of hydraulic lime for the preparation of repair mortars or plaster has been reported in recent years (Iucolano et al., 2013). Hydraulic lime is also attractive for its favorable thermohygrometric features (i.e., transpiration, dehumidifying ability and insulation), which assure appropriate microclimatic conditions. According to these considerations, a natural hydraulic lime mortar was developed, which was obtained by replacing part of the natural aggregates (silica sand) with a fine synthetic aggregate derived from reprocessing of thermoplastic resins coming from the recycling of packaging. The aim of this research is to optimize the plastic waste addition in terms of physical and thermal performance of the resulting mortars.

2. Experimental

2.1 Materials

The binder used to manufacture the mortars studied in this research is a natural hydraulic lime (supplied by MGN srl, Vicenza), which according to the European Standards (UNI EN 459-1, 2001; UNI EN 459-2, 2001), belongs to the class designated as “NHL 3,5”. This hydraulic lime, hereafter referred to as NHL, was previously characterized by chemical, X-ray and

thermal analyses (Iucolano *et al.*, 2013).
All the mortars were obtained using two typologies of aggregate:
• a siliceous fine aggregate (S), supplied by Gras Calce company (Trezzo sull'Adda, Milan, Italy);
• a plastic aggregate (P), obtained from industrial waste, produced by the Company Vedelago Recycling Centre Ltd (Treviso) through a process that provides a plasticization and densification by extrusion of the polymeric fraction of the waste (figure 1 (a-d)). In particular, the recycled plastic material, called R-POMIX "POLIMAR" is classified as secondary raw material and it is compliant with the UNI 10667-16. The technical requirements, given by the supplier, are reported in Table 1.
The plastic aggregate mainly consists of suitably selected polymers, polyolefins (mostly polyethylene and polypropylene) and polyethylene terephthalate, which are ground,

Figure 1 – Recycled plastic sand.

Table 1 – Technical requirement of the plastic waste*.

CHARACTERISTIC	REQUIREMENTS
Polyolefin content	≥ 85% dry weight
Content of	
Other plastic materials	≤ 15% dry weight
Cellulosic materials	≤ 5% dry weight
Metals (except Al)	≤ 1% dry weight
Al content	≤ 1% dry weight
Bulk Density	300 kg/m^3
Humidity	≤ 10% dry weight

**Data given by the supplier.*

cleaned and sent to an extruder. Inside the extruder at 200 °C the transformation of the polymeric mass, fused and dense, into a plastic cast are obtained. The polymeric mass is then cooled and reduced in sand with particles < 8 mm.
Particle size distribution of the two aggregates was obtained by mechanical sieving, according to European Standards (UNI EN 933-1, 2009).
In order to complete the characterization of the plastic and silica aggregates, a sieving method, according to UNI EN 933-1, 1999, were performed. Both aggregates are classified as fine aggregates, since the main sieve size results lower than 4 mm (UNI EN 13139, 2003). In particular the synthetic sand (Figure 2) has a grain size < 2 mm and more than 95% of the sample passes through 1.4 mm mesh. In addition the silica sand presents a grain size < 1 mm (more than 90% already passing through a 0.5 mm mesh).

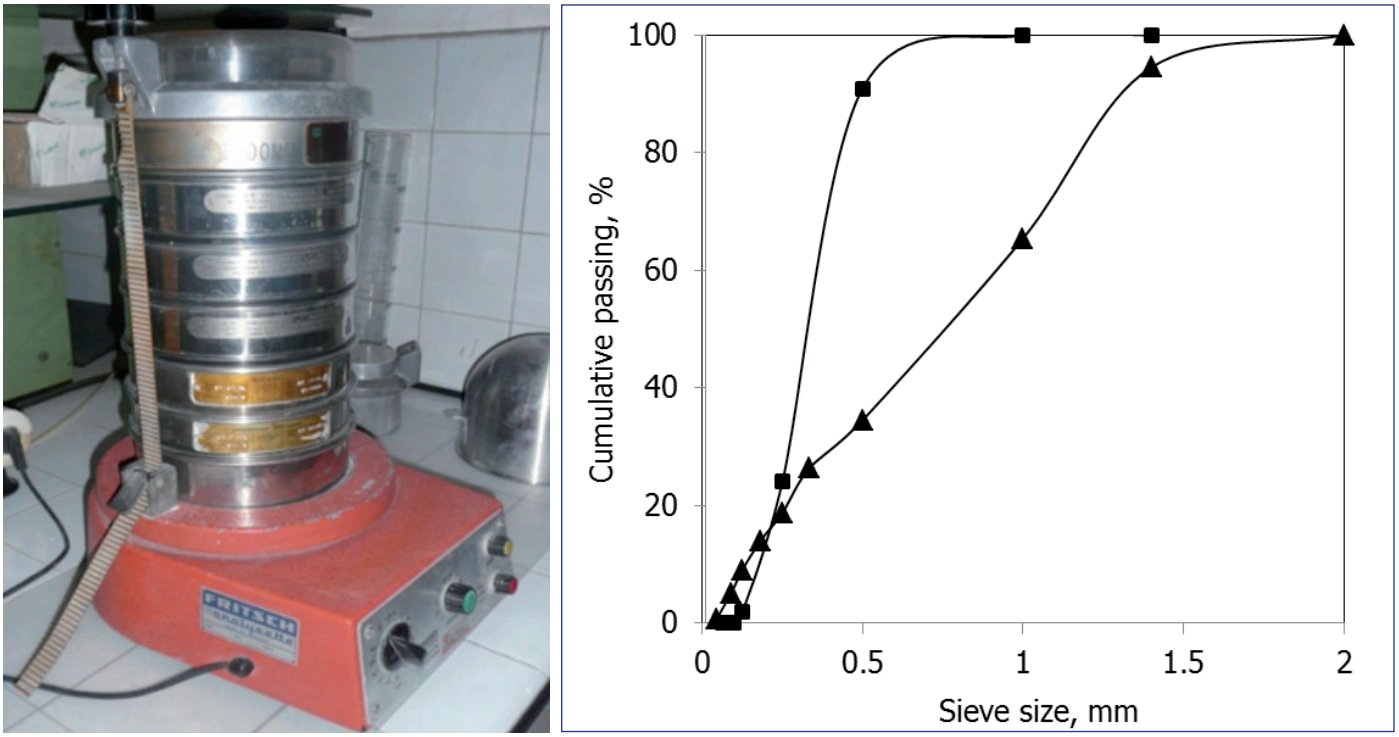


Figure 2 – Grain size distribution of plastic (▲) and siliceous (■) sand.

2.2 Methods

All the mortars were prepared as follow: the different components of the mortar were accurately weighed, mixed and dry-homogenized. Then, the appropriate amount of water was gradually added to this mixture. Therefore six mortars Mx were manufactured, where x (10, 15, 20, 25, 33 and 50%) corresponds to the weight amount of siliceous sand substituted by plastic sand. A reference mortar without the addition of synthetic aggregate (M_0) was also tested.
Real and apparent density, open porosity and pore size distribution were evaluated by mercury intrusion porosimetry, using a Micromeritics instrument (Autopore III).
Water vapour permeability measurements were carried out according to the UNI EN 1015-19, 2008. In particular, a disc of each mortar (d =12.5 cm; h = 3cm) was sealed over a KNO_3 saturated solution in a closed container at 93% relative humidity at 20°C. The containers were then placed in a climatic chamber (MSL Humychamber, mod. EC-125) at 20±2 °C and 50±5%relative humidity.
The test allows to evaluate the amount of mass transfer due to the diffusion of water vapour resulting from a difference in water pressure on the two parallel surfaces of the specimen. Each assembly was weighed at fixed time until constant mass weight was attained constant weight attainment, then water vapour transmission rate was determined by the change in mass at the steady state of the system. The water vapour permeability (W_{vp}) is a material constant, which is a function of density and porosity and it can be calculated using the following equation:

$$W_{VP} = \frac{t}{\frac{A\Delta P}{\Delta G/\Delta t} - R_A} \quad [kg \times m^{-1} \times s \times Pa]$$

where A is the cross-sectional area of the specimen perpendicular to flow (m^2), ΔP is the difference in the water vapour partial pressure (Pa) between the dry side and the moist side of the specimen, ΔG/Δt is the water vapour flux (kg/s), t is the thickness of specimen (m) and R_A the resistance to water vapour diffusion of the air interspace between specimen and

saturated solution (0.048□109 Pa m² s/kg for a 10mm air interspace). Another important parameter is the water vapour resistance (μ), which measures the material's relative reluctance to let water vapour pass through, and is measured in comparison to the properties of air. The μ-value expresses the difficulty that water vapour molecules find in passing through a mortar, so the lower the coefficient, the higher the permeability is.

The thermal conductivity of the mortars was evaluated according to ASTM: C518-10 using a heat flow meter Netzsch HFM 436 (Lambda series). This apparatus is able to work at temperatures (T) between -20°C and 100°C and provides reliable results for materials with a thermal conductivity between 0.005 and 0.5 W/mK. The sample is placed between two plates, kept at different temperatures, on which two-heat flow transducers are connected (Figure 3).

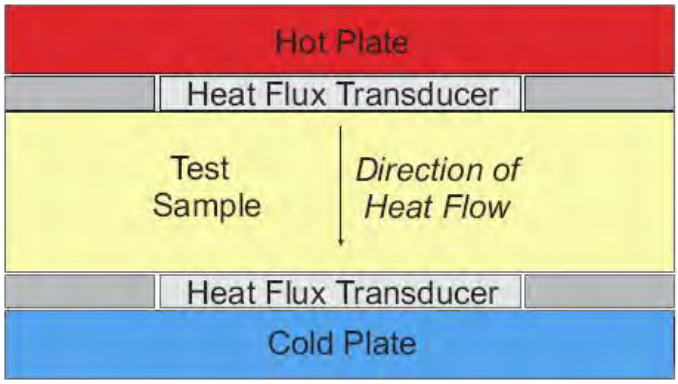


Figure 3 – Set up of the Netzsch HFM 436

The difference of temperature generates a heat flow from the hot to the cold plate (in accordance with the first principle of thermodynamics). When the thermal equilibrium is achieved, the instrument is able to determine the thermal conductivity (λ) of the sample. The experimental runs were carried out on specimens of size equal to 20x20x3 cm³, manufactured in wooden moulds.

For each sample, the measurement of λ was performed in triplicate, with Tm varying between 10 and 40°C, keeping constant the value ΔT equal to 20°C.

Finally, microstructure of the fracture surfaces of the hardened compacts was investigated by means of scanning electron microscopy (SEM, Cambridge S440).

3. Results and discussion

3.1 Physical properties

Table 2 reports the main physical properties of the mortars studied in the present work.

The use of plastic waste as partial replacement of silica sand contributes to reduce the specific weight of the composite mortars. In fact compared to the reference mortar (M_0) the real density of plastic waste mixtures tends to decrease from 8% to 33%. Accordingly Saika et al. have reported that, regardless type and size, the use of plastic aggregate generally resulted in a decrease in dry density of the mortars. Such behaviour can be firstly explained taking into account that the sand of synthetic origin is lighter than a common river sand.

Inspecting Table 2 it is possible to observe a big difference in terms of open porosity between reference material (M_0) and all the mortars manufactured by substitution of synthetic sand. It should be noted that the M_{50} mortar proved not to be compact enough to be characterized by means of mercury intrusion. It appears evident that the addition of plastic aggregate led to lighter and more porous mortars compared to the reference. In particular, the open porosity changed from about 34% for the M_0 to 46% for the M_{33}.

Moreover inspecting SEM image of the plastic sand (Figure 4) particle size and morphology appears extremely heterogeneous.

Table 2 – Physical properties of manufactured mortars.

Mortar	Apparent density (kg/dm³)	Real density (kg/dm³)	Open porosity (%)
M_0	1.65	2.50	34.0
M_{10}	1.42	2.30	38.2
M_{15}	1.30	2.16	39.8
M_{20}	1.23	2.11	41.8
M_{25}	1.06	1.86	43.1
M_{33}	0.90	1.67	46.1

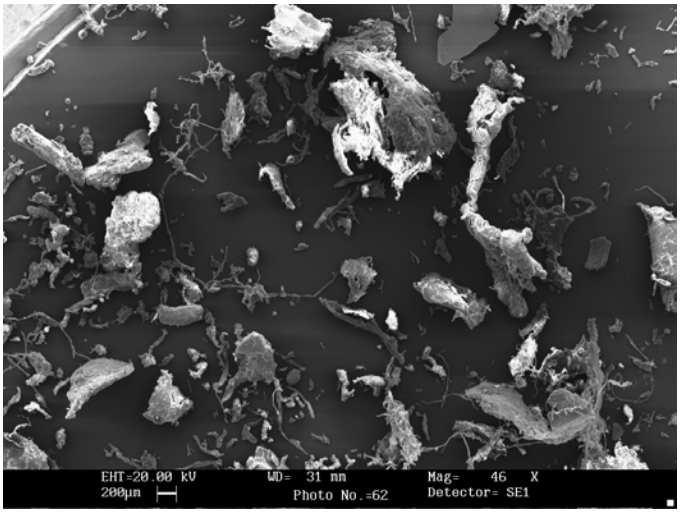


Figure 4 – SEM micrograph (46X) ofthe plastic waste sand.

In general, the interruption of the continuity of material microstructure, as a result of the inclusion of heterogeneities in a homogeneous body may cause an increase of the open po-

rosity. Specifically, the morphology of the plastic sand, more similar to fibers than particles, is responsible of a worsening of the mortar workability. In fact Iucolano et al. have demonstrated that the addition of short fibers in hydraulic mortars can promote the formation of micro cavities in the interfacial transition zone between lime paste and fibers, hindering the hydration and/or carbonation of lime paste. Several authors (Frigione, 2010; Eskander and Tawfik, 2011; Siddique, 2008;Ismail and Al-Hashmi, 2008;Saikia and de Brito, 2012) reported that plastic aggregates exhibit a series of drawbacks, mainly due to their poor chemical compatibility with inorganic matrix, which could lead to the formation of micro cavities responsible for the increase of porosity. Furthermore the increase of porosity can be due to some surface hydrophobicity or excess of gas trapped in the blend (Corinaldesi, 2011).

Figure 5 shows the distribution of porosity as a function of the average pore diameter. By inspection of such a figure, the mortar M_0 has a narrow pore size distribution, which is evidence of the presence of a large number of pores with diameters of the same size. In particular, there are only two types of pores: a more numerous one, with pore size around 1 μm and another one, much less numerous, with pores of greater size (about 100 μm).

Instead, observing the curves related to mortars M_{10}, M_{20} and M_{33} (chosen as representatives of the explored compositional range) it appears that, in addition to the above discussed increase of total porosity, there is a dual effect associated with the use of the plastic aggregate. Firstly, there is an increase of macroporosity (pores with diameters of the order of 100 μm) to the detriment of microporosity (pores with diameters of the order of few microns) and then there is an extremely varied and fragmented size distribution, with the formation of new pores characterized by extremely different diameters.

The morphology of the manufactured mortars, investigated by scanning electron microscopy (SEM), confirmed that the presence of synthetic sand results in an increase of porosity. In fact, figure 6 shows that M_0 exhibits a much more compact and homogeneous texture, with pores clearly smaller than, for example, M_{33}.

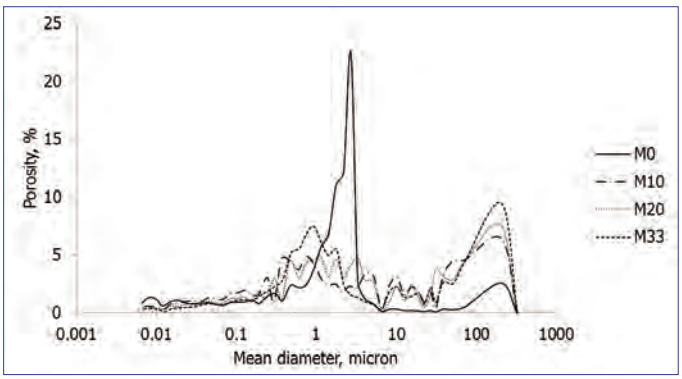
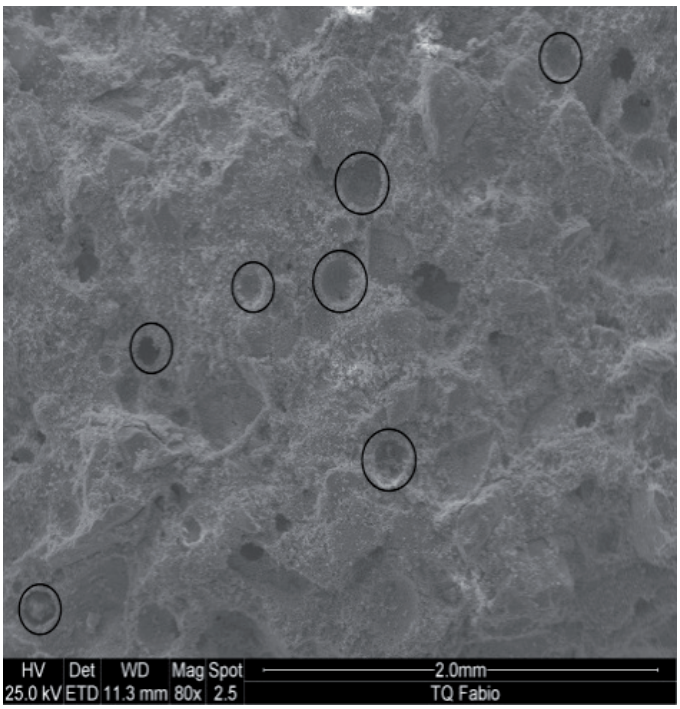
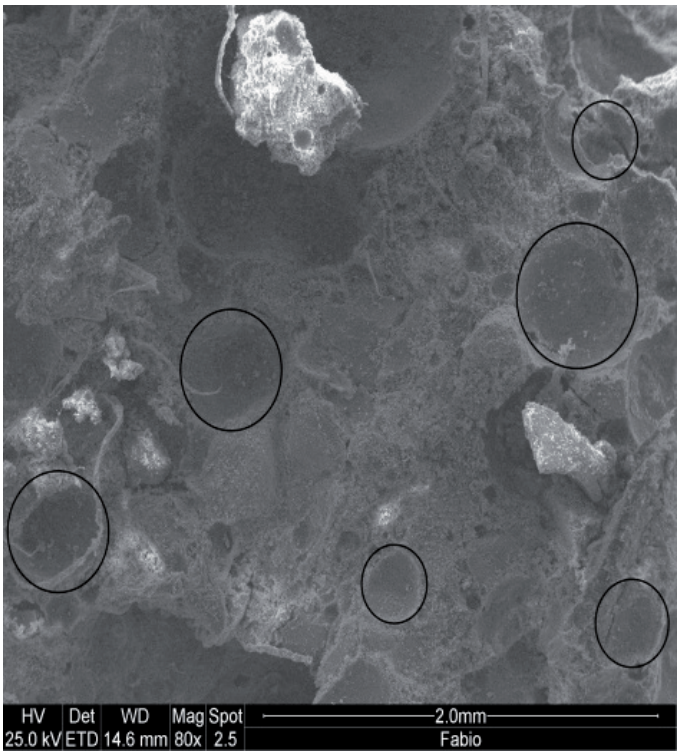


Figure 5 – Pore size distribution of M_0, M_{10}, M_{20} and M_{33}.



M_0



M_{33}

Figure 6 – SEM micrographs (80X) showing the different morphologies of M_0 and M_{33} mortars.

As far as the water vapour permeability is concerned, data reported in Table 3 show that the mortars manufactured with addition of synthetic sand are characterized, on the whole, by higher values of water vapour permeability ($2.8 \div 3.9 \times 10^{-11}$ kg/m•s•Pa) compared to the reference (8.58×10^{-12} kg/m•s•Pa).

Table 3 – Mean values of water vapour permeability (W_{VP})

and Water vapour resistance (μ).

	W_{vp}, (kg/m•s•Pa)	μ
M_0	8.58×10^{-12}	23
M_x[a]	$(2.8 \div 3.9) \times 10^{-11}$	5 ÷ 7

[a] x ranging between 10% and 50%

In the second column of Table 3, water vapour resistance values (μ) of mortars with or without plastic aggregate are reported too, since this feature is frequently used to classify any material for building industry. In particular the water permeability features of the mortars manufactured with plastic aggregate were summarized in a single item M_x, since the variation of plastic percentage (from 10% to 50%) does not involve significant changes in terms of water vapour permeability and water vapour resistance. The water vapour resistance, μ, determines the material's reluctance to let water vapour pass through. High μ-value means high resistance to water vapour transmission.

This behaviour is closely related to the above discussed increase of porosity: a greater porosity enhances the vapour molecules capability to penetrate inside the mortar. Accordingly Saikia et al. reported that the increase in porosity, due to weak bonding between binder and plastic aggregate, is the cause of the higher permeability of mortar containing plastic waste.

Great attention is paid to this feature, because of the frequent problems with condensation and mold in the buildings. All the mortars manufactured with plastic sand, regardless of percentage, present μ-values at least one order of magnitude lower than a typical cement mortars (μ-value = 5-7 and 80-100, respectively).

3.2 Thermal conductivity

The mean values of the coefficients of thermal conductivity (λ) relative to the reference mortar M_0 and to the mortars prepared with synthetic sand were reported in Figure 7.

The results obtained showed, first of all, that the values of λ do not vary significantly within the range of temperature considered (10-40°C), so in Fig. 7 only the λ-values at T=20°C were reported. By inspection of this figure it appears that all the mortars prepared by addition of synthetic sand exhibit a thermal conductivity coefficient lower than the reference mortar. The thermal conductivity of materials depends upon many factors, including their structure, material mixture proportioning, type of aggregate inclusions, density, porosity, etc. (Corinaldesi et al.,2011;Yesilata, 2009).

Generally the plastic waste aggregates, for example PET (Yesilata, 2009) or rubber (Corinaldesi et al.,2011;Yesilata, 2009) have significantly lower conductivity than the natural aggregate typically used in mortar or concrete manufacture. In particular the recycled plastic aggregate were characterized by values of thermal conductivity five times lower than the silica sand (0.28-0.30 W/mK and 1.3-1.4 W/mK respectively). Moreover the thermal insulating performance of the composite mortars containing plastic waste as aggregate is also strictly related to the porosity, which plays an important part in heat transfer.

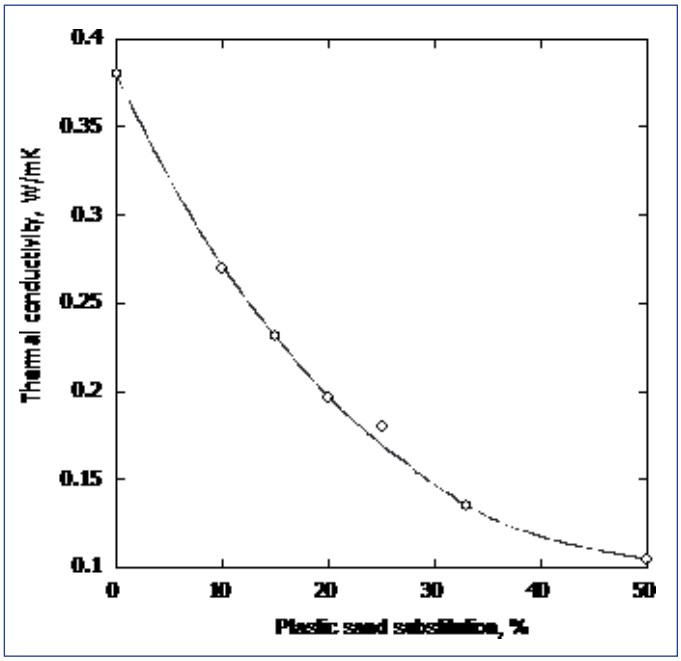


Figure 7 – Thermal conductivity (λ) measured at T_m=20°C and ΔT=20°C.

So the decreasing thermal conductivity came also from the increase in porosity induced by the synthetic sand. In fact the pores contain air which has a thermal conductivity (0.024 W/mK) much lower than all the other components of the mortar.

Finally, comparing the results with the literature (Corinaldesi et al.,2011), it appears particularly interesting that a replacement of only 20% of siliceous with synthetic sand is able to obtain a reduction of almost 50% of λ-value, passing from 0.38 W/mK of M_0 mortar to about 0.19 W/mK of M_{20}, with a marked gain in terms of thermal insulation. So the mortars containing plastic aggregates will have better thermal insulation properties than convectional mortars, which can be used to control heat loss from building during winter and heat gain during summer.

4. Conclusions

The experimental mortars have shown interesting potentiality as a base of green building materials, adding to the typical qualities of a natural hydraulic lime (widespread avail-

ability, low energy consumption during production, permeability, dehumidifying capacity) further features such as the low thermal conductivity. In fact, the prepared mortars have shown a value of thermal conductivity about 50% lower than a traditional mortar. This result is primarily due to lower thermal conductivity of the synthetic sand than silica, but also to the capacity of the aggregate plastic to facilitate the formation of micro voids. This improvement in porosity results in excellent thermal insulation performances. Another interesting feature of the studied mortars is the low water vapour resistance factor μ, 5-7 versus 80-100 for a cement mortar, which appears to be potentially useful for developing dehumidifying building materials, which can guarantee an adequate living comfort.

Finally one should consider that the use of secondary raw materials within the production phases of construction widens the virtuous cycle of disposal and reuse of waste for greater environmental protection and sustainable development.

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