Mechanical and thermal performance of concrete and mortar cellular materials containing plastic waste

José Luis Ruiz-Herrero [a,*], Daniel Velasco Nieto [a], Alberto López-Gil [a], Angel Arranz [b], Alfonso Fernández [c], Antolín Lorenzana [d], Sonia Merino [e], José Antonio De Saja [a], Miguel Ángel Rodríguez-Pérez [a]

[a] Cellular Materials Laboratory (CellMat), Condensed Matter Physics Department, University of Valladolid, Campus Miguel Delibes, Paseo de Belén n°7, Valladolid-47011, Spain
[b] Grupo INZAMAC, Polígono Industrial La Hiniesta, C/ Alto de la Albillera P: 7-8, Zamora 49024, Spain
[c] INCOSA Parque Tecnológico de Boecillo Recinto 2, Parcela 31, Boecillo, (Valladolid) 47151, Spain
[d] Centro Tecnológico CARTIF Parque Tecnológico de Boecillo, 205, Boecillo, (Valladolid) 47151, Spain
[e] RMD (Recuperación de Materiales Diversos), Ctra La Bañeza, km 7,5, Ardoncino (León), 24251, Spain

HIGHLIGHTS

- Waste plastics were used to produce concrete and mortar plastic compounds.
- Parameters as density, porosity, and water absorption were studied.
- Mechanical properties of mortar and concrete plastic compounds were measured.
- The studied materials showed an important decrease in thermal conductivity.

ARTICLE INFO

ABSTRACT

In this paper the improvement of thermal insulation behavior of concrete and mortar plastic compounds is presented. The materials studied were obtained by adding to mortar and concrete five different percentages of two types of plastic waste (polyethylene and PVC residues coming out of electric cable protective sheath). Parameters as density, porosity, water absorption and carbonation behavior were studied. The time evolution of mechanical properties (compression and flexural) were characterized to finally study and model the thermal conductivity, that is shown, in all studied cases, to have higher decrease than the expected.

1. Introduction

Plastic materials have become in recent decades an integral development part for different markets. The annual consumption of these materials has had a sustained growth, given their characteristics of low density, strength, ease of design, processability, durability, low weight and last, but not least, their low cost. These features have allowed its use in various sectors such as packaging industry, automotive, industrial applications, piping industry, construction, thermal and acoustic insulation [1].

The increase in production and consumption of polymeric materials likewise involves a growing waste output at the end of its life. This has led to huge quantities of plastic-related residues [2,3]. In this way, recycling has been recognized as a rational necessity, compared to alternative traditional deposit in landfill or incineration.

Recycling companies are the main sources of plastic waste management. In these companies the waste plastics are sorted, separated and treated for later use in production industries. The common treatment processes for plastic waste may involve

---

* Corresponding author.
  E-mail address: joseluis.ruiz@fmc.uva.es (J.L. Ruiz-Herrero).

manual or automatic sorting, crushing, sieving and eventually mechanical processing that allows disaggregation and separation of different materials associated with the polymers. Also in some cases it is used the electromagnetic separation (by using this procedure the magnetic metals that may accompany the polymeric residues are separated and recovered for subsequent use) or density separation by which different fractions of other materials, aggregates, nonmagnetic metal, etc. are separated, (buoyancy, air flow separation, etc.) classifying the various plastics according to their density and size.

Once classified, the polymer waste is ready to reentry into the raw materials market if there is added value in this secondary value chain. Unfortunately for many polymers this is not the case (thermoset, crosslinked thermoplastics, etc.).

The present paper is focused on the secondary use of two types of such materials without any added value to return into the secondary raw materials market; mainly crosslinked polyethylene (PE) and polyvinyl chloride (PVC), obtained primarily from crushing electrical copper and aluminum cables, whose envelopes (insulation) exterior and interior are principally formed by such polymers.

It is worth noting that plastic residues coming out of electric cable protective sheath have an added problem, the presence of flame retardant materials (as aluminum tri-hydroxide) that prevents its further secure processing.

The overall purpose of the study presented in this paper was to obtain cement matrix materials, where one of their phases was a polymeric residue, so that the compound may have non-structural applications. During the study, the main possible applications identified were the use of these materials as semi-structural lightweight concretes (or mortars) with improved thermal insulating properties, to use them as the core of sandwich panels for prefabricated enclosures, retaining walls for instance. Obtaining prefabricated lightweight building materials with improved thermal insulation characteristics was identified as target to give waste plastic materials a second opportunity apart of landfill or incineration.

There exists a vast literature on the issue of recycling plastic waste [4–12] being that the addition of polymeric waste materials to cementitious matrix has been studied from late 90s [13–19]. The commercial application of recycled polymer concrete is relatively new in the world of civil engineering [20–23]. The addition of polymer waste to concrete in various forms (fibers or aggregates), has a number of beneficial effects on the material properties resulting compound, as are weight and density reductions, improved mechanical energy absorption, better toughness, enhanced ductility and impact resistance, improvement of insulation capacity (acoustic and thermal) etc. Along with the above improvements and depending on the type of addition, it can be observed undesired effects, such as reduction of the compression strength or the durability of material due to different mechanisms [24–29].

Polyvinyl chloride (PVC), which is one of the waste materials used in this study, is a special case. PVC worldwide production exceeds 30 Mt annually [30], representing one fifth of the total production of plastics. PVC is the second largest volume production thermoplastic only overcome by polyethylene as volume leader in the plastics industry.

Since the 60s, PVC has been used in many products, and taking into account that its life is around 30–60 years (depending on type and treatment), PVC waste is expected to increase in the coming years [31,32]. But the recycling of PVC presents a major issue, because its incineration produces dioxins. There are some studies on the PVC residues treating, by steam gasification or pyrolysis [33–38], but it is clear that it does not exist an effective and appropriate way to recycle PVC. Therefore, there is no doubt that large

PVC waste amounts must be disposed of as solid waste, so there is a clear interest in the ways of recycling these residues.

In that sense, in this paper the results of mechanical and thermal properties measured for mortar and concrete plastic materials obtained with plastic waste (PVC + PE), are shown. These materials are not intended to be used as structural materials but rather as "functional" materials. Their thermal behavior characterization was selected initially because it was expected a reduction of thermal conductivity by adding plastic to a concrete or cement based compound. This improved thermal isolation behavior could act as added value for specific applications. What was really surprising was the intensity of the observed reduction as compared to the values predicted by our initial estimations.

2. Materials and method

2.1. Residues used

The waste materials used came from the triturating of "out of use" electrical wires through a procedure that allowed the whole segregation of the conductive metal and the polymeric protective sheath, producing completely disaggregated and heterogeneous mixture subsequently separated.

Metal separation of this mixture was achieved by densimetric methods that discriminate almost completely metal, with great density and polymer particles, whose density is much lower. This separation system has efficacy higher than 97% in metal discrimination, however the obtained polymer fraction is heterogeneous (mainly PE and PVC, but also small quantities of other polymers, trace metals and aggregates). The subsequent classification was performed in another separation system by densitometry in aqueous medium, which allows segregate in the first instance scrap metal contents in the polymer fraction and eliminate the content of another materials as aggregates, whose density and morphology is different from the treated polymers. Subsequently, the polymer fraction was separated and treated with pure water floatation rafts on sedimentation prepared for that purpose, in which the buoyancy of different types of polymers was used to classify them. Thus, typical compounds as polyethylene (PE) whose density is less than water, float, while the more dense as PVC compounds sink. The polymers were extracted and then dried and stored to yield PVCs and PEs with purities of around 80%.

The whole separation process was performed at an industrial scale in the facilities of RMD, a Spanish company, member of the research consortium, aimed at materials recycling.

The morphology of the waste materials obtained after the separation process and the huge amount of these stored without any further application (except landfill or incineration) are shown in Fig. 1. The average chemical composition of waste materials is collected in Tables 1 and 2. As can be seen there are other polymer phases present as polypropylene or polyamide.

2.2. Mortar samples preparation

Mortar samples preparation (Fig. 2) was performed according to Spanish standard UNE 83821 [39]. In brief, the design of dosage for the case of mortar has been carried out taking into account the following assumptions: It has been kept the sand/cement ratio constant at 3/1 and the same type of sand was used for all the samples.

For each sample consistency essay (according to Spanish standard UNE 83811 [40] was performed to calculate the mixing water required to obtain a constant consistency value for the different proportions of PVC or PE added.

A Portland Valderrivas cement type (CEM IV/B (V) 32.5 N) was used for all the samples. Different percentages, 0% (control sample), 2.5%, 5%, 10% and 20% of waste untreated plastics (PVC, PE and PVC + PE mixture) were added to produce the compounds.

Curing of the specimens was performed in a humid chamber at a constant temperature of 20 ± 1 °C and relative humidity of 98 ± 2.

2.3. Concrete samples preparation

Concrete samples preparation (Fig. 3) was performed according to Spanish standard UNE 83301 [41].

Different percentages 0% (control sample), 2.5%, 5%, 10% and 20% of waste untreated plastics (PVC, PE and PVC + PE mixture) were used.

The aggregates sizes used were between: 0/4, 0/8, 8/20 and 8/32 mm. Sieve analysis of the aggregates used was performed according to standard UNE EN 933-1 [42]. The cement used was CEM II/AV 42.5 R LA ROBLA type.

A remarkable effervescence phenomenon (Fig. 4, left) was observed during concrete-PVC compounds preparation. After several tests, it was determined that it could be related to some reaction occurring between alkali contained in the cement and the untreated PVC. The reaction that takes place between these two

Fig. 1. On the left image showing the samples morphology coming from the recycling of electric cable sheath. On the right, image showing part of the huge amount of this kind of plastics stored in RMD (Spanish company partner of the research consortium).

Table 1
Average chemical composition of the PE waste materials.

Composition	Weight percentage (%)
Water	0.14
Metallic residues	0.00
Inorganic fillers (talc)	3.22
Polyethylene (PE)	81.3
Polypropylene (PP)	9.50
Polyamide (PA)	1.32
Alkyd/acrylic compounds soluble in hexane	4.03
Polyvinyl chloride (PVC)	0.48

Table 2
Average chemical composition of the PVC waste materials.

Composition	Weight percentage (%)
Water	0.23
Metallic residues	0.07
Inorganic fillers (ATH and $CaCO_3$)	29.50
Polyethylene (PE)	1.06
Polypropylene (PP)	0.13
Polyamide (PA)	4.39
Polyvinyl chloride (PVC)	64.62

Fig. 3. Concrete samples preparation for the indirect tensile strength and bending tests.

2.4. Density

Density measurements were performed for all the studied materials according to Spanish standards, UNE EN ISO 1015-10 [43] (mortar samples) and UNE EN 12390-7 [44] (concrete samples).

2.5. Water absorption, porosity and carbonation

Water absorption, porosity and carbonation tests were performed on concrete samples to evaluate the capability of this type of concrete to avoid steel reinforcement corrosion.

Water absorption on concrete samples (28 days) was carried out by following the UNE-EN 772-11 standard [45].

Concrete samples porosity was measured by using a gas picnometer.

Determining the depth of carbonation (concrete samples) was carried through the colorimetric essay described in Spanish standard UNE 14630 [46]. This test determines the reduction of alkalinity in concrete carbonation and involves the use of a pH indicator that makes visible discoloration. This indicator consists of a solution of 1% phenolphthalein dissolved in 70% ethyl alcohol (Fig. 5).

components in an aqueous medium seems to be redox type and produces effervescence resulting from the gases released. The cement in contact with water generates pH between 12 and 13, and this, in turn, in interaction with the surface of the PVC generates effervescence. Sodium hydroxide solutions were prepared at different pH values and adding PVC effervescence was observed (Fig. 4, right).

To avoid the effect of effervescence it was decided to work the concrete with dry consistency (minimum amount of water needed for mixing and homogenizing of the components thereof).

A vibrating tool was used to improve samples compaction.

Curing of the specimens was performed in a humid chamber with a constant temperature of 20 ± 1 °C and a constant relative humidity of 98 ± 2.

Fig. 2. On the right mortar with added plastic samples preparation by means of tooling box. On the left an image of one of the mortar samples fractured in the bending test.

Fig. 4. Effervesce was observed during concrete samples containing PVC preparation. Sodium hydroxide solutions were prepared at different pH values and adding PVC effervescence was also observed.

First step is breaking the specimen and applying the phenolphthalein solution via spray. In a few minutes the color of the zones changes. The value adopted for the penetration depth of carbonation is the arithmetic average of the readings.

The measure of the depth of carbonation is carried out by spraying the solution of the indicator in the inner half of the fractured test part.

The area which is carbonated remains colorless (pH < 8), while the area becomes noncarbonated purplish red (pH > 9.5) or pink (8 < pH < 9.5). In the colorless area an arbitrary number of points are taken on which the corresponding measurements are made. The value adopted for the penetration depth of carbonation is the arithmetic average of the readings.

2.6. Mechanical properties

Mechanical properties were measured for mortar samples in compression and flexion according to UNE EN 1015-11 [47].

Concrete samples were measured in compression according to UNE 12390-3 [48], flexion UNE 12390-5 [49]. For concrete samples the indirect tensile properties and the elastic modulus were measured according to UNE 12390-6 [50] and UNE 83316 [51] respectively.

2.7. Thermal conductivity

Thermal conductivity measurements were performed through the transient plane source technique described elsewhere [52–56].

This transient plane source technique is based on the use of a thin metal strip as a continuous plane heat source. The strip is sealed between two thin polyimide films for electrical insulation. During the experiment, the hot disk sensor is sandwiched between two pieces of samples to be investigated (Fig. 6), and a small constant current is supplied to the sensor, that also serves as a temperature monitor, so that its temperature increase is accurately determined through resistance measurement. This temperature increase is highly dependent on the thermal transport properties of the material surrounding the sensor. By monitoring this temperature increase over a short period of time after the beginning of the experiment, it is possible to obtain accurate information on the thermal transport properties of the surrounding material [57]. By fitting the measured temperature increase data, to the predicted by the theoretical analysis of the transient term of the heat conduction equation (that relates the change in temperature of the sample as a function of time), it is possible to obtain simultaneously values for the thermal conductivity and diffusivity from one single measurement (Fig. 6). This "fitting" is not obvious and corresponds to the use of finite difference method to obtain the numerical


Fig. 6. Image of the concrete samples arrangement during the thermal conductivity measurements. During the experiment, the sensor is placed between two samples to be investigated, and a small constant current is supplied to the sensor, that also serves as a temperature monitor, so that its temperature increase is accurately determined through electrical resistance measurement.

solution of a partial differential equation. In our case this is implemented via software and hardware in the measurement equipment described in previously cited references.

3. Results

3.1. Density

The density measurement results are presented in Fig. 7 for mortars and in 8 for concretes. It is showed clearly that, in both cases, the higher the plastic content, the lower the density of the materials. There exist, as expected, a correlation between density
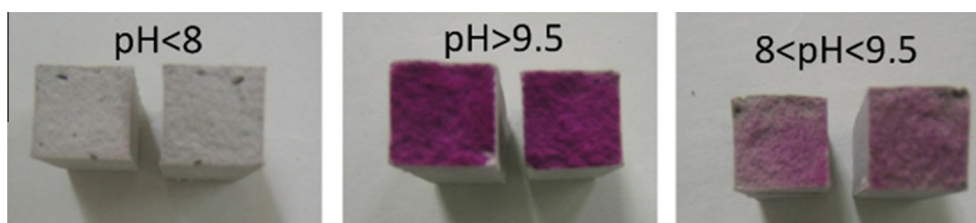
Fig. 5. As it can be seen in figure, the area which is carbonated remains colorless (pH < 8), while the area that becomes noncarbonated becomes purplish red (pH > 9.5) or pink (8 < pH < 9.5). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
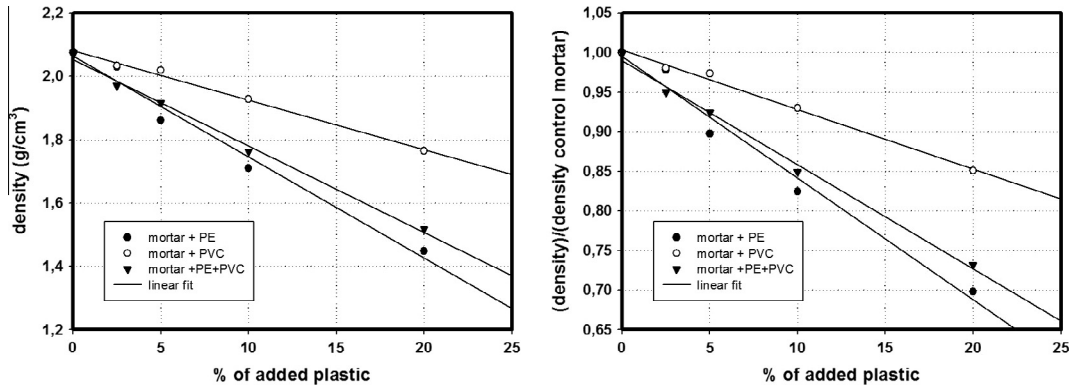
Fig. 7. Density values of mortar-plastic compounds-11 (left) and normalized values (right).
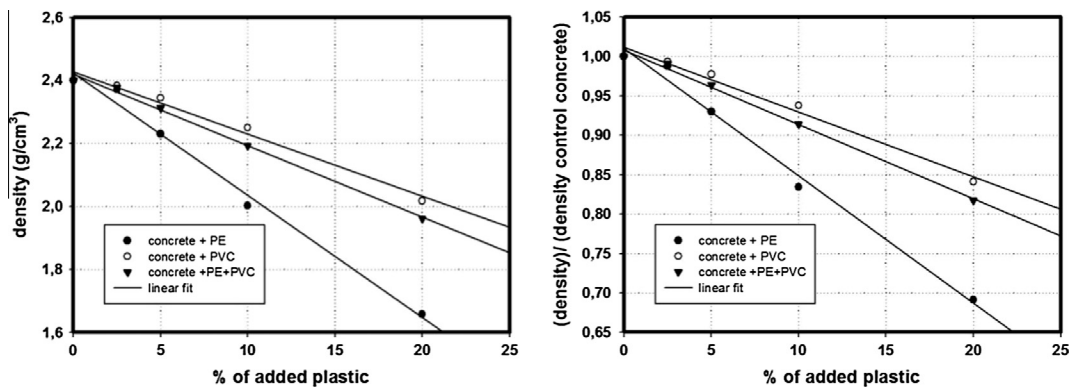

Fig. 8. Density values of concrete-plastic compounds (left) and normalized values (right).

and plastic content. In these figures also it is presented the density normalized at the control mortar and concrete values. In both cases the higher reduction (almost 30%) was achieved adding polyethylene (20%). Polyethylene density is lower than PVC density so measured values evolution was according to expected one.

In civil engineering works where the potential amount of materials needed is huge this is an interesting reduction for the case of the self weight of massive structures (see Fig. 8).

3.2. Water absorption, porosity and carbonation tests

Water absorption, porosity and carbonation tests were performed on concrete samples to evaluate the capability of this type of concrete to avoid steel reinforcement corrosion.

Water absorption on concrete was performed (28 days after production) was carried out by following the UNE-EN 772-11 standard [45]. The samples that showed the higher water absorption values were the polyethylene filled concretes.

Porosity values were also measured with the aid of a gas picnometer (Fig. 9) for concrete showing a clear correspondence with the water absorption data.

Carbonation (Fig. 10) is a natural process that occurs in concrete because the calcium bearing phases present are attacked by carbon dioxide of the air in the presence of water and converted to calcium carbonate. Ordinary carbonation results in a decrease of the porosity making the carbonated paste stronger. Carbonation is therefore an advantage for non-reinforced concretes. However, it is a serious disadvantage for reinforced concrete, as pH of carbonated concrete drops to about 7 (natural alkalinity of the concrete is around pH13 to pH8); a value below the passivation threshold of steel.
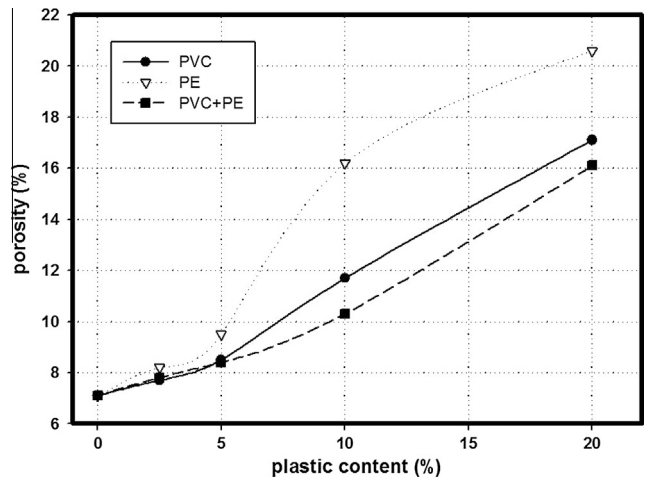

Fig. 9. Porosity values measured for concrete composites 28 days after their production.

The values obtained are represented in Fig. 11. These values were measured after 28 days elapsed since the samples production.

The higher carbonation depth values are those corresponding to PVC compounds followed by the PVC + PE concrete. This could be related, firstly with the presence of chlorine ion in the PVC and probably in the concrete and secondly with the high porosity of these compounds that enhance carbon dioxide diffusion.
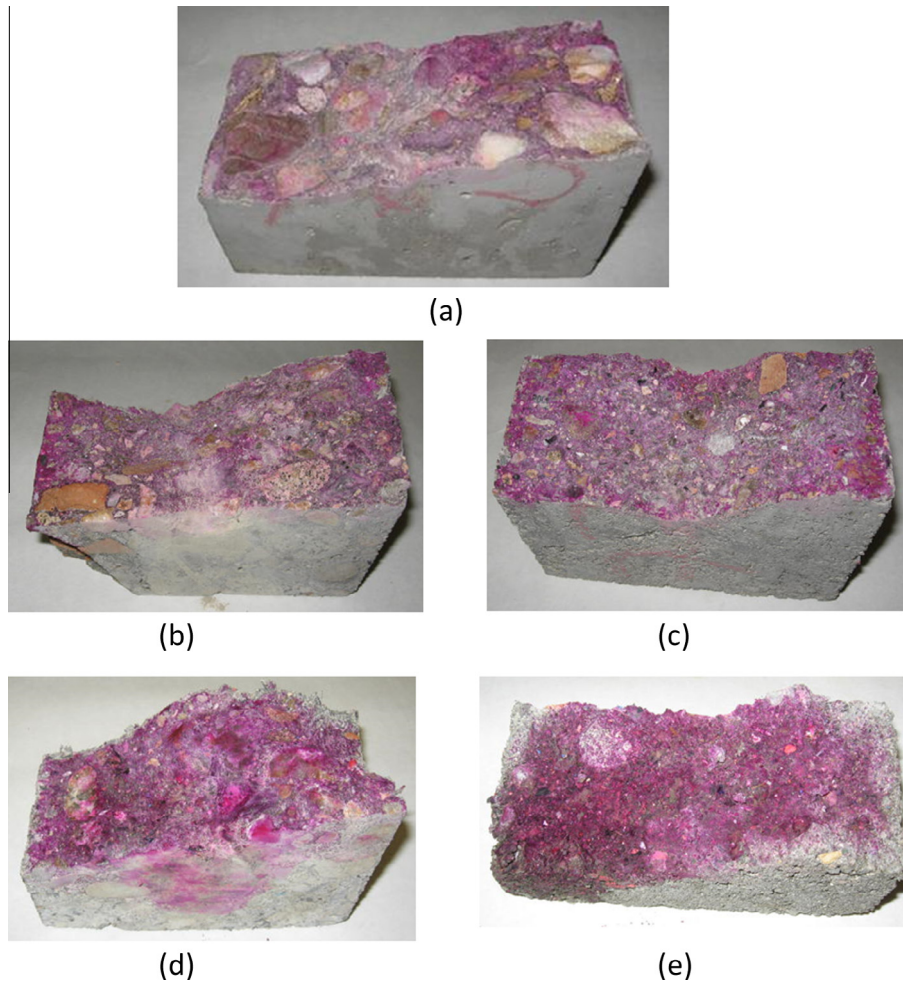
Fig. 10. Carbonation test on concrete specimens with 0% (control) (a), 2.5% (a), 5% (b), 10% (c) and 20% (d) of added PVC.

These results suggest the poor ability of these materials, especially those PVC based, to protect the steel reinforcements from corrosion.

3.3. Mortars mechanical properties

Although these materials were not intended to be part of primary structures it was considered necessary to obtain reference values for mechanical properties (flexural and compressive) to assure their load bearing capacity.

Mechanical properties time evolution was measured for all the cases, but only in one case (PVC-mortar) this evolution was recorded for long time values (up to 120 days). The reason to do so is the great amount of samples managed in those tests (several tons including mortar and concrete samples) and the limited space available in our lab.

In upper part of Fig. 12 the flexural strength temporal evolution for mortar-PVC is presented. It is clear at a first sight that the higher the plastic content the lower the values of strength. It seems also that the time interval from the flexural initial value to the stabilized one is reduced as plastic content is increased. Sample "curing" interval was reduced and interfered by the presence of PVC or air (porosity).

The same behavior can be seen in the case of the compressive strength which is showed in the lower part of Fig. 12 for the same type of samples. In this case, the "control" samples (0% of added PVC) compressive values are still evolving at 120 days from the
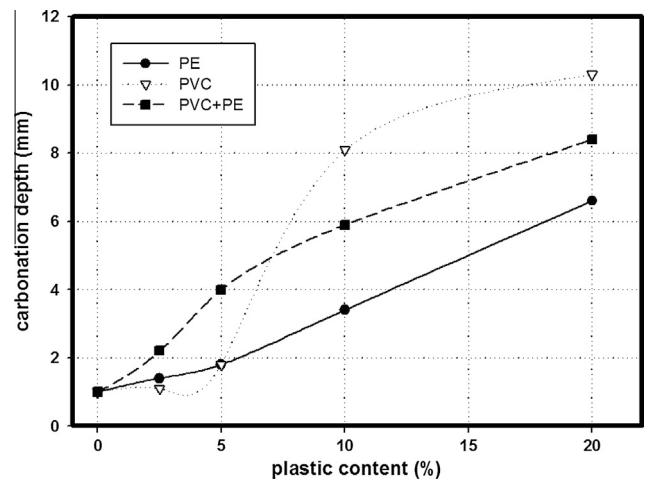
Fig. 11. Carbonation concrete values measured for concrete compounds 28 days after their production.

production date while the 10% and 20% PVC containing compounds are almost stabilized.

Flexural properties values (mixing of tensile and compressive response) are more than three times lower in the case of the 20% PVC containing samples as compared to control samples (measured at 119 days after production). Compressive properties values
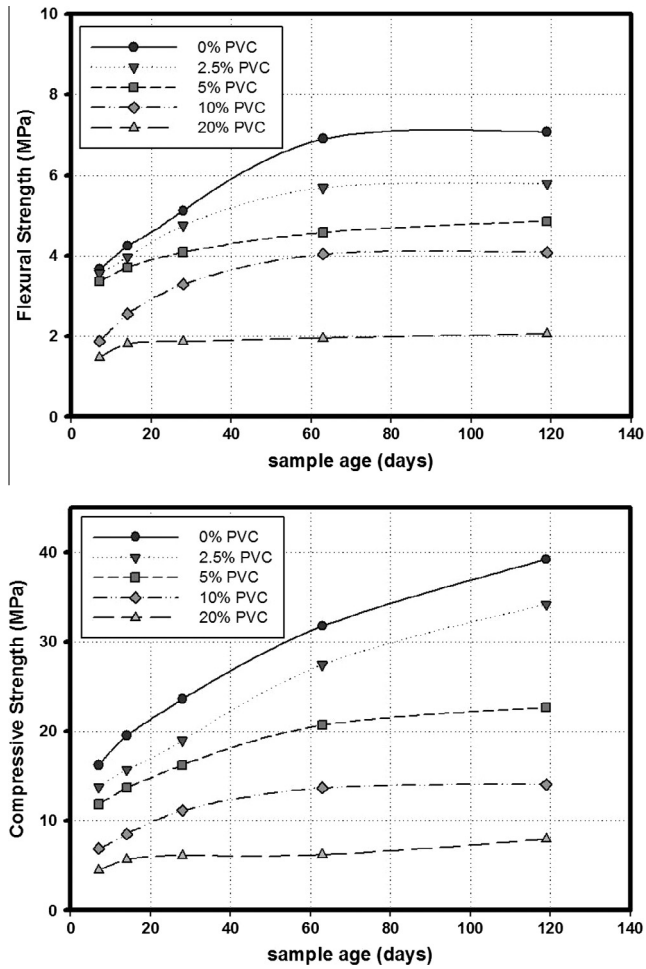
Fig. 12. Flexural and compressive strength temporal evolution measured for mortar-PVC samples.

are in average 5 times lower in the case of 20% PVC containing samples as compared to control samples. It is clear that in both cases (flexural and compressive) the gap between the mortar control values and the mortar plastic compounds increases with time (only in the case of the 5% samples compared to the 10% samples the difference is reduced with time).

In all the studied cases the mechanical measurement repeatability was low and the standard deviation values were comprised between 5% and 10% of the average values. In terms of repeatability, the worst cases were the 2.5% and the 20% plastic content.

The data that correspond to the mortar samples with PE and (PE + PVC) added followed the same pattern but were measured only up to 28 days of evolving. In both cases the higher the plastic content, the lower the mechanical properties. The maximum difference between the flexural values corresponds to 28 days after production and is about three times lower for the 20% PE samples compared to control ones. This difference increases with time going from 2 to 3 for the studied period of time (this is similar to the mortar with PVC evolution showed in Fig. 12 evaluated at the same period of time).

Compressive resistance difference between control samples and 20% PE ones evolves from 5 to 4. In fact taking the measurements errors into account it can be said that the difference did not change and was stabilized at a value between 4 and 5.

In Fig. 13 it is presented the experimental rig used for the mechanical tests.

3.4. Concretes mechanical properties

Once again, like in the previous case of mortar compounds, it is necessary to point out that these materials were not intended to be part of primary structures but it was considered necessary to obtain reference values for mechanical properties (flexural and compressive) to find their load bearing capacity typical values.

Mechanical properties evolution with time was measured for concretes and recorded up to 56 days. The numerical results of the mechanical tests are presented in Tables 3–5.

From tables and figures it is clear that:

- The higher the amount of plastic content (not regarding of the type) the lower the density.
- The higher the amount of plastic content, the lower the mechanical properties of the concrete materials.
- The higher the PE content in the compound, the lower the mechanical properties and the density.

It is necessary to note that for the concrete compounds samples containing a 20% of added plastic the surface quality was very poor. Specifically in the case of 20% of added PE the sample surface crumbled.

3.5. Thermal conductivity

In Fig. 14, the thermal conductivity of mortar-plastic compounds samples with different amounts of added recycled plastic is presented. It can be seen that the higher the plastic content in the compound, the lower the thermal conductivity. For a 20% of added plastic waste (PE) the thermal conductivity drops below one half of its original value. This is really an impressive reduction

Fig. 13. On the left, concrete composite compressive test image. On the right, concrete components four point bending test.

Table 3
Density and overall mechanical properties evolution of the concrete-PVC compounds studied.

	Control concrete	Concrete + 2.5% PVC	Concrete + 5% PVC	Concrete + 10% PVC	Concrete + 20% PVC
Compression samples density (kg/m³)	2399	2382	2344	2250	2018
Compressive strength 7 days (MPa)	30.0	27.4	21.3	15.0	6.0
Compressive strength 28 days (MPa)	34.6	31.9	23.3	16.3	6.6
Compressive strength 56 days (MPa)	46.0	34.8	24.3	21.4	9.0
Flexural samples density (kg/m³)	2418	2380	2353	2240	1938
Flexural strength 7 days (MPa)	3.5	3.3	3.2	3.2	1.3
Flexural strength 28 days (MPa)	4.5	4.5	4.5	3.4	1.4
Flexural strength 56 days (MPa)	5.8	5.3	4.7	3.8	1.7
Indirect tensile (MPa), 28 days	4.3	3.6	3.3	2.5	1.4
Relative Static compressive elastic modulus (MPa)	1	0.77	0.68	0.63	0.35

Table 4
Density and overall mechanical properties evolution of the concrete-PE compounds studied.

	Control concrete	Concrete + 2.5% PE	Concrete + 5% PE	Concrete + 10% PE	Concrete + 20% PE
Compression samples density (kg/m³)	2399	2370	2239	2002	1658
Compressive strength 7 days (MPa)	30.0	25.8	19.2	8.0	2.1
Compressive strength 28 days (MPa)	34.6	29.9	25.4	9.2	3.4
Compressive strength 56 days (MPa)	46.0	32.9	26.3	9.8	3.7
Flexural samples density (kg/m³)	2418	2373	2240	2016	1649
Flexural strength 7 days (MPa)	3.5	2.8	2.6	2.0	0.3
Flexural strength 28 days (MPa)	4.5	3.9	3.4	2.9	1.0
Flexural strength 56 days (MPa)	5.8	5.3	4.8	3.4	1.2
Indirect tensile (MPa) 28 days	4.3	3.2	2.7	1.1	0.7
Relative Static compressive elastic modulus (MPa)	1	0.76	0.61	0.30	0.08

Table 5
Density and overall mechanical properties evolution of the concrete-(PVC + PE) compounds studied.

	Control concrete	Concrete + 2.5% PE + PVC	Concrete + 5% PE + PVC	Concrete + 10% PE + PVC	Concrete + 20% PE + PVC
Compression samples density (kg/m³)	2399	2377	2312	2193	1961
Compressive strength 7 days (MPa)	30.0	22.6	20.2	13.5	3.8
Compressive strength 28 days (MPa)	34.6	30.8	23.2	18.7	4.0
Compressive strength 56 days (MPa)	46.0	31.9	25.2	19.5	5.1
Flexural samples density (kg/m³)	2418	2358	2322	2222	1902
Flexural strength 7 days (MPa)	3.5	3.0	2.8	2.3	1.1
Flexural strength 28 days (MPa)	4.5	4.1	3.6	3.1	1.3
Flexural strength 56 days (MPa)	5.8	5.4	4.5	3.8	1.4
Indirect tensile (MPa) 28 days	4.3	3.2	2.8	2.1	1.0
Relative Static compressive elastic modulus (MPa)	1	0.72	0.59	0.52	0.25
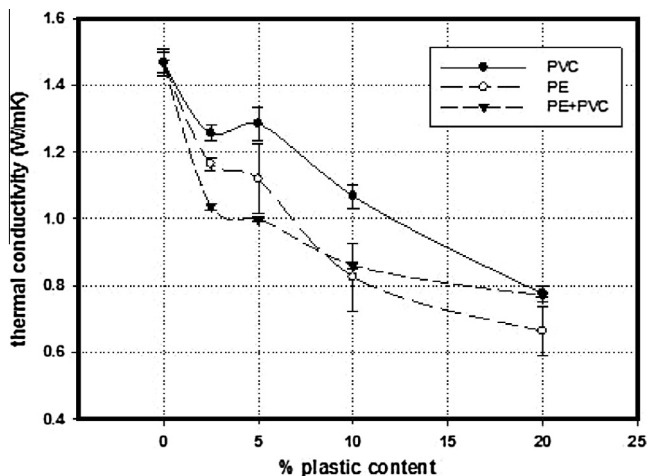
Fig. 14. Thermal conductivity of a series of mortar samples with different amounts of added recycled plastic. Like in Fig. 18, it can be seen again that the higher the volume content of plastic in the compounds, the lower the thermal conductivity.

that will be discussed later and that cannot be interpreted only taking into account the difference between the thermal conductivities of the components, plastic and control mortar (that forms the matrix of the compound).

Fig. 15 shows the thermal conductivity of a series of concrete compounds samples. Like in the previous case the higher the volume content of plastic in the material, the lower the thermal conductivity. For a 20% of added plastic waste (PVC or PVC + PE) the thermal conductivity drops to a third part of its original value.

It was not possible to measure the conductivity of the concrete compound with 20% added polyethylene due to the very poor surface state of the samples.

Once more the impressive reduction cannot be interpreted only in terms of the difference between the thermal conductivities of the components (plastic and control concrete).

It is very interesting to note that these materials show a remarkable combination of high thermal capacity (close to values of concrete or mortars) and relatively low thermal conductivity. Thermal capacity is related with the ability of a material to damp the exterior temperature oscillations (in cold or hot climates) while
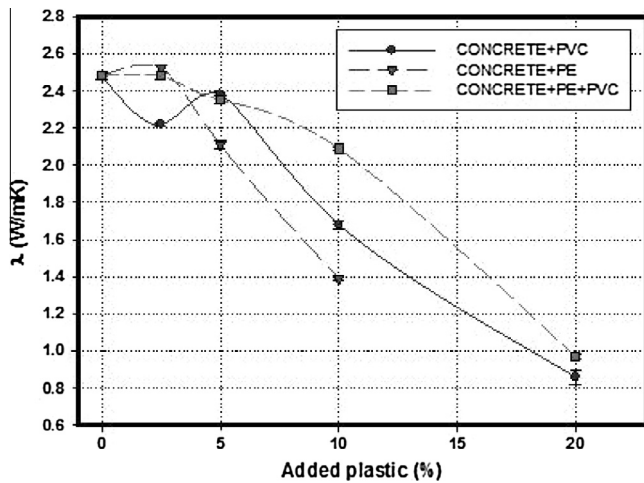
Fig. 15. Thermal conductivity of a series of concrete samples with different amounts of added recycled plastic. It can be seen that the higher the plastic volume content in the compound, the lower the thermal conductivity.

thermal conductivity (or thermal resistance which is simply the sample thickness divided by conductivity value) measures the capacity of a material as thermal insulator.

This thermal conductivity reduction is a very interesting fact that adds value to the set of materials under study, so it is worth pausing to consider from where the decrease in thermal conductivity arises.

4. Discussion

In this section the variation of three different aspects will be discussed, namely, density, mechanical properties and thermal properties.

4.1. Density

Density values drop with the plastic content. This is not shocking, but it was observed that density values were lower than the predicted ones by the rule of mixtures (taking the values of PVC density between 1350 and 1450 kg/m^3 and the PE density between 944 and 965 kg/m^3 and the measured control mortar or concrete density to make the calculations) for both concrete and mortar materials.

In the case of mortars by taking into account that the composite is formed by control mortar (including its own porosity), plastic and added porosity (due to the presence of irregular plastic particles or due to gas released in chemical reactions):

$$\rho_{compound} = \rho_{control}\chi_{vol,control} + \rho_{plastic}\chi_{vol,plastic} + \rho_{air}\chi_{vol,air} \qquad (1)$$

By simple calculations it is easy to demonstrate that the values of added porosity that fit the density to the rules of mixtures (which is exact in the density case) are the presented in the following tables (see Tables 6–8):

The message of these tables is clear: the higher the presence of PE, the higher the value of calculated porosity (see Table 9).

The experimental values showed that the higher value of porosity corresponds to the PE containing materials followed by the PVC and the PE + PVC. In fact, due to the low repeatability of the measures PVC and PVC + PE showed similar values.

The differences between the experimental porosity measured values and the theoretical ones could indicate that part of that is not an open porosity connected to surface and then cannot be detected by pycnometric methods.

Table 6
Mortars porosity mean values calculated for the theoretical density values to fit the measured ones.

% of added plastic	Porosity PE (%)	Porosity PVC (%)	Porosity PE + PVC (%)
0	0	0	0
2.5	0.8	1.1	3.9
5.0	7.6	1.1	5.3
10.0	12.2	3.8	10.5
20.0	19.4	8.5	17.6

Table 7
Measured mortar compounds porosity mean values.

% of added plastic	Porosity PE (%)	Porosity PVC (%)	Porosity PE + PVC (%)
0	6.3	6.3	6.3
2.5	7.0	6.9	7.0
5.0	8.3	8.1	8.2
10.0	14.0	12.0	10.1
20.0	19.9	17.2	16.5

Table 8
Concretes porosity mean values calculated for the theoretical densities values to fit the measured ones.

% of added plastic	Porosity PE (%)	Porosity PVC (%)	Porosity PE + PVC (%)
0.0	0	0	0
2.5	0	0	0
5.0	4.1	0.2	1.1
10.0	10.5	2.1	3.5
20.0	18.9	7.6	8.1

Table 9
Measured concrete compounds porosity mean values.

% of added plastic	Porosity PE (%)	Porosity PVC (%)	Porosity PE + PVC (%)
0.0	7.1	7.1	7.1
2.5	8.2	7.7	7.8
5.0	9.5	8.5	8.4
10.0	16.2	11.7	10.3
20.0	20.6	17.1	16.1

So it seems that the compounds are formed by three main components: air, control mortar or concrete (forming the matrix material) and plastic. Control material is itself another compound with the presence of air.

This is a very interesting fact that would allow considering in the qualitative mechanical and thermal modeling that the properties of the studied compounds would be a mixture of those of the control matrix, the plastic and air.

4.2. Mechanical properties

Initially, to try to explain the experimental values measured, three different simple models taken from literature [58,59] were used to try to fit the strength values to the experimental ones and none of them were capable to fit them properly.

In model 1, for a good compatibility between the "matrix" (control mortar/concrete) and the "reinforcement" (plastic) the upper strength of the compound could be taken as:

$$\sigma_u = f(\sigma_r) + (1 - f)\sigma_m \qquad (2)$$

where f is the volume fraction of reinforcement, σ_r is the reinforcement strength and σ_m the matrix strength.

This expression represents clearly an upper bound that is not taken into account the particulate nature of the compound.

In model 2, for a weak compatibility between the matrix (control mortar/concrete) and the reinforcement (plastic) the lower strength of the composite could be taken as (lower bound):

$$\sigma_l = \sigma_m \left[1 + \frac{1}{16} \left(\frac{f^{1/2}}{1-f^{1/2}} \right) \right] \qquad (3)$$

Finally in model 3 there is no contribution of the reinforcement to the values of strength.

$$\sigma_u = (1-f)\sigma_m \qquad (4)$$

None of these models were capable to fit the mechanical data. All of them overestimate the values. It was a little surprising that even the last model in which it was considered only the presence of the blank as matrix was unable to approach to the experimental data.

Also it was noted that the difference between the experimental and the models predicted values was higher with increasing porosity (higher plastic content) (See Fig. 16).

Simple models were not capable to fit the experimental data; even in the case of Eq. (4) in which it was considered only the mechanical behavior of the matrix material. Also is worth noting that the difference between the models predicted values and the measured ones was higher as plastic content increased.

A question arise: is the structure of the solid evolving as plastic and porosity increase?

To evaluate this option it was considered the possibility of the estimation of the cellular nature effects of the studied solid through the use of a more advanced model, for this kind of solids to try to fit the compression data [60,61]:

$$\frac{\sigma_f}{\sigma_s} \propto C_1 \left(C_2 \frac{\rho_f}{\rho_s} \right)^{3/2} + C_3 \left(\frac{\rho_f}{\rho_s} \right) + C_4 \qquad (5)$$

where σ_f is the compressive strength of the cellular solid (mortar or concrete), σ_s is the compressive strength of the control material, C_1, C_2, C_3 and C_4 are constants that depend only on geometry of the cellular solid, ρ_f is the density of the cellular solid and ρ_s is the density of the control material.

In this model, the mechanical contribution of the plastic was ignored, only was considered the presence of air and control material forming a cellular solid.

The key point is the determination of the density of this cellular solid ρ_f.

It is easy to demonstrate that in a cellular solid [60] the volume percentage of air (the porosity Φ that in our case was measured experimentally) and solid material (control matrix in this case) can be calculated by:

$$\Phi = 1 - \frac{\rho_f}{\rho_s} \qquad (6)$$

From this expression, ρ_f density of this cellular solid can be obtained readily.

In Figs. 17 and 18 the fittings for mortar and concrete are presented. The fittings for mortar are very good while those for concretes are worse.

In both cases presented the tendency is clearly the predicted by Eq. (5). This seems to indicate that the properties of the control matrix (mortar or concrete) are able to predict the mechanical behavior in compression only by considering that we are in front of a cellular solid. This is not a predictive model but rather indicates that the samples are no longer behaving like continuum ones but instead, they are following the mechanics of the cellular solids formed by control matrix and air or plastic bubbles that add very
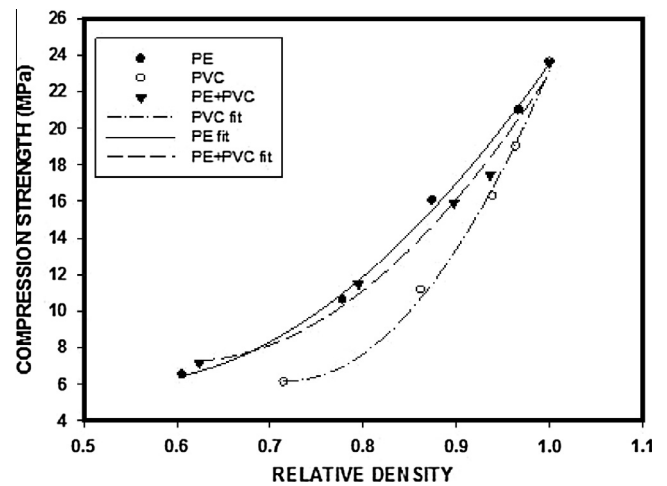

Fig. 17. Mortar compounds compression strength values were nicely fitted using a polynomial of relative density (Eq. (5)).
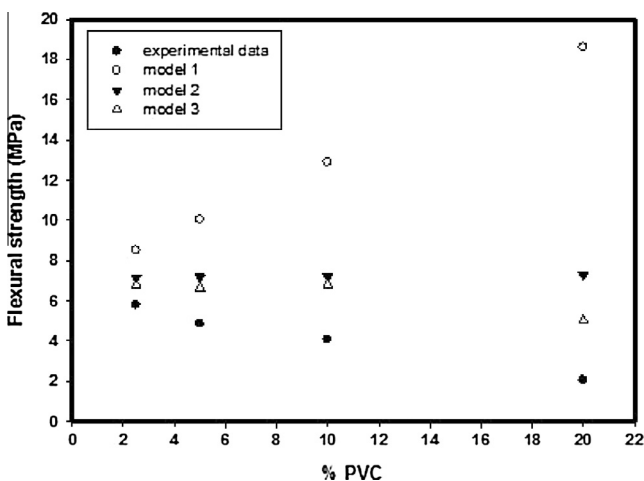

Fig. 16. Experimental and predicted values in the case of flexural strength of mortar-PVC composites.
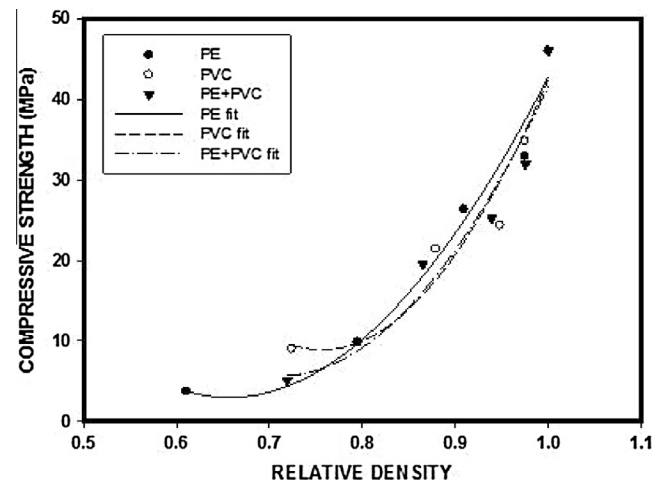

Fig. 18. Concrete compounds compression strength values fitting using a polynomial of cellular solid relative density (Eq. (5)).

little to the mechanical response of the compound. This is pretty surprising and needs further examination.

It is clear that the resulting materials had low mechanical properties. Though these materials were not intended to be part of primary structures, it is necessary to point out that their mechanical properties can be improved easily by using a higher cement content (to improve the control matrix properties).

4.3. Thermal conductivity

The intense decrease in thermal conductivity showed in Figs. 14 and 15 with the increasing plastic content in mortars and concretes is a highly interesting fact that adds value to the set of materials under study, so it is worth pausing to consider from where the decrease in thermal conductivity arises.

Following the scheme presented in the case of the mechanical properties, simple models based again on rules of mixtures were used to try to fit the measured values. In these models, the components of the compound were control (matrix) mortar or concrete (including porosity) and plastic content. Like in the case of the mechanical properties, these models were unable to fit the thermal conductivity data. The conductivity predicted by cited models were always higher than the measured values.

Final compound can be considered as formed by the original material (which we called control mortar) PVC added and trapped air. (The original control mortar in turn is a compound consisting of sand, cement and air bubbles).

The following values were used for the calculations of the theoretical conductivity:

Control mortar conductivity (measured) = 1.47 W/m K.
Control concrete conductivity (measured) = 2.48 W/m K.
Conductivity of PVC (estimated literature values) = 0.12–0.25 W/m K.
Conductivity of LDPE (estimated literature values) = 0.31–0.36 W/m K.
Air conductivity at 20 °C 0.024 W/m K.

It was assumed that the thermal conductivity can be calculated to a first approximation by a simple mixture model (upper bound) [58,59].

$$\lambda_{compound} = \lambda_{control}\chi_{vol,control} + \lambda_{plastic}\chi_{vol,plastic} \tag{7}$$

where λ represents plastic and blank mortar thermal conductivities and the χ are the respective volume fractions.

Even starting from the lowest to the conductivity of plastic values, the model cannot predict reasonably the data obtained from the measurements. Moreover, it estimates for the initial values of thermal conductivity of mortars (see conductivity at 0% PVC) minor values than those finally measured experimentally. In any case, although the model predicts qualitatively, as expected, it does not predict quantitatively.

The first correction proposed was to incorporate to the model the porosity, that is, the volume fraction of air, further shown by the presence of irregular plastic grains.

$$\lambda_{compound} = \lambda_{control}\chi_{vol,control} + \lambda_{plastic}\chi_{vol,plastic} + \lambda_{air}\chi_{vol,air} \tag{8}$$

It is important to note that this porosity does not include the amount of air that may be present in the blank mortar, that is, with 0% of plastic content, that is already taken into account effectively, since the control conductivity values introduced in the model are experimentally measured ones.

In Tables 10 and 11 the mean porosity values calculated for mortars and concretes are presented.

Table 10
Mortars predicted porosity according to model represented by Eq. (8).

% of added plastic	Porosity PE	Porosity PVC	Porosity PE + PVC
0	0	0	0
2.5	19.1	12.5	27.7
5.0	20.2	8.4	28.2
10.0	36.6	19.1	33.5
20.0	39.9	30.8	31.1

Table 11
Concretes predicted porosity according to model represented by Eq. (8).

% of added plastic	Porosity PE	Porosity PVC	Porosity PE + PVC
0	0	0	0
2.5	0	8.3	0
5.0	10.7	0	0.7
10.0	35.6	23.4	6.7
20.0	–	47.6	43.1

These values were calculated fitting Eq. (8) to the experimental data of measured thermal conductivity of the materials.

In the case of mortars it is clear that the porosity predicted values are much higher than the measured ones. In the case of concretes, up to 5% of plastic content, the predicted porosity is lower than the measured while for 20% the porosity is higher. In both cases, concretes and mortars, the presented models are unable to fit the experimental data consistently.

Following again the scheme presented in the case of the mechanical properties it was studied the possibility of modeling the resulting composite as a cellular solid.

For a cellular solid, thermal conductivity not taking into account the radiation term, can be expressed as [62–66]:

$$\lambda = \lambda_g\left(1 - \frac{\rho_f}{\rho_s}\right) + C\left(\frac{\rho_f}{\rho_s}\right)\lambda_s \tag{9}$$

C depends only on cellular structure and can be calculated readily once known the rest of parameters involved in the equation:

Where ρ_f is the density of the cellular composite, ρ_s is the density of the control (mortar or concrete), λ_g is the thermal conductivity of air (0.024 W/m K) and λ_s is the measured thermal conductivity o the control matrix (mortar or concrete).

Taking C as variable in the equation, the model results are impressive (see Tables 12 and 13).

Table 12
Mortars measured and predicted values for thermal conductivity using Eq. (9), taking C as a variable.

Mortar compounds	Relative density	Measured conductivity (W/m K)	Constant C	Calculated conductivity (W/m K)
PE	1.000	1.467	1.00	1.467
	0.967	1.163	0.81	1.164
	0.874	1.118	0.86	1.119
	0.778	0.825	0.71	0.827
	0.606	0.663	0.73	0.667
PVC	1.000	1.467	1.00	1.467
	0.964	1.254	0.88	1.255
	0.939	1.282	0.93	1.283
	0.862	1.064	0.84	1.066
	0.715	0.769	0.72	0.762
PE + PVC	1.000	1.467	1.00	1.467
	0.936	1.037	0.75	1.038
	0.897	0.998	0.75	0.999
	0.795	0.861	0.74	0.868
	0.624	0.774	0.84	0.778

Table 13
Concretes measured and predicted values for thermal conductivity using Eq. (9) and taking *C* as variable.

Concrete compounds	Relative density	Measured conductivity (W/m K)	Constant C	Calculated conductivity (W/m K)
PE	1.000	2.480	1.00	2.480
	0.975	2.520	1.00	2.418
	0.909	2.110	0.93	2.116
	0.795	1.390	0.70	1.394
	0.611	–	0.69	1.054
PVC	1.000	2.480	1.00	2.480
	0.975	2.219	0.915	2.213
	0.948	2.378	1.00	2.352
	0.879	1.677	0.76	1.670
	0.724	0.854	0.47	0.850
PE + PVC	1.000	2.480	1.00	2.480
	0.975	2.480	1.02	2.418
	0.939	2.351	1.00	2.330
	0.865	2.092	0.97	2.094
	0.719	0.974	0.54	0.978

These results indicate that, like in the case of the compressive strength, the blank material properties are capable of explaining the thermal conductivity observed values both in mortars and concretes only by taking into account the appearance of a cellular structure.

The unexpected additional decrease in thermal conductivity cannot be explained merely by the presence of plastic and porosity. The additional reduction in the solid conductivity term of Eq. (9) could be related to the "tortuosity" induced in the solid phase by the emergence of a cellular structure.

5. Conclusions

The studied mortar and concrete materials had low density, due, in one hand to the presence of plastic aggregates and in the other to the increased induced porosity.

The resulting materials, in both cases mortars and concretes, presented low mechanical properties that can be easily enhanced by improving the matrix properties. The decrease in mechanical properties cannot be explained only by the presence of plastic and porosity. For the studied materials compressive strength follows a law, Eq. (5) characteristic of a cellular solid model, whose matrix is the control mortar or concrete

The studied materials showed an important decrease in thermal conductivity that cannot be explained merely by the presence of plastic and porosity. Thermal conductivity can be predicted accurately by using Eq. (9) corresponding to a cellular solid model, whose matrix is the control mortar or concrete.

The results obtained in the case of mechanical and thermal properties are highly independent of the plastic used supposing that it has no chemical interaction with the cement matrix.

The use of plastic waste is an interesting way to extend life of non-reusable plastics in civil engineering applications providing mortars and concretes with low mechanical properties but increased thermal insulation properties.

Acknowledgements

References

[1] K.S. Rebeiz, A.P. Craft, Plastic waste management in construction: technological and institutional issues, Resour. Conserv. Recycl. 15 (1995) 245–257.
[2] Rafat Siddique, Jamal Khatib, Inderpreet Kaur, Use of recycled plastic in concrete: a review, Waste Manage. 28 (2008) 1835–1852.
[3] David Lazarevic, Emmanuelle Aoustin, Nicolas Buclet, Nils Brandt, Plastic waste management in the context of a European recycling society: comparing results and uncertainties in a life cycle perspective, Resour. Conserv. Recycl. 55 (2010) 246–259.
[4] S.M. Al-Salem, P. Lettieri, J. Baeyens, Recycling and recovery routes of plastic solid waste (PSW): a review, Waste Manage. 29 (2009) 2625–2643.
[5] Mehdi Sadat-Shojai, Gholam-Reza Bakhshandeh, Recycling of PVC wastes, Polym. Degrad. Stab. 96 (2011) 404–415.
[6] Kotiba Hamad, Mosab Kaseem, Fawaz Deri, Recycling of waste from polymer materials: an overview of the recent works, Polym. Degrad. Stab. 98 (2013) 2801–2812.
[7] Ardavan Yazdanbakhsh, Lawrence C. Bank, A critical review of research on reuse of mechanically recycled FRP production and end-of-life waste for construction, Polymers 6 (2014) 1810–1826.
[8] Yongxiang Yanga, Rob Boom, et al., Recycling of composite materials, Chem. Eng. Process. 51 (2012) 53–68.
[9] Cemal Meran, Orkun Ozturk, Mehmet Yuksel, Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene, Mater. Des. 29 (2008) 701–705.
[10] S.M. Al-Salem, P. Lettieri, J. Baeyens, The valorization of plastic solid waste (PSW) by primary to quaternary routes: from re-use to energy and chemicals, Prog. Energy Combust. Sci. 36 (2010) 103–129.
[11] D. Froelich, E. Maris, N. Haoues, State of the art of plastic sorting and recycling: feed back to vehicle design, Miner. Eng. 20 (2007) 902–912.
[12] T.R. Naik, S.S. Singh, B.S. Brodersen, Use of post-consumer waste plastics in cement-based composites, Cem. Concr. Res. 26 (1996) 1489–1492.
[13] O. Yazoghli Marzouk, R.M. Dheilly, M. Queneudec, Valorization of post-consumer waste plastic in cementitious concrete composites, Waste Manage. 27 (2007) 310–318.
[14] Rafat Siddique, Jamal Khatib, Inderpreet Kaur, Use of recycled plastic in concrete: a review, Waste Manage. 28 (2008) 1835–1852.
[15] F. Iucolano, B. Liguori, et al., Recycled plastic aggregate in mortars composition: effect on physical and mechanical properties, Mater. Des. 52 (2013) 916–922.
[16] Nabajyoti Saikia, Jorge de Brito, Use of plastic waste as aggregate in cement mortar and concrete preparation: a review, Constr. Build. Mater. 34 (2012) 385–401.
[17] Benito Mas, Antoni Cladera, et al., Concrete with mixed recycled aggregates: influence of the type of cement, Construct. Build. Mater. 34 (2012) 430–441.
[18] Brahim Safi, Mohammed Saidi, et al., The use of plastic waste as fine aggregate in the self-compacting mortars: Effect on physical and mechanical properties, Construct. Build. Mater. 43 (2013) 436–442.
[19] R. Siddique, J. Khatib, I. Kaur, Use of recycled plastic in concrete: a review, Waste Manage. 28 (2008) 1835–1852.
[20] Xiang Shu, Baoshan Huang, Recycling of waste tire rubber in asphalt and Portland cement concrete: an overview, Constr. Build. Mater. 67 (2014) 217–224.
[21] R.V. Silva, J. de Brito, Nabajyoti Saikia, Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates, Cem. Concr. Compos. 35 (2013) 23–31.
[22] Vivian W.Y. Tam, C.M. Tam, A review on the viable technology for construction waste recycling, Resour. Conserv. Recy. 47 (2006) 209–221.
[23] Zahra Niloofar Kalantar, Mohamed Rehan Karim, Abdelaziz Mahrez, A review of using waste and virgin polymer in pavement, Construct. Build. Mater. 33 (2012) 55–62.
[24] Semiha Akçaözoglu, Kubilay Akçaözoglu, Cengiz Duran Atis, Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA), Compos.: Part B 45 (2013) 721–726.
[25] B. Yesilata, Y. Isıker, P. Turgut, Thermal insulation enhancement in concretes by adding pet waste and rubber pieces, Constr. Build. Mater. 23 (2009) 1878–1882.
[26] A.M. Papadopoulos, State of the art in thermal insulation materials and aims for future developments, Energy Build. 37 (2005) 77–86.
[27] H.S. Dweik, M.M. Ziara, H.S. Hadidoun, Enhancing concrete strength and thermal insulation using thermoset plastic waste, Int. J. Polym. Mater. 57 (2008) 635–656.
[28] George C. Hoff, Porosity-strength considerations for cellular concrete, Cem. Concr. Res. 2 (1972) 91–100.
[29] Bjørn Petter Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities, Energy Build. 43 (2011) 2549–2563.
[30] Dietrich Braun, Recycling of PVC, Prog. Polym. Sci. 27 (2002) 2171–2195.
[31] Mehdi Sadat-Shojai, Gholam-Reza Bakhshandeh, Recycling of PVC wastes, Polym. Degrad. Stab. 96 (2011) 404–415.
[32] Y. Saeki, T. Emura, Technical progresses for PVC production, Prog. Polym. Sci. 27 (2002) 2055–2131.

[33] S. Kim, Pyrolysis kinetics of waste PVC pipe, Waste Manage. 21 (2001) 609–616.

[34] W.M. Quiao et al., Waste polyvinylchloride derived pitch as a precursor to develop carbon fibers and activated carbon fibers, Waste Manage. 27 (2007) 1884–1890.

[35] M.J.P. Slapak, Design of a process for steam gasification of PVC waste, Resour. Conserv. Recycl. 30 (2000) (2000) 81–93.

[36] C. Jaksland, E. Rasmussen, T. Rohde, A new technology for treatment of PVC waste, Waste Manage. 20 (2000) 463–467.

[37] Rosa Miranda, Jin Yang, Christian Roya, Cornelia Vasile, Vacuum pyrolysis of PVCI. Kinetic study, Polym. Degrad. Stabil. 64 (1999) 127–144.

[38] L. Sorum, M.G. Gronli, J.E. Hustad, Pyrolysis characteristics and kinetics of municipal solid wastes, Fuel 80 (9) (2001) 1217–1227.

[39] UNE 83821 Mortars, Test methods, Hardened mortars, Determination of flexural and compressive strength.

[40] UNE 83811 Mortars, Test methods, Fresh mortars, Determination of consistence, Flow table (reference method).

[41] UNE 83301 Test of concrete, Making and curing of specimens.

[42] UNE-EN 933-1:2012: tests for geometrical properties of aggregates – Part 1: determination of particle size distribution – sieving method.

[43] UNE-EN 1015-10:2000: methods of test for mortars for masonry Part 10: determination of dry bulk density of hardened mortar.

[44] UNE EN 12390-7: testing hardened concrete – Part 7: density of hardened concrete.

[45] UNE-EN 772-11:2001 methods of test for masonry units – Part 11: determination of water absorption of aggregate concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units.

[46] UNE-EN 14630:2007:0. Products and systems for the protection and repair of concrete structures – test methods – determination of carbonation depth in hardened concrete by the phenolphthalein method.

[47] UNE-EN 1015-11:2000/A1:2007: methods of test for mortar for masonry – Part 11: determination of flexural and compressive strength of hardened mortar.

[48] UNE-EN 12390-3:2003: testing hardened concrete – Part 3: compressive strength of test specimens.

[49] UNE-EN 12390-5:2009: testing hardened concrete – Part 5: flexural strength of test specimens.

[50] UNE-EN 12390-6:2010: testing hardened concrete – Part 6: tensile splitting strength of test specimens.

[51] UNE 83316:1996: concrete tests, Determination of the modulus of elasticity in compression.

[52] Silas E. Gustafsson, Ernest Karawacki, M. Nazim Khan, Transient hot-strip method for simultaneously measuring thermal conductivity and thermal diffusivity of solids and fluids, J. Phys. D: Appl. Phys. 12 (1979) 1411–1421.

[53] Mattias Gustafsson, Ernest Karawacki, Silas E. Gustafsson, Thermal conductivity, thermal diffusivity and specific heat of thin samples from transient measurements with hot disk sensors, Rev. Sci. Instrum. 65 (2) (1994) 3856–3859.

[54] Silas E. Gustafsson, Transient planes source techniques for thermal conductivity and thermal diffusivity measurements of solid materials, Rev. Sci. Instrum. 62 (3) (1991) 797–804.

[55] Marcelo Antunes, Vera Realinho, et al., Thermal conductivity anisotropy in polypropylene foams prepared by supercritical CO_2 dissolution, Mater. Chem. Phys. 136 (2012) 268–276.

[56] E. Solórzano, M.A. Rodriguez-Perez, J.A. de Saja, Thermal conductivity of cellular metals measured by the transient plane source method, Adv. Eng. Mater. 10 (6) (2008) 596–602.

[57] Yi. He, Rapid thermal conductivity measurement with a hot disk sensor, Part 1. Theoretical considerations, Thermochim. Acta 436 (2005) 122–129.

[58] M.F. Ashby, Criteria for selecting the components of composites, Acta Mater. 41 (1993) 1313–1335.

[59] M.F. Ashby, On the engineering properties of materials, Acta Metall. 37 (1989) 1273–1293.

[60] L.J. Gibson, M.F. Ashby, Cellular Solids: Structure and Properties, second ed., Cambridge University Press, 1997.

[61] Fabrice Saint-Michel, Laurent Chazea, Jean-Yves Cavaille, Emanuelle Chabert, Mechanical properties of high density polyurethane foams I. Effect of the density, Compos. Sci. Technol. 66 (2006) 2700–2708.

[62] L.R. Glicksman, Heat Transfer in Foams, in: Low Density Cellular Plastics: Physical Basis of Behavior, Chapman Hall, 1994.

[63] N.C. Hilyard, A. Cunninghan (Eds.), Low Density Cellular Plastics: Physical Basis of Behavior, Chapman Hall, 1994.

[64] J.A. Martínez-Díez, M.A. Rodríguez-Pérez, J.A. de Saja, L.O. Arcos y Rábago, O.A. Almanza, The thermal conductivity of a polyethylene foam block produced by a compression moulding process, J. Cell. Plast. 37 (2001) 21–42.

[65] M.A. Rodríguez-Pérez, Propiedades Térmicas y Mecánicas de Espumas de Poliolefinas, Doctoral Thesis, Universidad de Valladolid, 1998.

[66] P.G. Collishaw, J.R.G. Evans, An assessment of expressions for the apparent thermal conductivity of cellular materials, J. Mater. Sci. 29 (9) (1994) 2261–2273.