Sustainable aggregates from secondary materials for innovative lightweight concrete products

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Large quantities of waste materials are generated from manufacturing processes, industries and municipal solid wastes. As a result, waste management has become one of the major environmental concerns in the world. The increasing awareness about waste management and environment-related issues has led to substantial progress in the utilization of wastes or by-products like plastics as an attractive alternative to disposal. The use of post-consumer plastics in the concrete manufacturing represents an effective solution both to the problem of reducing their environmental impact and to the development of sustainable building industry. The production of new construction materials using recycled plastics is important to both the construction and the plastic recycling industries. In this paper the viability of some secondary plastic materials as aggregates for concrete is assessed. Three different types of plastic scraps (polyurethane foams, tyre rubber and scraps resulting from the sorting of recycled plastics from solid urban wastes) were processed in order to allow their use as aggregates for non-structural concretes. Several mixtures based on recycled aggregates and Portland cement were then manufactured; a large characterization campaign was performed checking how the different amounts of the investigated recycled materials influence the final performances in terms of density, workability, mechanical strength and insulation. The obtained results confirmed that the examined sustainable aggregates could be used for the manufacturing of innovative lightweight concretes products. The potential benefits for industries and society are three: reducing the landfill disposal of several types of solid waste, providing new cost-effective building materials and ensuring the environmental sustainability of the new products.

Key words: Aggregates from secondary plastics, lightweight concretes, thermal insulation, innovative construction components

1 Introduction

A substantial growth in the consumption of plastic is observed all over the world in recent years; this has led to huge quantities of plastic-related wastes [Saikia *et al*, 2012]. Recycling of plastic waste to produce new materials such as concretes aggregates has economic and ecological advantages and is considered one of the best solution for disposing of plastic waste. The development of new construction materials using recycled plastics is significant for both the construction and the plastic recycling industries. Moreover, post-consumer plastic aggregates can be successfully and effectively used to replace traditional aggregates [Siddique *et al*, 2008]. Recent studies have reported the promising use of polymers (polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), expanded polystyrene (PS) and others) in the production process of concrete. In particular, the large growth in the use of plastic materials has generated a growing interest worldwide in reusing recycled polymers [Liguori *et al*, 2014]. Although several studies have demonstrated that waste plastics can be beneficially incorporated in concrete, it is important to observe that not all waste materials are suitable for such use [Zanaib *et al*, 2008].

The research reported in this paper is focused on the assessment of the viability of secondary plastics as aggregates for concretes. Plastic scraps explored in this study are rigid polyurethane (PU) foams, Mixed Plastic Waste (MPW) coming from the sorting process of Municipal Solid Waste (MSW) and exhausted rubber tyres. The research on the use of rigid PU foam waste as aggregate for concrete, despite the relatively low cost and good chemical compatibility with cement, is very poor and some limitations have been also evidenced [Mounanga P. *et al*, 2008]; however it has been demonstrated its suitability for non-structural lightweight concretes [Verdolotti *et al*, 2008]. With respect to aggregate from MPW tested in this research it has a mixed composition (it mainly consists of PE and PP but also PET), therefore its behaviour in concrete might differ from similar plastics tested in other studies. Previous research activities[1] have demonstrated the feasibility, processing

[1] Carried out by CETMA in collaboration with a company operating in the materials recycling sector.

specific mixed plastic scraps, to obtain recycled aggregates (referred to as "Remix") in both lower and higher density (NUMIX project "High performance lightweight aggregate for concrete from recycling of plastic waste", CIP-ECOINNOVATION 2008, Project n. ECO/08/239110/SI2.535262); however their potential for concretes manufacturing still need to be fully validated. As far as concerns the use of recycled tyre rubber aggregates some practical applications have been proposed but it was also evidenced that their incorporation into concretes was not always successful due to rubber-cement paste incompatibility [Shu *et al*, 2014]. In other studies the use of recycled rubber tyres for concretes with good thermal insulation performance has been demonstrated [Cairns *et al*, 2004]. These three waste materials have been selected since they are available in quantities large enough for feeding the concrete industry and, at the same time, represent a socio-economic problem as there are low chances for their re-use in more added-values applications. The availability, across Europe, of these waste streams to be converted into aggregates has been quantified in [Arena *et al.*, 2015] together with the analysis of rules for re-use and integration of recycled aggregates in concrete at European level.

The use of sustainable aggregates from specific secondary materials in conventional cement binder systems is one of the goal of the SUS-CON project ("SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials", FP7/2007-2013, Grant Agreement No. 285463). The main outcomes related to the development of these aggregates and their integration within lightweight concretes are reported in this paper. The first part of this work is focused on the secondary materials investigated, their processing to obtain eco – friendly lightweight aggregates and the relevant characterizations to assess their suitability for concretes production. The second part of the work deals with the use of the sustainable aggregates with traditional binders to make lightweight concretes. Several mixtures have been studied and the relation among design parameters and concretes performance (i.e. workability, mechanical and insulating behaviour) have been discussed. The concretes have been developed first on the lab scale and then, for assessing their integration in traditional production cycles, on the industrial level. On the basis of the performances achieved, real non-structural applications have been proposed for these lightweight eco – friendly concretes with recycled plastic aggregates; their performances have been finally compared with those of similar commercial products.

2 Production of lightweight aggregates from secondary materials

2.1 *Rigid Polyurethane foams aggregates*

Recycled Polyurethane (PU) aggregates are made from rejected, non-conform parts or scraps of rigid polyurethane foams. A typical manufacturing process basically consists in mechanical breaking the material to allow size reduction. The first step consists in crushing the raw material into small pieces and then feeding them into the shredding mill. Finally, the material is sieved and separated in different grades.

2.2 *Mixed plastics aggregates*

The remaining plastic debris from the sorting of plastics from Municipal Solid Waste (MSW), commonly defined Mixed Plastic Waste (MPW), are the basis of these aggregates that mainly consist of PE and PP but also PET. Aggregates, herein referred as Remix (RX), have been produced in two different forms, Remix HD (high density) and Remix LD (light density) respectively. Remix HD is obtained by an extrusion process, while Remix LD by an extrusion/foaming process (using foaming agents also from waste) applied on Remix HD. [2]

Polyurethane *Mixed plastic waste* *Tyre rubber*

Figure 1: Secondary raw materials for producing aggregates

2.3 *End-of-life rubber tyres aggregates*

Recycled tyre rubber (TR) recycled aggregates are fabricated trough the processing of scraps resulting from the sorting of end-of-life vehicles tyres. A typical production process begins with the removal of metallic and textile fibers from the tyres, followed by mechanical fragmentation. The tyres are firstly crushed with a system of knives and then enter to a granulator where are processed into aggregates of different gradings.

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[2] The process for producing expanded granules (Remix LD) has been patented by CETMA, these aggregates, in combination with extruded aggregates (Remix HD), have been never tested in other studies.

3 Characterization of lightweight aggregates from secondary materials

In order to assess the suitability of the lightweight aggregates from secondary materials (PU, RX, TR) for concretes manufacturing, physical, mechanical and chemical characterizations have been carried out according to specific standards[3] (Table 1):

- loose bulk density [EN 1097-3];
- particle size distribution – sieving method [EN 933-1];
- particle density and water absorption – pycnometric method [EN 1097-6, Appendix C];
- resistance to compression [EN 13055-1, Appendix A];
- chemical tests [EN 1744-1].

Density has been evaluated in terms of both loose bulk density and particle density. The first parameter is related to the level of packaging of the dried aggregate, its shape and size while the second one is more representative of the behavior of the aggregate within the cement paste in the fresh state. As all the tested aggregates have shown particle density lower than 2000 kg/m^3, they can be classified as lightweight aggregates [EN 206-1]. Finally, according to HSE (Health, Safety and Environment) assessments, it can be stated that the developed aggregates can be all classified as not hazardous materials.

4 Integration of lightweight aggregates from secondary materials in concrete production cycle

For a complete assessment of the suitability of the sustainable lightweight aggregates from secondary materials for concretes manufacturing, the compatibility with traditional cements has been evaluated. To this aim, several mixtures have been designed, optimized

Polyurethane *Remix HD* *Remix LD* *Tyre rubber*

Figure 2: Aggregates resulting from secondary materials processing

[3] Developed for traditional aggregates.

to get the desired properties and tested. Recycled aggregates (PU, RX, TR in the available grades), natural aggregates, ordinary Portland cement (OPC, type I 42.5 R, density 3.1 kg/m^3), water and superplasticizer additives were used. The method used to design, proportioning and mixing is detailed in the Guide for Structural Lightweight-Aggregate Concrete (ACI 213R-14). The following tests have been performed:

- workability or slump test [EN 12350-2] to assess the consistency class of the fresh concrete;
- density at the fresh state [EN 12350-6];
- compressive strength with aging time [EN 12390-3] on cubes (15 x 15 x 15 cm);
- tensile splitting resistance with aging time [EN 12390-6] on cylinders (d = 15 cm, h = 30 cm);
- thermal conductivity [EN 12664] on prisms (15 x 15 x 7 cm);
- ultrasonic pulse velocity investigations [EN 12504-4] on slabs (30 x 30 x 5 cm).

Table 1: Overview of recycled aggregates properties according to specific standards

Aggregate typology/size		Physical properties			Mechanical properties
		Loose bulk density [kg/m^3]	Particle density [kg/m^3]	Water absorption [%]	Resistance to compression [N/mm^2]
Polyurethane (PU)	0-4 mm	256	-	-	-
	4-8 mm	336	330	10	1.35
	8-16 mm	164	300	11	1.60
Remix (RX)	Remix HD (0-2 mm)	-	-	-	-
	Remix HD (3-7 mm)	290	810	10	2.50
	Remix LD (8-12.5 mm)	359	660	22	2.15
Tyre rubber (TR)	0-0.6 mm	764	-	-	-
	0.6-2 mm	403	-	-	-
	2-4 mm	422	-	-	-
	3-7 mm	459	970	6	0.20
	8-16 mm	419	1090	5	0.18

Table 1: Overview of recycled aggregates properties according to specific standards (continued)

Aggregate typology/size		Chemical properties			
		Acid soluble sulphates [%]	Water soluble chloride salts [%]	Total sulphur content [%]	Organic impurities
Polyurethane (PU)	0-4 mm 4-8 mm 8-16 mm	0.18	0.03	0.13	acceptable
Remix (RX)	Remix HD (0-2 mm)	-	-	-	-
	Remix HD (3-7 mm)	0.01	0.13	0.03	-
	Remix LD (8-12.5 mm)	0.15	0.02	1.06	absent
Tyre rubber (TR)	0-0.6 mm 0.6-2 mm 2-4 mm 3-7 mm 8-16 mm	0.08	0.02	0.27	acceptable

Table 2: Preliminary trials: results

		Consistency class	Fresh concrete aspect
PU	1	S2	No undesired phenomena
	2	S5	
RX	1	S1	Swelling and bleeding phenomena
	2	S3	Bad mixability, Incoherent mix
TR	1	S1	No undesired phenomena
	2	S4	

4.1 *Laboratory optimization of concretes*

4.1.1 Compatibility investigations

In order to evaluate the compatibility of the innovative lightweight aggregates with traditional binders (OPC), several mixtures were prepared and inspected on the fresh conditions for undesirable effects such as segregation, bleeding or swelling.

PU and TR aggregates showed no undesired phenomena but for RX aggregates based concretes low mixability, incoherent mixtures and swelling phenomena were observed. This behavior might be related to aggregates shape (being Remix HD flakes and Remix LD expanded granules) but most probably to a possible effect of residual impurities in RX aggregates, therefore in the following experiments cleaner types were tested.

4.1.2 Concretes development

Taking into account the findings of the preliminary experiments a wider experimental program has been carried out. The main purposes were:

- concretes optimization on the lab scale;
- identification of the best recipes in the view of the subsequent industrial optimization.

Several mixtures have been designed and tested, both on the fresh and on the hardened state (Figure 3). Mix design parameters (i.e. water/cement ratio, aggregates/paste ratio, aggregates proportioning, percentage of natural aggregates) have been optimized to obtain concretes with a proper workability, good consistency, without bleeding or segregation phenomena and with suitable mechanical performance.

Figure 3: Slump evaluation and preparations of cubic specimens for compressive testing (from left to right)

Mixtures based on polyurethane aggregates (Table 3)

An overall evaluation of PU-based mixtures has led to these conclusions:

- the use of natural aggregates is necessary to obtain a concrete of good consistency and to enhance the compressive strength;
- a good compromise in terms of workability and mechanical performances is obtained with a water/cement ratio of 0.55.

Mixtures based on Remix aggregates (Table 4)

An overall evaluation of RX-based mixtures has led to these conclusions:

- the use of natural sand aggregates is necessary to obtain an appropriate workability and acceptable compressive strength;
- a good compromise in terms of workability and mechanical performances is obtained with a water/cement ratio of 0.45;
- a good insulating behavior is also obtained.

Mixtures based on tyre rubber aggregates (Table 5)

An overall evaluation of TR-based mixtures has led to the following conclusions:

- the water/cement ratio has to be kept low (0.40) to avoid too wet samples and related difficulties in handling or testing;
- a good workability has been reached without adding natural aggregates; this is a key strength of TR aggregates in comparison with the other typologies even if, as expected, this counts against the concrete resistance.

Summary

Mixtures based on sustainable aggregates and OPC have been successfully optimized on lab level. The final densities of the developed concretes range from approximately 1000 - 1200 kg/m^3, therefore these can be definitely considered as lightweight concretes [EN 206-1]. The use of small amounts of natural aggregates allows to adjust the consistency and, as expected, improves the mechanical resistance. The final compressive strength goes from around 1.4 MPa to 9.4 MPa; moreover, due to the use of lightweight plastic aggregates, satisfactory thermal insulation properties have been achieved (0.25 W/mK for RX-based concretes).

Table 3: PU-based mixtures (lab optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	400	0.45	0%	S2	813	755	3.9
2	400	0.60	0%	S1	953	805	4.8
3	400	0.60	30%	S5	1346	1289	10.3
4	400	0.50	30%	S3	1283	1210	9.1
5	400	0.55	30%	S4	1253	1182	9.4
6	400	0.55	15%	S2	1090	1001	5.6

Table 4: RX-based mixtures (lab optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)			
	Cement content [kg/m³]	w/c	Natural aggr. [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Comp. streng. [MPa]	Tens. split. resist. [MPa]	Therm. cond. [W/mK] @10°C
1	400	0.50	0%	S1	860	769	1.6	-	-
2	400	0.45	20%	S4	1102	1054	5.6	-	-
3	400	0.45	30%	S4	1172	1120	5.9	1.3	0.25

Table 5: TR-based mixtures (lab optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	400	0.50	0%	S4	1250	1163	1.9
2	400	0.47	0%	S4	1040	963	0.9
3	400	0.40	0%	S4	1051	997	1.4

4.2 ***Industrial optimization of concretes***

Based on the results achieved on the lab scale, an industrial optimization phase has been carried out in order to assess the integration of the developed concretes in traditional production cycles. For each recycled aggregate typology, the objective was the production of concretes having specific requirements in compliance with target applications such as blocks, panels for facades, floor screeds or floor screeds undelay (Table 6).

The experimental approach consisted in a parametric study aimed at the optimization of design parameters (i.e. cement content, water/cement ratio and natural aggregate percentage) to fulfil the target requirements. The concretes were tested both in fresh and hardened conditions in terms of mechanical properties, thermal resistance (lambda values) and acoustic insulation behavior (qualitatively evaluation through ultrasonic pulse velocity - UPV – tests). The influence of aggregates properties on the concretes performances was evaluated; the compatibility of the aggregates with ordinary binders, traditional procedures as well as mixtures reproducibility were also discussed.

4.2.1 Workability and mechanical strength

Recycled polyurethane-based concretes

On the basis of the obtained results (Table 7) the following correlations among design parameters and concretes performance can be drawn:

- compressive strength decreases when decreasing the amount of cement from 400 kg/m^3 to 350 kg/m^3;
- for a given water/cement ratio the compressive strength increases if the amount of natural aggregates increases;
- as expected, compressive strength decreases reducing the natural aggregate percentage and, on the other side, increasing the amount of PU the compressive strength and workability of the fresh concrete decreases.

Table 6: Target performances for different concrete products

Aggregate typology	Target application	Target properties		
		Workability	Density [kg/m^3]	R_{ck} [MPa]
PU	Blocks	S1 - SCC	700-1500	3-20
RX	Panels for facades (or part of it)	S4 - SCC	350-1700	5-24
TR	Floor screed	S4 - SCC	700-1200	3-10
	Floor screed underlay	S1 - SCC	500-800	1-6

Table 7: PU-based mixtures: design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	400	0.54	46%	S5	1387	1318	14.1
2	400	0.44	46%	S4	1497	1454	14.5
3	400	0.43	36%	S2	1412	1336	13.5
4	350	0.66	30%	S1	1203	1100	5.5
5	400	0.55	33%	S1	1275	1218	9.0
6	400	0.54	34%	S1	1253	1199	9.3

Taking into consideration these outcomes mixture 6 (400 kg/m^3 of cement, w/c 0.54, 34% of natural aggregates) was considered the most suitable for building blocks production. In addition, mixture 2 complies with the requirements for panels fabrication.

Overall, concretes based on recycled polyurethane aggregates have shown good reproducibility as well as good compatibility with traditional materials and procedures used for concretes manufacturing. Regarding the influence of aggregates properties on the produced concretes it was observed that:

- the slump is lower than that of concretes based on traditional aggregates, due to the higher water absorption of PU;
- the morphology of PU aggregates has also considerable influence on workability but however acceptable for blocks or eventually panels fabrication.

Mixed plastic waste-based concretes

The development of concretes based on Remix consisted in three different optimization steps. Design parameters such as natural aggregate content, water/cement ratio and cement content have been monitored and their relation with the final performance evaluated (Table 8, Table 9 and Table 10). The reproducibility of mixture 1, already tested in the lab, and its performances were confirmed. As expected, a decrease of compressive strength with the reduction of natural aggregates content has resulted. On the contrary, workability was not affected by the reduction of natural aggregates within the concretes.

Figure 4: PU-based concretes optimized for blocks (left) and panels (right)

It was confirmed that the workability is negatively affected by the water/cement reduction, going from S4 (w/c 0.45) to S3 (w/c 0.37); on the other side, the compressive strength was improved. In order to further improve the workability, while assuring a suitable compressive strength, it was decided to fix the water/cement ratio at 0.40 for the following trials (Table 10). According to these results a good compromise in terms of workability and mechanical strength can be obtained using 450 kg/m^3 of cement and 0.40 as water/cement ratio. For all these mixtures workability, density and compressive strength were suitable for the target application. Mixture 2 (450 kg/m^3 of cement, w/c 0.40, 20% of natural aggregates) was selected having slightly better consistency than mixtures 3 and 4 and including, at the same time, less natural aggregates than mixture 1. The performance of mixture 2 match the requirements for panels fabrication.

Table 8: RX-based mixtures (natural aggregate optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m^3]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m^3]	Density [kg/m^3]	Compressive strength [MPa]
1	400	0.45	30%	S4	1102	1063	5.5
2	400	0.45	20%	S4	910	896	3.1
3	400	0.45	10%	S4	860	819	3.1
4	400	0.45	0%	S4	734	710	2.0

Table 9: RX-based mixtures (water/cement optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	400	0.37	20	S3	1179	1155	8.7
2	400	0.37	10	S3	1097	1062	7.0

Table 10: RX-based mixtures (cement optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	450	0.40	30%	S4	1191	1183	8.9
2	450	0.40	20%	S4	1115	1076	8.3
3	450	0.40	10%	S4	1108	1097	9.0
4	450	0.40	0%	S4	908	881	5.3

Consistency evaluation

Cubes preparation for compression resistance tests

Figure 5: RX-based concrete for panels

Overall, the mixtures based on recycled mixed plastic aggregates have shown a good reproducibility, both at the fresh and hardened conditions; their compatibility with traditional materials and procedures for concretes preparation were also satisfactory and no undesired (e.g. swelling or segregation) phenomena were observed. Regarding the influence of aggregates properties on the produced concretes it was observed that:

- the use of Remix aggregates has no negative effects on the concrete workability;
- as expected, the concretes have lower compressive strength if compared with traditional concretes but however acceptable for panels fabrication.

Recycled tyre rubber-based concretes

The development of concretes based on tyre rubber consisted in three different optimization steps. Design parameters such as cement amount, water/cement ratio and natural aggregates addition have been monitored and their relation with the final performance evaluated (Table 11, Table 12 and Table 13). Considering the density it seems that these formulations are not properly suitable for floor screed underlay; on the other hand a reduction in cement content should result in a lower density but could also compromise workability and mechanical resistance. Due to this reason the suitability of these concretes for floor screed was evaluated. From the results obtained it was evidenced that the consistency of the fresh concrete was enhanced increasing the amount of cement. Moreover, as expected, a higher amount of cement resulted in better mechanical properties. For these reasons, it was decided to use 500 kg of cement per m^3 of concrete. In order to further increase the compressive strength, the water/cement ratio was decreased

Figure 6: Slump test on tyre rubber based concrete (left) and aggregates distribution observed in the cross section (right)

from 0.45 to 0.43 (Table 12). The workability of mixture 3 (w/c 0.43), if compared with mixture 2 (w/c 0.45), decreased from S4 to S2; on the other side, the compressive strength increased even if it was not reached the required strength of 3MPa (floor screed). Aiming

Table 11: TR-based mixtures (amount of cement optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
1	400	0.45	0%	S1	1020	965	1.0
2	500	0.45	0%	S4	1275	1240	2.1

Table 12: TR-based mixtures (water/cement optimization): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)		
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compr. strength [MPa]	Tensile splitting resistance [MPa]
3	500	0.43	0%	S2	1226	1196	2.6	0.3

Table 13: TR-based mixtures (effect of natural aggregates): design parameters and results

	Design parameters			Fresh concretes performance		Hardened concretes performance (28 days aging)	
	Cement content [kg/m³]	w/c	Natural aggregate [% vol]	Slump class	Density [kg/m³]	Density [kg/m³]	Compressive strength [MPa]
4	500	0.43	2%	S1	1350	1338	2.9

at the mechanical resistance it was decided to use a w/c ratio of 0.43 and besides the addition of small amount of natural aggregate was investigated. As the obtained density was higher than required for floor screed and not so much improvement in the compressive strength was achieved, the addition of higher amounts of natural aggregates to adjust the workability or to improve the mechanical resistance was excluded. Taking into account the obtained results, mixture 3 (500 kg/m^3 of cement, w/c 0.43, without natural aggregates) was the closest to the assigned requirements even if not fully suitable for floor screed.

Overall, regarding the compatibility of recycled tyre rubber aggregates with traditional materials and procedures for concretes preparation the generation of bubbles during the mixing process was observed. Regarding the influence of aggregates properties on the produced concretes it was observed that:

- it is less likely that the segregation effects appear in this kind of concretes than in conventional lightweight concretes;
- lightweight concretes made with tyre rubber recycled aggregates reached lower mechanical strengths than conventional lightweight concretes (approximately 10 MPa less) even if they could find application when the mechanical performance are not so the main requirements.

4.2.2 Thermo–acoustic insulation properties

Thermal conductivity tests (lambda measurements) and ultrasonic pulse velocity (UPV) tests, which were intended only to give a qualitative indication about acoustic insulation

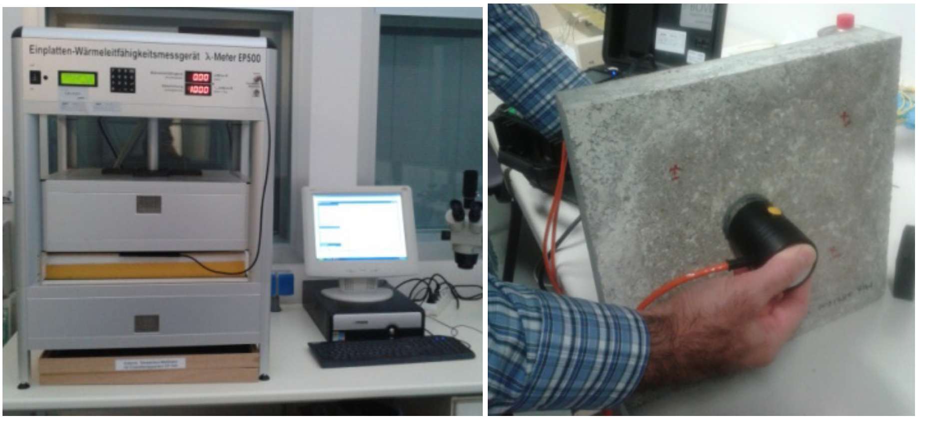

Figure 7: Equipment used for the evaluation of thermal (left) and acoustic insulation (right)

properties, have been carried out (Figure 7). These testes have been performed on three concretes specimens, one for each aggregate typology tested, resulting as the best performing according to the industrial optimization activities.
Regarding to thermal conductivity tests (Table 14) the lowest conductivity was obtained for the TR-based specimen (0.20 W/mK at 10°C), while the higher conductivity was reached for PU-based specimen (0.33 W/mK at 10°C). Only plastic aggregates, which are intrinsically less conductive materials, have been used for TR-based concretes. These properties of the concretes can be exploited for applications where thermal insulation performance are required. Moreover, comparing the developed concretes with a typical lightweight concrete based on expanded clay, having similar density, the thermal insulation properties resulted certainly superior (density 1100 kg/m^3 and lambda of 0.45 W/mK for concretes with expanded clay [4]).
According to UPV tests outcomes (Table 15) going from PU to TR-based specimen the time needed by the ultrasonic pulse to pass through the material increases and, accordingly, the pulse velocity decreases. The best performance have been reached by the TR-based specimen, which contains only plastic aggregates; on the contrary, reducing the amount of plastic materials, like in the case of RX and PU specimens, the acoustic transmission was negatively affected. For comparison, it can be considered that for traditional concretes the pulse velocity ranges between 3000 and 5000 m/s [Malhotra, 2004]. It is evident that the

Table 14: Thermal behavior: a comparison among developed concretes

	Density [kg/m^3]	Lambda [W/mK]			Target application
		10°C	25°C	40°C	
PU	1131	0.33	0.33	0.34	Blocks
RX	1098	0.25	0.25	0.26	Panels
TR	1047	0.20	0.20	0.20	Thermal insulting components

Table 15: Acoustic behavior (qualitative): a comparison among developed concretes

	Density [kg/m^3]	Average transit time [µs]	Average pulse velocity [m/s]
PU	1267	15	3307
RX	1229	18	2729
TR	1079	23	2208

[4] www.cornaviera.it

concretes specimens here tested have overall lower tendency to transmit ultrasonic pulses and this can be attributed to a specific internal structure and composition.

4.2.3 Final considerations

The performances achieved by the concretes developed in this study were finally compared with those of similar concretes already on the market. At this aim, as reference product, a commercial lightweight concrete based on expanded polystyrene (EPS) has been considered. This reference concrete has density 1000 kg/m³, compressive strength of 5 MPa and thermal conductivity 0.35 W/mK. Overall, satisfactory performances have been obtained for the products developed within this research with respect to the reference concrete, mainly in terms of thermal insulation. Similarly, the mechanical performances are better for PU and RX-based concretes while TR-based concrete has shown the lower mechanical resistance; however for this concrete the best insulating behavior have been demonstrated. In conclusion, the density of the lightweight concrete products herein developed (1050-1130 kg/m³) are comparable with that of EPS-based concrete (1000 kg/m³) but, interestingly, the mechanical performances are better for PU and RX-based concretes and the thermal conductivity is lower for all the concretes studied (Figure 8).

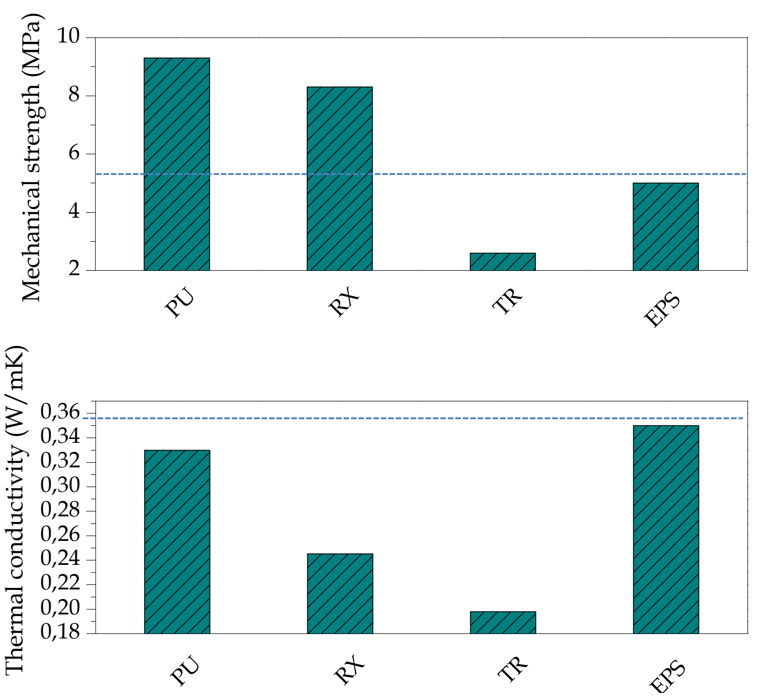

Figure 8: Comparison of lightweight concretes in terms of mechanical and thermal performance

5 Conclusions

This study was focused on the assessment of the viability of specific secondary plastics to be converted into sustainable aggregates and then integrated in the production cycle of concrete. The materials herein explored were rigid polyurethane foams, Mixed Plastic Waste (MPW) of the sorting process of Municipal Solid Waste (MSW) and exhaust rubber tyres. These plastics were processed into aggregates and, more specifically, the aggregate based on MPW (referred to as "Remix") have been developed in our previous studies. For assessing the suitability of all these aggregates for concretes production, physical-mechanical and chemical characterizations as well as HSE evaluations were performed. It has been demonstrated that such aggregates resulting from recycled plastics have the requirements to be considered as lightweight aggregates for concretes production. However, for a complete assessment of their suitability for concretes preparation, a detailed analysis of their compatibility degree with cement mixtures was necessary. Several mixtures have been studied and the relation among design parameters and concretes performance (i.e. consistency, mechanical and insulating behaviour) have been discussed. The concretes have been successfully optimized first on the lab scale and then in the plant, for assessing their integration in traditional production cycles. The use of recycled plastic aggregates resulted in the development lightweight concretes (density 1050-1130 kg/m^3). Mechanical properties of the optimized concretes were satisfactory (2.6-9.3 MPa) but the most important change brought about by the use of plastic was the low thermal conductivity (0.20-0.33 W/mK). The concretes have also shown a lower tendency to transmit ultrasonic pulses; this gives a qualitatively indication about their acoustic insulation properties. The findings of this study has also led to identify, depending on the performance achieved by each concrete, potential target non-structural applications such as blocks, panels for facades or insulating components. In conclusion in this study the addition of recycled plastic aggregates in the manufacturing of concretes has been demonstrated; this can be considered a way to reduce the environmental impact of waste plastics and, moreover, it allows the development of innovative building materials.

References

Cairns R., Kew H. Y., Kenny M. J. (2004). The use of recycled rubber tyres in concrete constructions – Final report, University of Strathclyde.

Liguori B., Iucolani F. (2014). Recycled plastic aggregates in manufacturing of insulating mortars. *CSE Journal*, ISSUE 1 | Materials Engineering, 93-99.

Malhotra V. M., Carino N. J. (2004). Handbook on Nondestructive Testing of Concrete.

Mounanga P., Gbongbon W., Poullain P., Turcry P. (2008). Proportioning and characterization of lightweight concrete mixtures made with rigid polyurethane foam wastes. *Cement and Concrete Composites*, 30 (9), 806-814.

Arena, W., Attannasio, A., Marseglia, A., Pascale, S., Ristoratore, E., Rocco, B., Saracino, S. and Urbano, G. (2015), Market availability and mapping of waste streams across the EU27, SUS-CON publication, available from www.sus-con.eu.

Saikia N., de Brito J. (2012). Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. *Construction and Building Materials*, 34, 385-401.

Shu X. , Huang B. (2014). Recycling of waste tire rubber in asphalt and Portland cement concrete: An overview. *Construction and Building Materials*, 67 (B), 217-224.

Siddique R., Khatib J., Kaur I. (2008). Use of recycled plastic in concrete: A review. Waste Management, 28 (10), 1835-1852.

Verdolotti L., Di Maio E., Lavorgna M., Iannace S., Nicolais L. (2008). Polyurethane–Cement-Based Foams: Characterization and Potential Uses. *Journal of Applied Polymer Science*, 107, 1-8.

Zainab Z., Enas A., AL-Hashmi (2008). Use of waste plastic in concrete mixture as aggregate replacement. *Waste Management*, 28, 2041–2047.