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ScienceDirect
Ciência & Tecnologia dos Materiais 29 (2017) e162–e166
http://ees.elsevier.com/ctmat

Special Issue "Materiais 2015"

Mechanical behaviour analysis of polyester polymer mortars reinforced with tire rubber fibres

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Abstract

Tires effective reutilization has become an important research topic in recent years due to the stockpiles increase that creates environmental problems. Recent European regulations forbid the tires burning and landfilling, setting several recycling objectives. Within this context, the reutilization of tire rubber recyclates into cement and polymer concrete materials, as reinforcement or aggregate replacement, has received lately a great attention. The present work aim is to analyse the modifications induced by tire rubber addition in the mechanical properties of polyester based polymer mortars (PM). The effect of different tire rubber fibre amounts (0.1, 0.4 and 0.5 wt.%) were analysed in this investigation. Plain polymer mortar was also prepared for comparison. Mechanical behaviour of both reinforced and plain polymer mortars formulations was assessed by flexural and compressive tests. Flexural and compressive strength improvements were particularly significant for PM trial formulation reinforced with the higher amount of tire rubber fibres. The observed trend on mechanical properties seems to indicate that higher increases could be achieved with higher amounts of tire rubber fibres. Thus, further experiments will be required in order to determine the critical amounts of rubber fibre reinforcement that define the turning points on material trend behaviour of PM.

Keywords: Polymer mortar; tire rubber fibres; fibre reinforcement; mechanical characterization.

1. Introduction

Tires effective reutilization has become an important research topic in recent years due to the stockpiles increase that creates environmental problems. Recent European regulations forbid the tires burning and landfilling, setting several recycling objectives. Therefore, tire rubber particles reutilization in concrete materials as reinforcement has received lately a great attention [1-4]. Tires are mainly made up of rubber, carbon black, steel and textile components as reinforcing materials. The most commonly used tire rubber is styrene-butadiene copolymer. Natural rubber and poly-butadiene are also included in the tires production. All the materials used in the tires production are 100% recyclable [5], and mechanical recycling, i.e., tires grinding with size reduction to particulate and fibrous material, is one of the most interesting waste management approaches [2]. The resultant recycled material is a pulverized polyester/nylon fibres and rubber particles (fluff) mixture [6].

The reuse of these recyclates into polymer concrete materials (PC) is an interesting option to be considered in the construction sector, especially if improvements in PC final properties could be achieved. PC materials are high performance resin based concretes, in which a polymer acts as binder matrix for the mineral

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http://dx.doi.org/10.1016/j.ctmat.2016.07.009

aggregates [7]. High mechanical strength, improved resistance to chemical and frost attack, reduced water permeability and excellent bond to several substrates are some of the enhanced features of these materials over cement based concretes. As a mortar (PM) it can be placed with thickness less than 5 mm. Other advantages include fast curing time, ability to form complex shapes and excellent finishing, which are significant assets in the production of precast concrete elements [7-9]. Nevertheless, at present, the main asset of PC materials over conventional concretes is their great ability for incorporating recycled waste products, mainly owned to hermetic nature of resin matrix. Most of the successful applications reported involve either industrial by-products or end-of-life products [4,10-16].

Under this framework, the present work is aimed at assessing the potential added-values induced by tire rubber recyclates addition in the mechanical properties of polyester based PM. Recycling and reuse of tire rubber wastes into PC based products will potentially reduce the costs relative to raw materials acquisition, and will lead, at the same time, to more environmental sustainable products.

2. Materials and Methods

2.1. Raw materials and manufacturing procedures

In the production of PM, a commercially available unsaturated polyester resin, with the trade name of AROPOL FS3992 (Ashland, Matexplás) was applied as binder matrix. It is a rigid resin type with 40-44% styrene content, high reactivity and low viscosity, typically used in pultrusion processes. The resin system has high impregnation ability and allows a high content of mineral fillers and aggregates incorporation, which are essential requirements to produce PM. The main physical and mechanical properties of cured resin are defined in Table 1. AROPOL 3992 FS polymerization process was induced at room temperature using cobalt octoate (Octoacto CO 1%) as promoter and methyl ethyl ketone peroxide in phthalate (Peroxan ME 50L) as initiator. The catalytic system was provided by Matexplás.

As mineral aggregates, a foundry sand with silica high-grade (> 99.0%) and fine uniform grain size (d_{50}=245 μm) was used. This sand is processed by Sibelco, Lda, and commercialised by Fundipor under the technical name SP55.

The selected recycled tire rubber fibres (Fig. 1 a)) were provided by a confidential company through the Autonomous University of the State of Mexico. The recycled fibres had 0.92 g/cm^3 density, an average diameter of 22.5 μm and an average length of 2000 μm. In Figs. 1 b) and c) the fibre surface characteristics are shown. Some fibres show roughness on their surface and others smooth surfaces.

Table 1. Physical and mechanical properties of cured resin.

Property	Method	Values
Heat distortion temperature (ºC)	ASTM D 648	90-100
Water absorption (%)	ASTM D 570	0.2
Tensile strength (MPa)	ASTM D 638	50-70
Flexural strength (MPa)	ASTM D790	90-110
Barcol hardness	ASTM D 2583	45
Ultimate elongation (%)	ASTM D 638	3

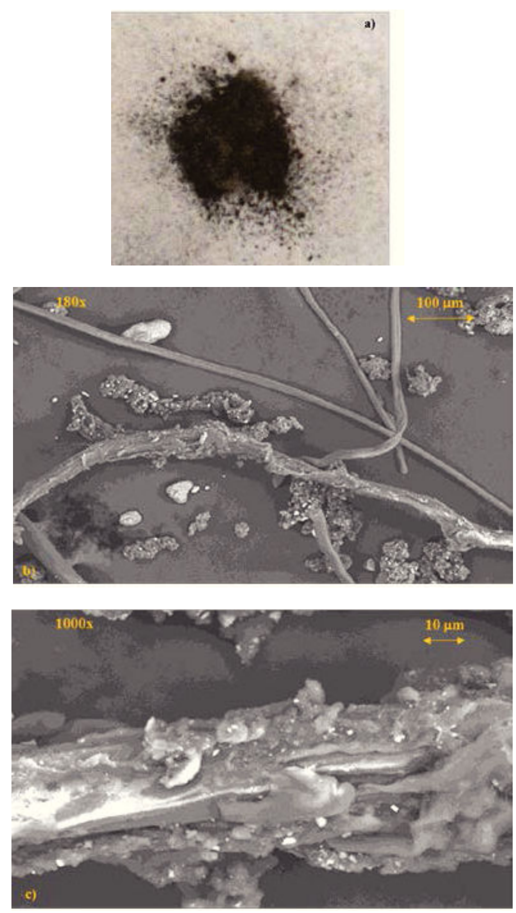

Fig. 1. Images of recycled-tire fibres: a) tire fibres, b) SEM at 180x and c) SEM at 1000x.

Definite fibres contents (0.1, 0.4 and 0.5 wt.%) were mixed in an automatic mixer with the foundry sand aggregates. In order to prevent eventual inhibition of polymerization process due to moisture presence, both sand aggregates and recycled fibres were previously oven-dried for 1h at 120ºC to reduce their moisture content to less than 0.2% by weight. Unsaturated polyester resin was firstly manual mixed with the promoter (0.5 wt.%) and the initiator (3.0 wt.%), and then thoroughly mixed with the sand aggregates-fibres mixture in the mechanical mixer. For all PM formulations, polyester resin system to total filler (fibres and sand) weight ratio was maintained equal to 3:17 (15 wt.% resin and 85 wt.% filler). Plain PM was also prepared for comparison purposes. The final mixtures were poured into standard prismatic moulds and the specimens were allowed to cure at 30ºC for 24h in a climatic chamber. After the cure treatment, the specimens were removed from the moulds and post-cured in an air-circulating oven for 3h at 80ºC.

2.2. Tests procedures

Flexural tests of PM specimens were performed according to RILEM CPT PCM-8 test procedure [17]. This recommendation covers the flexural test method for PM in three-point loading. The tests were carried out in a universal mechanical testing machine (INSTRON 4208), equipped with 100 kN load cell, at the loading rate of 1.0 mm/min over a span length of 100 mm. For each formulation four specimens with the standard dimensions of 40x40x160 mm were tested.

One of the two leftover parts of each broken specimen in bending was tested afterwards in compression at the loading rate of 1.25 mm/min, following the procedure described in UNE-EN 1015-11 test standard [18]. Compression tests were also carried out in a universal mechanical testing machine (INSTRON 4208), equipped with a 300 kN load cell.

Flexural and compressive testing set-ups are presented in Fig. 2, as well as some examples of fracture surfaces of PM test specimens after bending test.

Shore D hardness of PM formulations was measured according to ISO 868 [19] using a commercial CEAST® (Turin, Italy) durometer. The hardness tests were performed over one of the two leftover parts of each broken specimen in bending. The thicknesses of the samples were 40 mm, and the measuring points were at least 9 mm from any edge and 6 mm apart.

To calculate the void content of the PM formulations the Method C from ASTM D 2734 was followed [20].

All specimens were previously conditioned at 23°C/50% RH for 24 hours before testing.

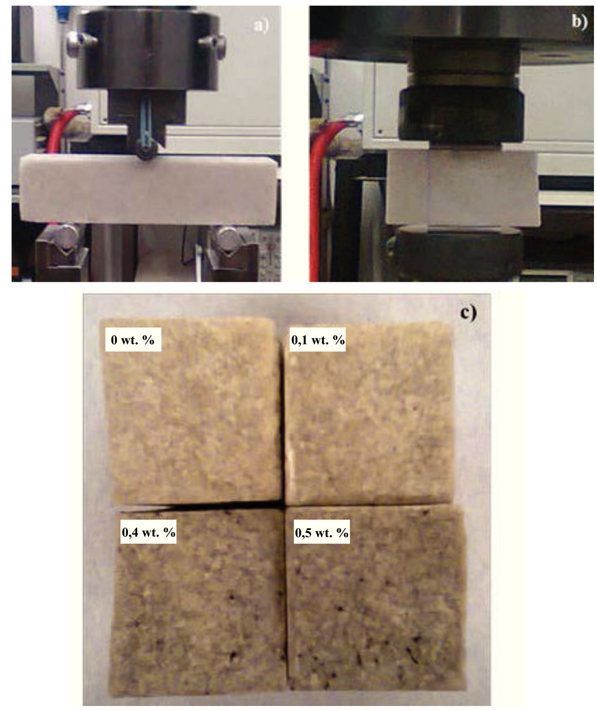

Fig. 2. a) Flexural, b) Compressive testing set-ups and c) Fracture surfaces of PM test specimens after flexural tests

3. Experimental Results and Discussion

3.1. Data test results

Mechanical test results, in terms of flexural strength (σ_f), flexural elastic modulus (E_f), flexural toughness (R) and compressive strength (σ_c) are summarized in Table 2. Presented values represent the average values obtained for 5 specimens of each trial formulation and correspondent standard deviations. Typical shapes of flexural and compressive load-deflection curves are plotted in Figs. 3 and 4, respectively.

Table 2. Flexural and compression tests results.

Formulation	σ_f (MPa)	E_f (GPa)	R (Nmm)	σ_c (MPa)
0 wt.%	10.67 ± 2.61	0.72 ± 0.22	1187.44 ± 185.65	29.52 ± 3.17
0.1 wt.%	9.19 ± 0.15	0.69 ± 0.13	1062.67 ± 112.46	20.01 ± 0.41
0.4 wt.%	10.82 ± 0.57	0.62 ± 0.14	1448.00 ± 399.09	15.64 ± 2.05
0.5 wt.%	15.09 ± 1.87	0.79 ± 0.13	1705.64 ± 328.10	44.09 ± 5.33

Flexural toughness was calculated as the area under the load-deflection curve up to the failure of the specimen, according to RILEM-CPT PCM-8 specifications [17].

Average Shore D hardness (H), density (ρ) and theoretical void volume content (%V) of PM formulations are presented in Table 3. Density and void volume content were computed with basis on measured weight after curing.

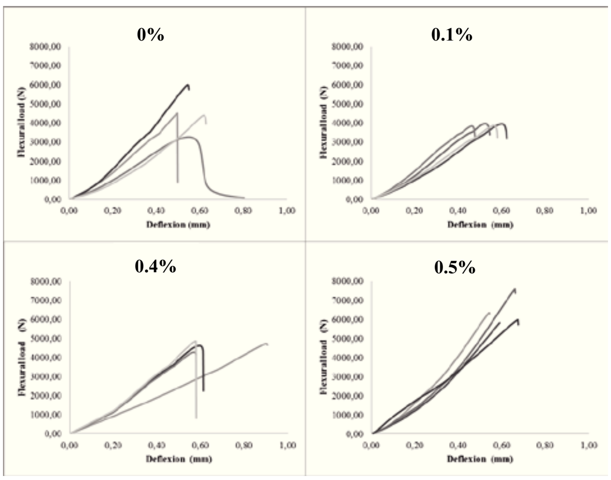

Fig. 3. Flexural load-deflection curves.

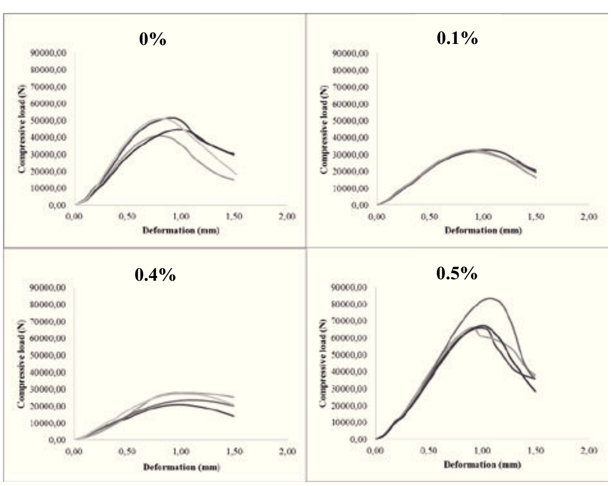

Fig. 4. Compressive load-deflection curves.

Table 3. Shore D hardness and void content tests results.

Formulation	H	ρ (g/cm^3)	%V
0 wt.%%	78.00±1.00	1.78±0.06	19.63±2.82
0.1 wt.%	64.00±2.35	1.77±0.02	19.78±0.96
0.4 wt.%	68.20±2.05	177±0.04	19.44±1.91
0.5 wt.%	78.40±2.41	1.80±0.03	18.12±1.36

3.2. Analysis and discussion

According to test results, the mechanical properties of modified PMs are negatively affected by the incorporation of recycled tire rubber fibres, at least, for fibre contents up to 0.4 wt.%. However, for the highest amount of tire rubber fibres (0.5 wt.%), all mechanical properties of reinforced PMs are considerably improved when compared to plain PM formulation. Average compressive and flexural strength increase of 49.38% and 41.40%, respectively, were observed with regard to unmodified mortars. For the formulations with lower contents of fibre incorporation, 0.1 and 0.4 wt.%, relative compressive strength decrease of 32.20% and 47.01% occurred, in turn. It was also verified a reduction of 13.84% on the average flexural strength of PM formulation with 0.1 wt.% of fibre amount, and a slight rise of 1.40% in the formulation with 0.4 wt.% fibre content. Flexural elasticity modulus and stiffness followed nearly the same trend observed for mechanical strengths.

As the same way as the mechanical properties, Shore D hardness decreases with the addition of the different amounts of fibres up to 0.4% in weight of fibre content. For the highest amount of fibre content, average Shore D hardness slightly increases.

The decay on properties demonstrated by tire rubber fibre modified PM with the lowest fibre concentrations is probably related with a poor fibre-matrix adherence. When the fibres volume fraction increases, mechanical interaction is improved due to a better anchoring effect that leads to higher mechanical properties. Also, the contribution of tire rubber fibre to filler fraction of sand aggregates, leading to an inferior void volume for dry-packed aggregate, has probably a relevant role in this feature. Aggregate gradation design should aim to produce aggregates mixtures with the maximum bulk density and the minimum voids content. Generally, this leads to higher strength materials, due to improved aggregate agglomeration.

The observed trend on mechanical properties seems to indicate that higher increase could be achieved with higher amounts of tire rubber fibres. Thus, further experiments will be required in order to determine the critical amounts of rubber fibre reinforcement that define the turning points on material trend behaviour of PM.

4. Conclusions

Experiments were performed in order to determine the effect of tire rubber fibres on mechanical behaviour of polyester based mortars. The influence of different tire rubber fibres contents (0.1 wt.%, 0.4 wt.% and 0.5 wt.%) were investigated. The key findings of the use of tire rubber fibres in PM testing programme are as follows:

– The incorporation of recycled tire rubber fibres up to 0.4 wt.% into polyester based PM as partial aggregate replacement leads, in general, to high decrease on mechanical properties of resultant PM;

– However, the aggregate replacement by larger amounts of the same type of recycled material (0.5 wt.%) conducts to significant improvements on both flexural and compressive behaviours of admixed PM with regard to unmodified PM;

– The variation of Shore D hardness with increasing addition amounts of fibres follows, closely, the same trend behaviour already observed as regard to mechanical properties;

– Observed variation in mechanical and physical properties is likely related to the distinct void volume contents found for the different PM formulations.

These findings highlight a cost-effective end-use application for recycled tire rubber wastes as partial aggregate replacement for PM with added-value mechanical performance. Further experiments will be required in order to determine the critical amounts of rubber fibre reinforcement that define the turning points on material's trend behaviour.

Acknowledgements

The financial support of FCT, COMPETE, FEDER, QREN and ERDF (under PTDC/ECM/110162/2009 project, SFRH/BPD/98869/2013 grant and NORTE-07-024-FEDER-000033 project), Autonomous University of the State of Mexico (under UAEM 3054/2011SF grant), scholarship CONACYT and the collaboration of Mr. Miguel Martínez López in this study are gratefully acknowledged.

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