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Properties and durability of HPC with tyre rubber wastes

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ABSTRACT

An estimated 1000 million tyres reach the end of their useful lives every year and 5000 millions more are expected to be discarded in a regular basis by the year 2030. Up to now a small part is recycled and millions of tyres are just stockpiled, landfilled or buried. This paper presents results about the properties and the durability of HPC with partial replacement of sand by tyre rubber wastes. Fly ash and metakaolin are used as partial cement replacement. The durability performance was assessed by means of capillary water absorption and resistance to sulphuric acid attack. The results show the existence of a synergetic effect between fly ash and metakaolin that minimizes the strength loss associated to the use of rubber waste. Results also show that is possible to use rubber waste up to 15% and still maintain a high resistance to acid attack. The mixes with 45% fly ash and 15% metakaolin show a much higher resistance to sulphuric acid attack than the reference mix independently of the rubber waste content.

1. Introduction

All over the world billions of tyres are being discarded and buried representing a serious ecological threat. By the year 2030 the number of tyres from motor vehicles is expected to reach 1200 million representing almost 5000 million tyres to be discarded in a regular basis [1]. The implementation of the Landfill Directive 1999/31/EC [2] and the End of Life Vehicle Directive 2000/53/EC [3] banned the landfill disposal of waste tyres creating the driving force behind the recycling of these wastes. A possible solution relates to the use of tyre rubber waste as aggregate replacement in concrete. Tyre rubber aggregates are obtained from waste tyres using two different technologies: mechanical grinding at ambient temperature or cryogenic grinding at a temperature below the glass transition temperature. The first method generates chipped rubber to replace coarse aggregates. As for the second method it usually produces crumb rubber to replace fine aggregates [1]. Some research has already been conducted on the used of waste tyre as aggregate replacement in concrete showing that rubber aggregates reduces concrete workability [4] and compressive strength [5]. The strength loss is much more profound when coarse rubber aggregates are used which is due to the low adhesion between these wastes and the cement paste, but several authors recommend different treatments to enhance the adhesion of the rubber aggregates [6–8]. Previous investigations also show that concrete composites containing tyre rubber waste are known for their high toughness [9], meaning that they are specially recommended for concrete structures located in areas of severe earthquake risk and also for the production of railway sleepers. Although the studies about the properties of concrete with tyre rubber wastes are abundant the ones related to the durability are scarce justifying further investigations. Besides, so far investigations using rubber wastes were made using normal-strength concretes thus meaning that using a low water/binder concrete (HPC [10]) constitutes a research area yet to be explore.

2. Experimental work

2.1. Materials, mix design and concrete mixing

The characteristics of the aggregates used to make the concrete mixtures are shown in Table 1 and Fig. 1a. The rubber waste was supplied by Recipneu and was produced by cryogenic grinding at a temperature below the glass transition temperature. It has a dimension between 1 mm and 2.4 mm (Fig. 1b). An ordinary Portland cement (CEM II 42.5) was used. The chemical composition of the cement is presented in Table 2. The metakaolin used in this study was subjected to a thermal treatment at 650 °C during a few seconds using a flash calcination apparatus. It has a BET surface of 19.2982 m^2/g and its chemical composition is shown in Table 3. The fly ash was supplied by Endesa Generation S.A. and according to the NP EN 450-1 it belongs to B class and has an N class fineness modulus. Its chemical composition is shown in Table 4. Several concrete mixes with a water/binder ratio of 0.35 and 500 kg/m^3 of binder were designed using the Faury concrete mix design method ($A = 26$, $B = 1.5$) [11,12]. The concrete mixes are described in Table 5. The concrete mixtures were named according to their content. For instance C_5RW_15CV_15MK is related to a concrete mixture with 5% of rubber waste, 15% fly ash and 15% of metakaolin. A second generation super plasticizer based on polycarboxylic ether polymers (Glenium Sky 526) was used at appropriate percentages in order to retain the slump of the fresh concrete between 100 and 150 mm (class S3 of NP EN 206-1 [13]). An extra concrete mix was designed complying with the requirements of EN

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Table 1
Characteristics of the sand and of the coarse aggregates.

	Max dimension	Fineness modulus	Fine content	Density (kg/m^3)	Water absorption	Resistance to abrasion in the Los Angeles test (%)
Sand	5.6	3.3	⩽3	2660	0.2	–
Coarse aggregates	8	5.9	⩽1.5	2620	0.6	⩽40

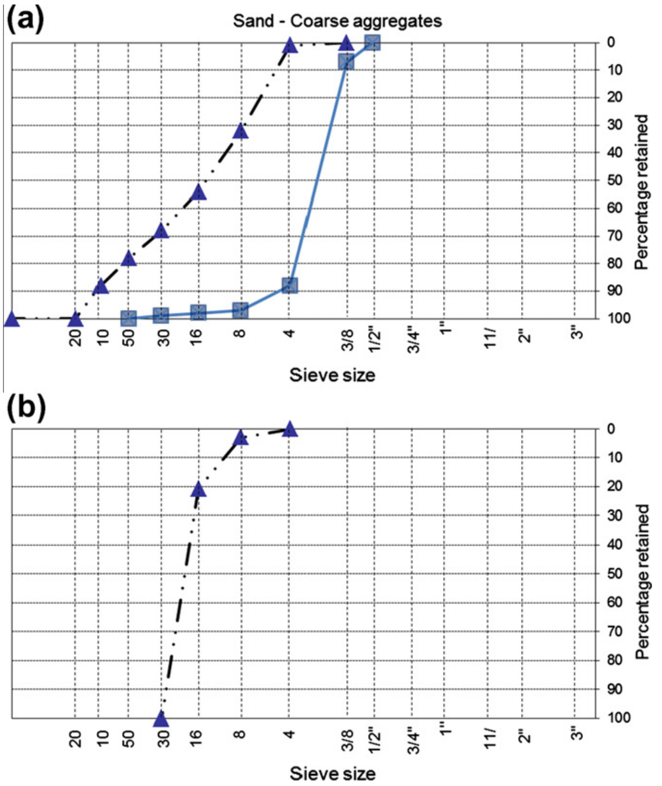

Fig. 1. Particle size distribution: (a) Sand and coarse aggregate; (b) rubber waste.

206-1. Concrete. Part 1: Specification, performance, production and conformity for concrete structures exposed to highly aggressive chemical environment (class XA3). This mixture had a 28 days compressive strength of 60 MPa.

2.2. Experimental procedures

2.2.1. Compressive strength

The compressive strength was performed under NP EN 206-1 [13]. The concrete specimens were conditioned at a temperature equal to 21 ± 2 °C cured in a moist chamber until they have reached the testing ages. Tests were performed on $50 \times 50 \times 50\ mm^3$ concrete specimens. Compressive strength for each mixture was obtained from an average of three cubic specimens determined at the age of 7 and 28 days of curing.

Table 2
Portland cement composition.

Constituents (%)	Cement II-42.5
SiO2	10.26
Al_2O_3	1.657
Fe_2O_3	3.996
CaO	76.928
MgO	0.884
Na_2O	0.000
K_2O	1.048
SO_3	4.243
TiO_2	0.326
P_2O_5	0.105
Zn	0.242
ZrO_2	0.062
Other minor oxides	0.249

2.2.2. Capillary water absorption

Capillary water absorption was carried out using cubic specimens with 15 cm high. After 28 days in a moist chamber the specimens were placed in an oven at 45 °C for 14 days. The test consists in placing the specimens in a container with enough water to maintain immersed one of the sides of the sample. This test was carried out according to the Standard LNEC E393 [14]. Water absorption has been measured after (10, 30, 60, 90, 120, 180, 360, 480, 1440, 2880 and 4320) min. Capillarity water absorption was obtained from an average of three specimens.

2.2.3. Resistance to sulphuric acid attack

The resistance to acid attack followed a variation of the ASTM C-267 (Standard test methods for chemical resistance of mortars, grouts, and monolithic surfacings and polymer concretes).

The test used in the present investigation consists in the immersion of $150 \times 150 \times 150\ mm^3$ concrete specimens with 56 days curing in a 10% of sulphuric solution during 28 days. The resistance to acid attack was assessed by the differences in weight of dry specimens before and after acid attack at 1, 3, 7, 14 and 28 days.

3. Results and discussion

3.1. Compressive strength

Fig. 2 shows the compressive strength of the mixes with rubber wastes. The standard deviation was low and the coefficient of variation do not exceed 10% meaning that the results were statistical relevant. The increase of rubber wastes leads to serious compressive strength loss as reported by other authors [5]. At this level only the 5% rubber wastes mix seems to be feasible. When compared to the compressive strength of the reference mix, this mix

Table 3
Chemical composition of metakaolin (%).

LOI	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	TiO_2	Other minor oxides
1.56	54.25	39.90	1.51	1.79	0.08	0.18	0.41	0.23

Table 4
Chemical composition of the fly ash (%).

$SiO_2 + Al_2O_3 + Fe_2O_3$	Reactive SiO_2	Free CaO	Reactive CaO	$K_2O + Na_2O$	MgO	SO_3
89.9	40.8	0.1	2.7	0.25	1.9	0.12

Table 5
Concrete mix proportions per cubic metre of concrete.

	Cement (kg)	Fly ash (kg)	Metakaolin (kg)	Sand (kg)	Rubber waste (kg)	Coarse aggregates (kg)	Water (l)	SP (l)
C_ref	500	–	–	1256	–	430	174	8.7
C_15MK	425	–	75	1231	–	440	174	8.7
C_30CV	350	150	–	1179	–	461	174	8.7
C_60CV	200	300	–	1106	–	488	174	8.7
C_5RW	500	–	–	1192	63	430	174	8.7
C_10RW	500	–	–	1130	126	430	174	8.7
C_15RW	500	–	–	1067	188	430	174	8.7
C_5RW_30CV	350	150	–	1120	60	461	174	8.7
C_5RW_60CV	200	300	–	1151	55	488	174	8.7
C_10RW_30CV	350	150	–	1061	118	461	174	8.7
C_10RW_60CV	200	300	–	995	111	488	174	8.7
C_15RW_30CV	350	150	–	1002	177	461	174	8.7
C_15RW_60CV	200	300	–	940	166	488	174	8.7
C_5RW_15CV_15MK	350	75	75	1132	60	455	174	8.7
C_5RW_45CV_15MK	200	225	75	1063	56	483	174	8.7
C_10RW_15CV_15MK	350	75	75	1073	119	455	174	8.7
C_10RW_45CV_15MK	200	225	75	1007	179	483	174	8.7
C_15RW_15CV_15MK	350	75	75	1014	179	455	174	8.7
C_15RW_45CV_15MK	200	225	75	951	168	483	174	8.7
C_XA3	360	–	–	1438	–	493	128	6

Ref – control; MK – metakaolin; CV – fly ash; RW –tyre rubber waste; SP – super plasticizer.

has a 31% compressive strength decrease at 28 days curing. The mixes with a higher rubber percentage show a very severe compressive strength loss. Fig. 3a shows the compressive strength of mixes with partial replacement of cement by fly ash and metakaolin. The results confirm previous investigations [15], showing that fly ash has very slow hydration characteristics thus providing very little contribution to early age strength, as to metakaolin possess a high reactivity with calcium hydroxide having the ability to accelerate cement hydration [16]. Fig. 3b shows the compressive strength of mixes with rubber wastes and partial replacement of cement by fly ash. The mix with 5% rubber wastes and 30% fly ash is the only one that is associated to a high compressive strength, above 40 MPa, exceeding the majority of compressive strength classes used in the construction industry [17]. Fig. 3c shows the compressive strength of mixes with rubber wastes and partial replacement of cement by fly ash and metakaolin. The results show the synergetic effect of fly ash and metakaolin minimizes the strength loss associated to the use of rubber waste. When compared to the compressive strength of the reference mix, the one with 5% rubber wastes and 15% fly and 15% metakaolin has a 23% compressive strength decrease at 28 days curing.

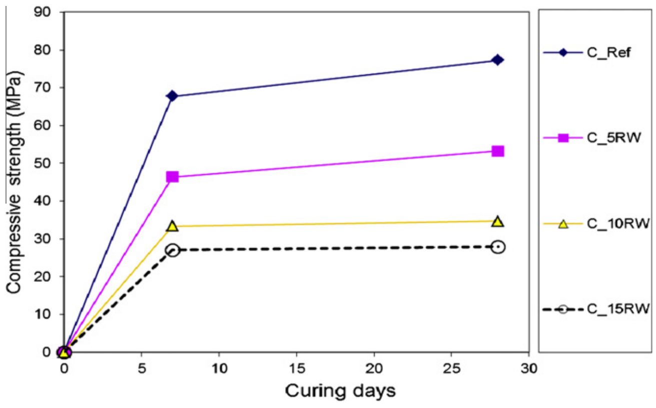

Fig. 2. Compressive strength of the mixes with rubber wastes.

3.2. Capillary water absorption

Fig. 4 shows the capillary water absorption coefficients of mixes with rubber wastes. As expected an increase in the rubber percentage leads to high water absorption coefficients. The partial replacement of cement by pozzolanic additions also leads to an increase in the water absorption coefficients (Fig. 5a). Nevertheless, the capillary water absorption of all the concrete mixes used in this investigation is very low (Fig. 5b and c). As a comparison a C20/25 strength class concrete (the most used strength class in Europe [17] has capillary water absorption coefficient between 0.85 and 2.6 kg/m^2 h$^{0.5}$ [18]. Some authors even report the use of surface treatments to achieve concrete surfaces with similar capillary water absorption coefficients [19].

3.3. Resistance to sulphuric acid attack

Fig. 6 shows the mass loss after sulphuric acid attack of mixes with rubber wastes. The increase in the rubber percentage leads to a higher mass loss degree. The mix with 15% metakaolin and the mix with 30% fly ash underperformed against the reference mix, however, that was not the case of the mix with 60% fly ash which shows a mass loss after 28 days that is 10% lesser when compared to the reference concrete (Fig. 7a). These results confirm previous findings about the fact that the presence of pozzolanic admixtures was found to lower the detrimental effect of acid attack on concrete [20,21]. The mixes with rubber waste and fly ash show a resistance to sulphuric acid attack lower than the reference mix (Fig. 7b). The mix with 5% rubber waste and a partial replacement of cement by 15% fly ash and 15% metakaolin has almost the same resistance to sulphuric acid attack of the reference mix (Figs. 7c and 8). All the mixes with 45% fly ash and 15% metakaolin show a much higher resistance to sulphuric acid attack than the reference mix independently of the rubber waste content. Since the reference mix has much lower capillary water absorption than the mixes with 45% fly ash and 15% metakaolin this means that the rate of acid ingress into concrete has a lower influence than the solubility of calcium hydroxide that must be lower in the latter case. The mix complying with the requirements of EN 206-1 for concrete structures exposed to highly aggressive chemical environment (class XA3) showed a worst resistance to

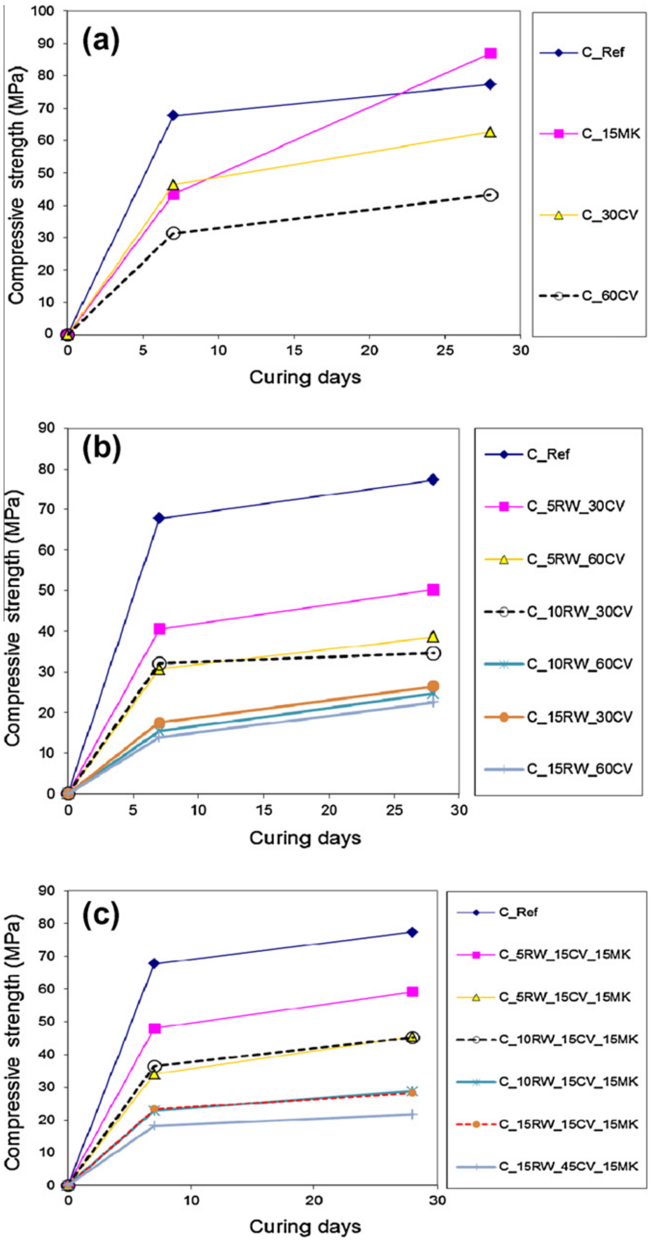

Fig. 3. Compressive strength of the: (a) mixes with partial replacement of cement by fly ash and metakaolin; (b) mixes with rubber wastes and partial replacement of cement by fly ash; (c) mixes with rubber wastes and partial replacement of cement by fly ash and by metakaolin.

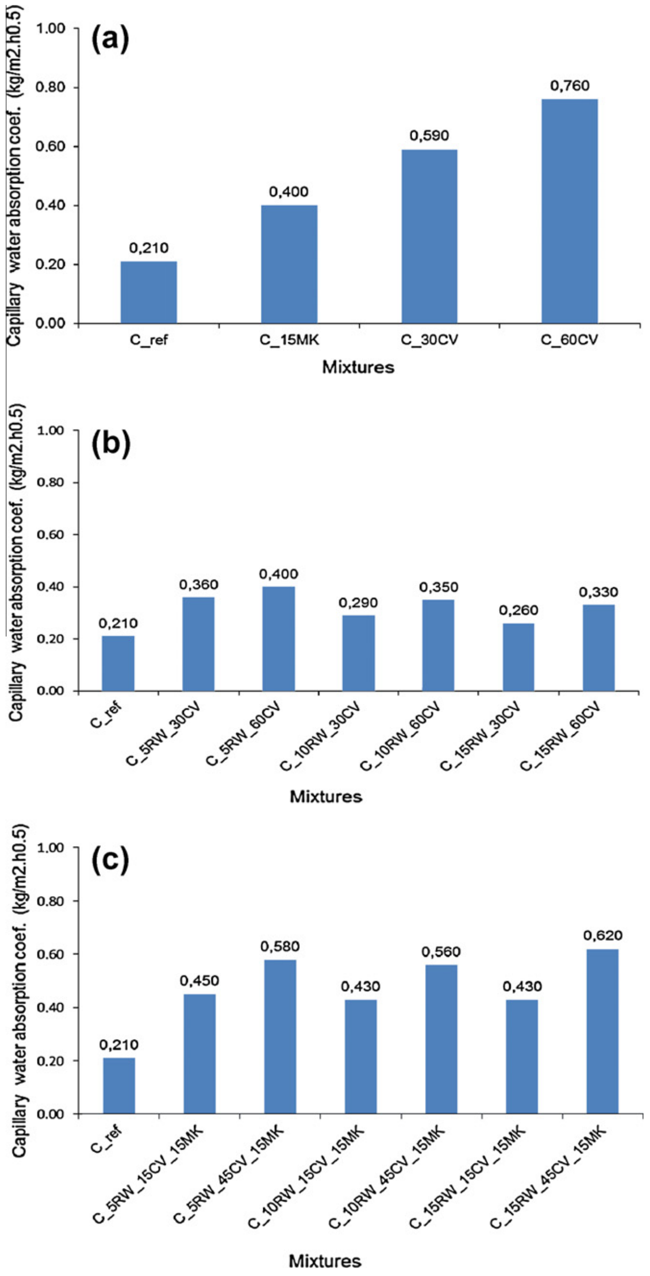

Fig. 5. Capillary water absorption coefficient of mixtures with: (a) partial replacement of cement by fly ash and by metakaolin; (b) rubber wastes and partial replacement of cement by fly ash; (c) rubber wastes and partial replacement of cement by fly ash and by metakaolin.

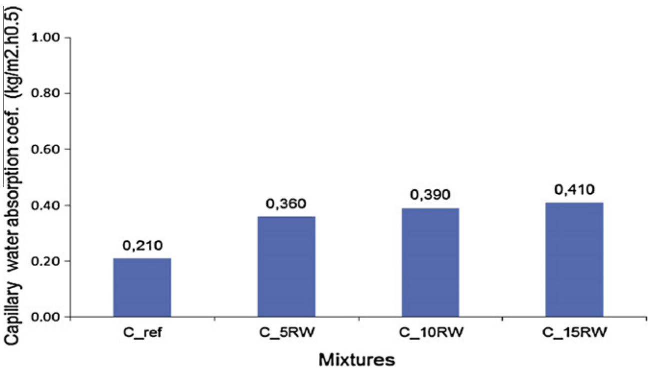

Fig. 4. Capillary water absorption coefficient of mixes with rubber wastes.

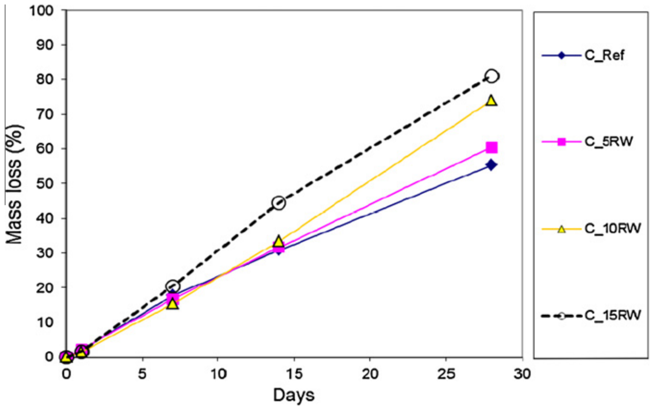

Fig. 6. Mass loss after sulphuric acid attack of mixes with rubber wastes.

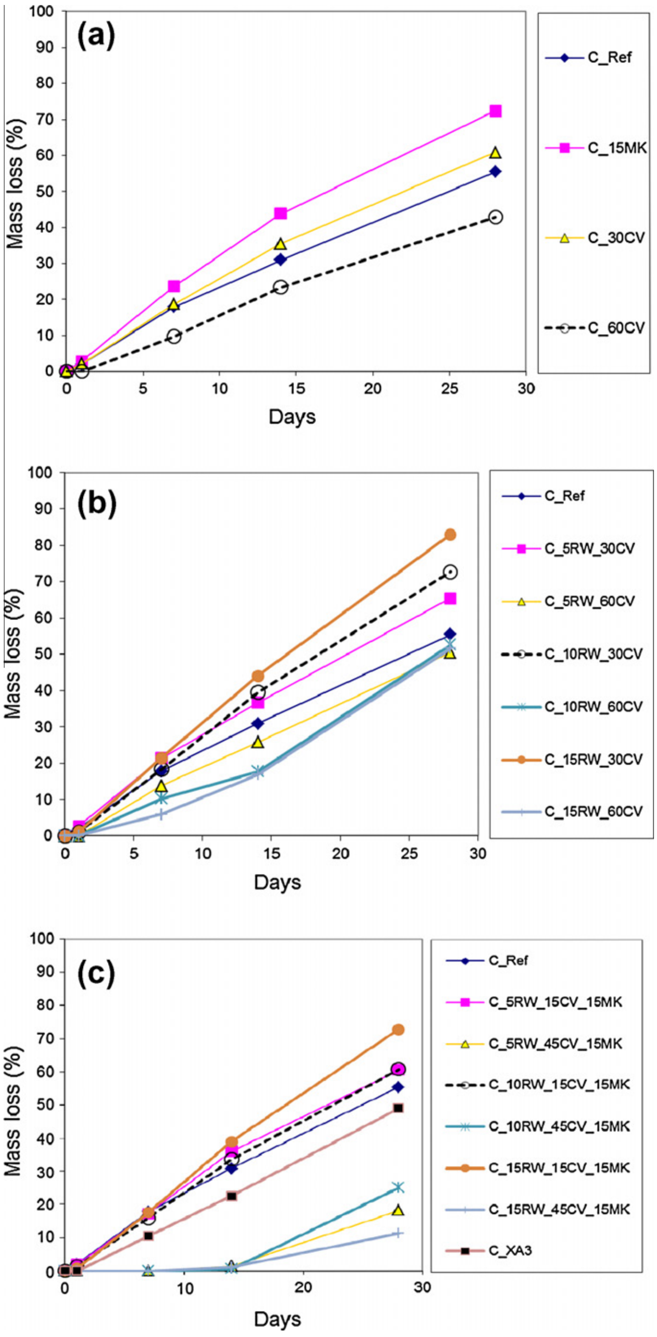

Fig. 7. Mass loss after sulphuric acid attack of mixes with: (a) partial replacement of cement by fly ash and by metakaolin; (b) rubber wastes and partial replacement of cement by fly ash; (c) rubber wastes and partial replacement of cement by fly ash and by metakaolin.

sulphuric acid attack than the mixes containing rubber wastes and with 45% fly ash and 15% metakaolin. This means that the new mixes with rubber wastes, fly ash and metakaolin could be recommended for sulphuric acid resistance applications such as sewer pipes concrete, an hot area due to the rapid deterioration of concrete in sewage systems [22]. This also means that the requirements of EN 206-1 for concrete structures exposed to highly aggressive chemical environment should be revised.

4. Conclusions

From the information presented in this paper, the following conclusions can be drawn:

1. The increase of rubber wastes leads to serious compressive strength loss.
2. The synergetic effect between fly ash and metakaolin minimizes the strength loss associated to the use of rubber waste.
3. Is possible to use of rubber waste up to 15% and still maintain a low capillary water absorption.
4. The mix with 5% rubber waste and a partial replacement of cement by 15% fly ash and 15% metakaolin has almost the same resistance to sulphuric acid attack of the reference mix.
5. The mixes with 45% fly ash and 15% metakaolin show a much higher resistance to sulphuric acid attack than the reference mix independently of the rubber waste content.
6. The mix complying with the requirements of EN 206-1 for concrete structures exposed to highly aggressive chemical environment (class XA3) showed a worst resistance to sulphuric acid attack than the mixes containing rubber wastes, 45% fly ash and 15% metakaolin.

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Fig. 8. Photos of concrete specimens with 5% rubber wastes and partial replacement of cement by 15% fly ash and by 15% metakaolin after immersion in sulphuric acid solution during 1, 3, 7, 14 and 28 days.

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