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Cementitious Composites with Rubber Particles from Recycled Tyres: Physical and Mechanical Properties

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Abstract

This work describes a statistical analysis of the mechanical properties of cementitious composites made with recycled rubber inclusions for sustainable structural applications. The rubber particles from recycled tyres were used as replacement of quartz inclusions in the mortars. A full factorial design ($7^1 2^2$) was performed to investigate the effect provided by the rubber particles size and fraction on the physical and mechanical properties of the cementitious composites. The results show that the use of rubber particles reduces the overall density, compressive strength and modulus of elasticity, and increases the apparent porosity, water absorption and permeability. Large pores in the composites are present when large size particles are used. The low water/cement ratio adopted in this work did not allow a full hydration of the cementitious phase, which further reduced the overall mechanical performance. Some cementitious composite configurations have however shown acceptable mechanical properties for non-structural applications in civil engineering.

Keywords: composite, full factorial design of experiment, mechanical properties, permeability, recycling, tyre rubber wastes

1. Introduction

The rate of growth of the construction industry in developing countries causes a progressive depletion of available natural raw building materials. A significant effort has been made by the R&D community to develop new sustainable materials with good mechanical performance and relatively low manufacturing cost. The reuse of different solid wastes as aggregates for concrete and mortar is an example of those new classes of building materials. Among the solid waste produced in the transport industry, scrap tyres constitute a clear example of a product with significant impact to the environment. One billion tyres are scrapped every year, and 5 billions more are expected to be discarded on a regular basis until 2030. A small part is recycled, but millions of tyres are just stockpiled, landfilled or buried (Pacheco-Torgal *et al.* 2012). In Brazil, 67.3 millions tyres were produced in 2010, corresponding to a rise of 15% compared to the production in 2009 (ANIP 2011). In the USA more than 300 million tyres are currently stored (Batayneh *et al.* 2008), while the UK disposes approximately 46 million tyres each year. Since European Union directives have banned the disposal of used tyres (whole and shredded) in landfills, there is a real and urgent need to identify routes for reuse or recycling of the scrapped tyre rubber (WRAP 2007).

The diverse chemical composition and cross-linked structure of rubber in tyres are the prime reason to explain their resistance to bio and chemical degradation, photochemical decomposition and to high temperatures (Sienklewicz *et al.* 2012). New techniques and machinery have been developed to grind and separate the steel and rubber, making them possible to be reused as raw materials mainly in civil construction applications (Mujal-Rosas *et al.* 2011). Pelisser *et al.* (2012) have evaluated a lightweight concrete composite in which the sand was replaced by rubber particles. Lightweight concrete fabricated with 40wt% presented a compressive strength of 20MPa and a thermal conductivity suitable for building materials with improved energy efficiency, with consequent reduction in their operating costs (Pelisser *et al.* 2012, Yesilata *et al.* 2008). Turgut & Yesilata

(2008) have studied the properties of lightweight and low cost concrete masonry units based on rubber particle additions, showing improved heat resistance. Aiello & Leuzzi (2010) have evaluated the properties of concrete mixtures (fresh and hardened) with partial substitution of coarse and fine aggregates with different volume percentages of scrap tyres rubber particles. The rubberized concrete composites ("rubcrete") showed lower unit weight compared to plain concrete and good overall workability. However, Rubcrete with coarse aggregate replaced by the rubber particles showed a significant reduction of the compressive and flexural strength. On the other hand, the post-cracking behaviour of this rubberized concrete was improved when rubber shreds replaced coarse aggregate, with good energy absorption and ductility similar to the ones observed in fibre-reinforced concrete (Aiello & Leuzzi 2010). Also Mavroulidou & Figueiredo (2010) have investigated the physical and mechanical properties of concrete containing recycled tyre aggregates and found that, despite a significant loss in strength, this type of concrete is acceptable for various applications requiring medium to low compressive strength. Ling *et al.* (2010) have observed that the rubber particles in concrete pavements must not exceed 20wt% of sand replacement to avoid excessive reduction in compressive strength. The same main author recommended also that the substitution of rubber in concrete masonry units should not exceed 10wt% for structural applications and 40wt% for non-structural applications (Ling 2011). Nacif *et al.* (2013) have investigated the mechanical properties of cementitious composites with rubber particles inclusions and observed that a compressive strength higher than 20MPa can be obtained with 15wt% of rubber particle with sizes between 0.84mm and 0.58mm using 0.35 w/c (water to cement) ratio; this could represent a viable and economical recycling alternative for some construction applications. Correa *et al.* (2010) have investigated the substitution of natural aggregate in mortar mixes with vulcanized rubber particles. In that study, the replacement of sand by rubber particles made the composite significantly more difficult to manufacture and contributed to the weakening of the interface transition zone (ITZ) between the aggregate and the cement matrix of the hardened mortar. Meshgin et al. (2012) have observed that the employment of tyre rubber wastes in isolation mortar reduced the compressive and flexural strength, as well as the thermal conductivity when the rubber content was increased. However, fracture behaviour was gradual and not brittle, and evidence was given about the presence of an adequate interface between the rubber particles and cement in mechanical and chemical terms.

To the best of the authors' knowledge, this current paper describes one of the first attempts to use a robust design of experiment (DoE) approach to investigate the effect of scrap tyre rubber particles on the physical and mechanical properties of mortar for civil engineering applications. A full factorial design was performed to identify the effect of the following factors: (i) substitution of quartz with rubber having different size, (ii) water to cement ratio (w/c) and (iii) use of a superplasticizer admixture. The properties of the composites that were the subject of this paper were the bulk density, apparent porosity, water absorption, permeability, the compressive strength and modulus of elasticity.

2. Material and Methods

2.1 Raw Materials

Portland cement mortars were prepared using Type III (ASTM) cement supplied by Holcim-Brazil. The reference aggregates were quartz particles supplied by Moinhos Gerais Company (Brazil). Tyre Remoulder Mantiqueira (Brazil) supplied the rubber particles. The superplasticizer admixture (Sika ViscoCrete 6500) was provided by Sika-Brazil. The quartz and rubber particles were classified by sieving in the following three size ranges: 1.18 mm – 600 μm, 600 μm – 300 μm, and 300 μm – 150 μm (hereafter designated as coarse, medium and fine particles, respectively). The coarse, medium and fine particle ranges were mixed to obtain an equivalent particle size distribution, as recommended by the ASTM-C144 standard (2011) for mortar production. The quartz particles were replaced with rubber particles based on the particle size ranges and amount described in Table 1.

2.2 Design of Experiment

Design of Experiment (DOE) and Analysis of Variance (ANOVA) were used to determine the significance of each factor on the output parameters. The software Minitab version 14 was used for the statistical analysis. It is worth reminding that a full factorial design of type n^k consists in investigating all the possible combinations of the experimental factors (k) and the respective levels (n). The result of the factorial n^k corresponds to the number of the experimental conditions investigated (Wu and Hamada, 2000). The experimental factors (levels) considered in this work were the substitution of quartz with rubber (100% quartz, coarse range, medium range, fine range, coarse/medium range, medium/fine range and 0% quartz), w/c ratio (0.4 and 0.5) and adding of superplasticizer (0 and 0.5 wt%). The sample population for the DoE, therefore, corresponded to a full factorial design of $7^1 2^2$ (Table 2). The output parameters considered in this DoE (i.e., responses) were the water absorption, the bulk density and the apparent porosity (ASTM C642, 2013), as well as the oxygen permeability

(Cabrera & Lynsdale, 1988), the compressive strength and modulus of elasticity (ASTM C780, 2012). The number of specimens was calculated based on destructive and non-destructive tests, 2 replicates and 28 experimental conditions. Seven samples were fabricated for each condition per replica, providing 392 specimens. A microstructural analysis was also performed to correlate the mechanical properties with the particles/matrix interaction.

The morphology of the quartz and rubber particles was assessed using an optical microscope. The packing density was measured by using a graduate beaker and a precision balance. The beaker was filled with 500g of particles and vibrated for 5 minutes. The bulk volume was measured to calculate the packing density, and the apparent density was obtained using a gas pycnometer Micromeritics AccuPyc 1330.

Table 1. Particle size distribution for mortar and work setup

Particle size distribution for mortar (ASTM C144)		Equivalent grading – work setup	
Retained particles sieve	wt%	Particle size range [US-Tyler] - µm	(wt%)
4.75-mm (No. 4)	0	[16-30 US-Tyler] 1180µm – 600µm	30%
2.36-mm (No.8)	5		
1.18-mm (No. 20)	25		
600-µm (No. 30)	30	[30-50 US-Tyler] 600µm – 300µm	50%
300-µm (No. 50)	20		
150-µm (No. 100)	10	[50-100 US -Tyler] 300µm – 150µm	20%
75-µm (No. 200)	10		

Table 2. Full factorial design ($7^1 2^2$)

Setup	Substitution of quartz (size-amount)*	w/c ratio	Admixture (%)	Setup	Substitution of quartz (size-amount)*	w/c ratio	Admixture (%)
C1	None	0.4	0	C15	F (20wt%)	0.5	0
C2	None	0.4	0.50	C16	F (20wt%)	0.5	0.50
C3	None	0.5	0	C17	C/M (30/50wt%)	0.4	0
C4	None	0.5	0.50	C18	C/M (30/50wt%)	0.4	0.50
C5	C (30wt%)	0.4	0	C19	C/M (30/50wt%)	0.5	0
C6	C (30wt%)	0.4	0.50	C20	C/M(30/50wt%)	0.5	0.50
C7	C (30wt%)	0.5	0	C21	M/F (50/20wt%)	0.4	0
C8	C (30wt%)	0.5	0.50	C22	M/F (50/20wt%)	0.4	0.50
C9	M (50wt%)	0.4	0	C23	M/F (50/20wt%)	0.5	0
C10	M (50wt%)	0.4	0.50	C24	M/F (50/20wt%)	0.5	0.50
C11	M (50wt%)	0.5	0	C25	Quartz (100wt%)	0.4	0
C12	M (50wt%)	0.5	0.50	C26	Quartz (100wt%)	0.4	0.50
C13	F (20wt%)	0.4	0	C27	Quartz (100wt%)	0.5	0
C14	F (20wt%)	0.4	0.50	C28	Quartz (100wt%)	0.5	0.50

* C = coarse; M = medium; F = fine fraction

2.3 Fabrication of Samples

Mortars were mixed following the recommendations of the standard ASTM C1329 (2012), in order to reduce the uncertainties in the manufacturing process. A cement/aggregate ratio of 1:3 was used based on the same standard (ASTM C1329, 2012). The extreme composites configurations (C1 and C28 in Table 2) were fabricated to verify the rheology of the system. Polymeric cylindrical moulds were used to manufacture the samples. The moulds had dimensions of 47.5mm in diameter and a height/diameter ratio of 2 to ensure the homogeneity of the samples. After a curing period of 28 days, the samples were cut using a precision saw prior to compression testing. Figure 1 shows only a series of samples belonging to the C1 and C7 composites as an example. The mixing time (~5min) and vibration time (~30s) at 1.5Hz were kept constant.

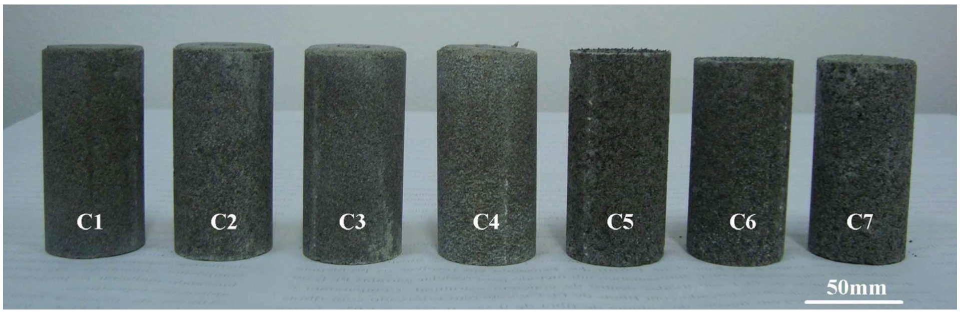

Figure 1. Cylindrical samples from C1 to C7 composites

3. Results

3.1 Characterization of the Particles

The morphology of the quartz and rubber particles at 50× of magnification can be observed in Figures 2a-c and 2d-f, respectively. Quartz and rubber particles exhibit a non-spherical shape. The rubber particles, however, appeared to possess more complex shapes with higher surface area, which can be attributed to the scraping process of the waste tyres. Table 3 shows the packing and apparent density for both aggregates. It is possible to observe that there is a direct correlation between the size of the rubber particles and their packing density, which is not evident for the quartz particles.

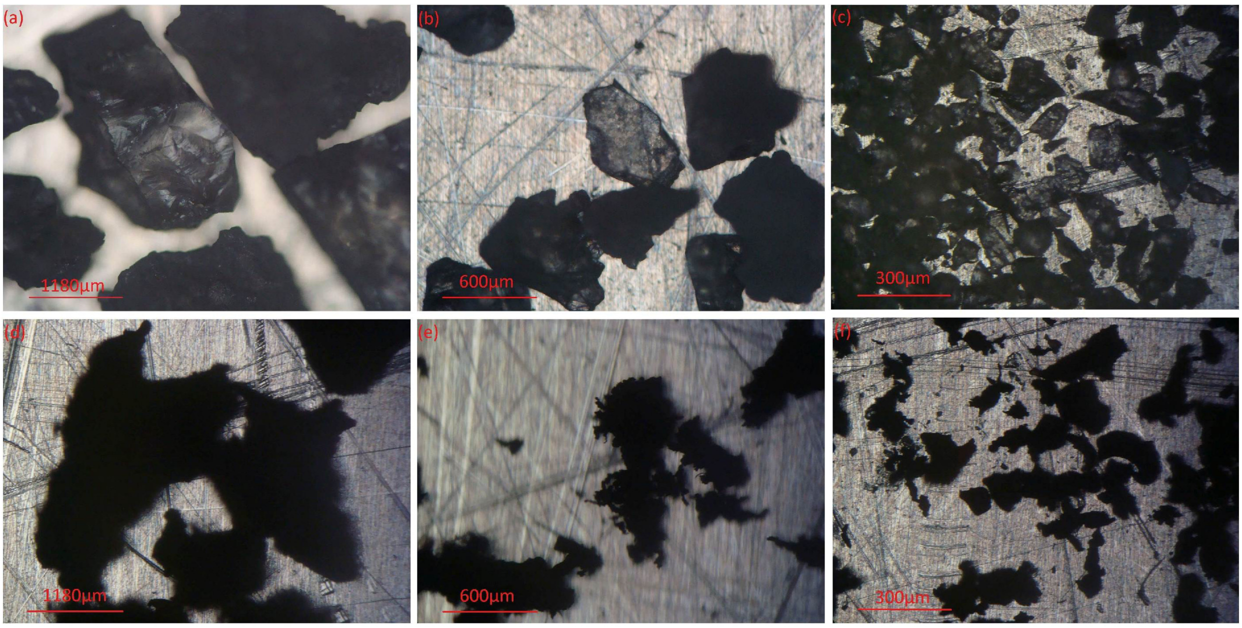

Figure 2. Morphology of the quartz particles (a) 1180 µm; (b) 600 µm; (c) 300 µm and rubber particles (d) 1180 µm; (e) 600 µm; (f) 300 µm

Table 3. Physical properties of quartz and rubber particles

Property	Particle size	Quartz	Rubber
Packing density	1180µm	1.27 g/cm^3	0.32 g/cm^3
	600 µm	1.35 g/cm^3	0.29 g/cm^3
	300 µm	1.28 g/cm^3	0.27 g/cm^3
Apparent density	1180µm 600 µm 300 µm	2.83 ± 0.45 g/cm^3	1.24 ± 0.11 g/cm^3

3.2 Analysis of Variance

Table 4 shows the results of the Analysis of Variance (ANOVA). The P-values indicate which of the effects in the design are statistically significant, based on the examination of the data from the replicates. If the P-value is less or equal to 0.05 (95% of reliability) the main and/or interaction factor is significant. The main effect of a factor must be considered individually only if there is no evidence that it does not interact with other factors. When one or more effect of interaction of superior order is significant, the factors that interact should be considered jointly (Wu and Hamada, 2000). P-values equal to or less than 0.05 were highlighted in bold in Table 4, however, the underlined P-values represent those that have been assessed in the main or interaction effect plots. The adjusted R² represents how well the data fit the model. The R^2 values found in Table 4 are all higher than 82%, satisfying the ANOVA conditions.

Table 4. Analyses of variance (ANOVA)

		P-values ≤ 0.05					
	Factors	Bulk density	Porosity	Water absorption	Permeability	Compressive strength	Modulus of elasticity
Main factors	Substitution of quartz	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
	w/c ratio	<u>**0.000**</u>	**0.000**	**0.000**	0.123	<u>**0.000**</u>	**0.001**
	Admixture	**0.000**	**0.000**	**0.000**	0.965	**0.000**	**0.002**
Interaction of factors	Substitution of quartz* w/c ratio	0.264	**0.000**	**0.000**	0.638	**0.040**	**0.000**
	Substitution of quartz* Admixture	<u>**0.000**</u>	**0.000**	**0.000**	<u>**0.017**</u>	<u>**0.000**</u>	**0.021**
	w/c ratio* Admixture	0.310	**0.000**	**0.009**	0.675	0.923	**0.026**
	Substitution of quartz* w/c ratio* Admixture	0.095	<u>**0.000**</u>	<u>**0.000**</u>	0.766	0.271	<u>**0.002**</u>
	R^2(adj)	99.23%	99.23%	99.30%	82.16%	96.36%	97.98%

3.3 Bulk Density

The bulk density data varied from 0.578 g/cm^3 to 1.610 g/cm^3. P-values lower than 0.05 reveals that the main factor or interaction significantly affects the response. All the main factors were significant (P-value=0.000, see

Table 4); however, only the factor "w/c ratio" (Figure 3) has been evaluated because an interaction effect between "substitution of quartz and admixture" was also significant (Figure 4).

Figure 3 shows the plot of the main effect of the w/c ratio upon the mean bulk density. A 7% increase of the bulk density was observed when the w/c ratio increased from 0.4 to 0.5. In general, the increase of the amount of water in Portland cement-based products is responsible for a reduction of the density. The opposite behaviour observed in the current study suggests that the w/c ratio of 0.4 was probably too low to provide an optimal rheology of the system, or a complete hydration of cement.

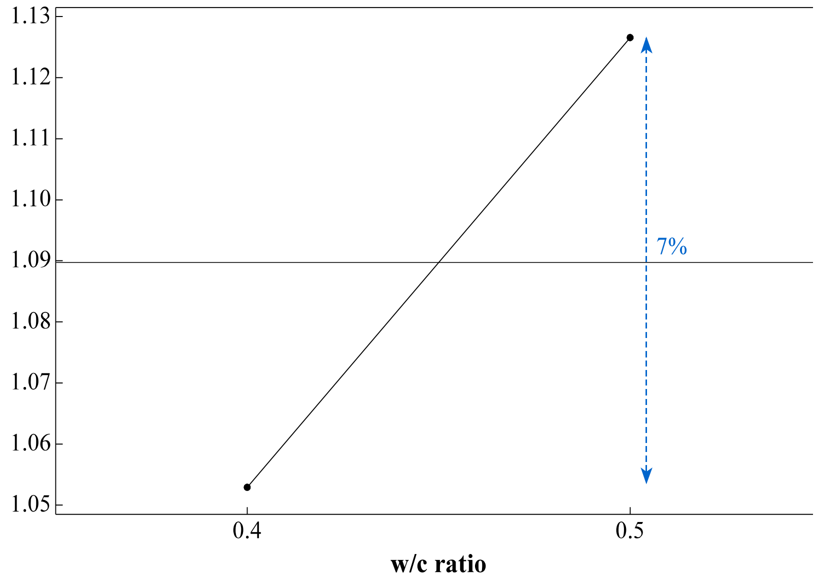

Figure 3. Main effect plot of w/c ratio for the mean bulk density

Figure 4 shows the plot of the interaction effect on the bulk density between the substitution of the quartz and inclusion of the admixture. It is possible to note that the use of the superplasticizer helped to slightly increase the bulk density, mainly when a large amount of quartz particles was added to the system. A significant variation of the bulk density was also observed (147%) between the composites fabricated with 100% of quartz particles and the ones with 100% of rubber particulates. The composites made with lower levels of rubber particles (such as coarse – 30wt% and fine - 20wt%) showed also a similar behaviour to the mixtures made from 100% of quartz particles. Figure 4 indicates that it is the percentage of rubber in the mixtures, rather than the particle sizes that significantly affects the bulk density.

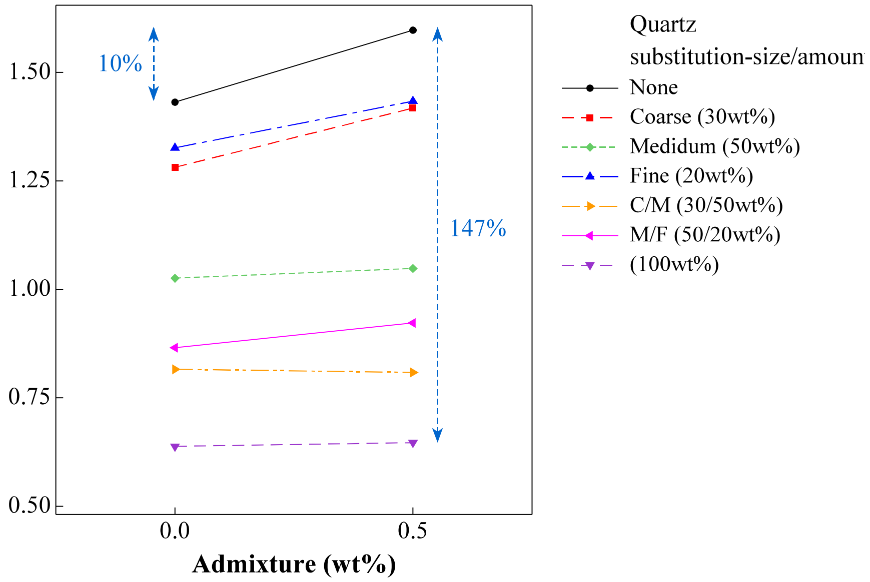

Figure 4. Interaction effect plot between the substitution of the quartz and use of admixture for the mean bulk density

3.4 Apparent Porosity

The apparent porosity was calculated using a water saturation method, commonly used for ceramic and cementitious materials. The analysis of the water absorption, therefore, has been omitted in this work, as the results can be considered analogous to those related to the apparent porosity.

The apparent porosity varied from 12.95% to 98.00%, corresponding to a water absorption variation from 14.12% to 72.37%. All main factors and interactions exhibited P-values lower than 0.05 (Table 4); therefore, only the third order interaction has been evaluated. Figure 5 shows a reduction of the apparent porosity when the water/cement ratio is increased, in line with what has been observed for the bulk density. The w/c ratio of 0.4 might not be able to provide adequate particle packing; as a consequence, the composites with w/c = 0.4 have higher porosity than the ones with w/c = 0.5. Similarly to what also observed for the bulk density, the porosity increased when the rubber replaced the quartz aggregates. The superplasticizer admixture was able to reduce the porosity for all the levels of quartz replacement, except for the case of medium/fine particle sizes. These results show that a 0.5% of admixture improved the flow characteristics of the mortars. This could be expected, as the main purpose of a superplasticizer is to reduce the w/c ratio without affecting the manufacturing of the mixture and achieving lower porosity and higher mechanical strength. However, Figure 5 also shows that the superplasticizer was more efficient to reduce the porosity when the upper level of w/c ratio (0.5) was employed. The porosity was reduced in 34 % when the w/c ratio was higher in composites with superplasticizer. This behaviour confirms that the admixture was not efficient when the w/c ratio was equal 0.4.

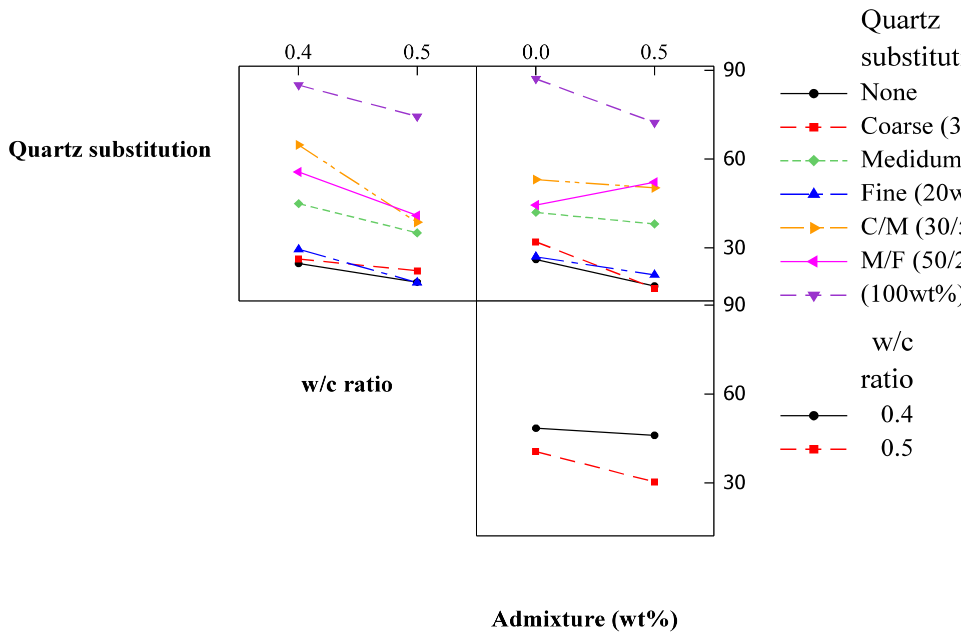

Figure 5. Plot of the interaction effect between quartz substitution, w/c ratio and admixture on the mean apparent porosity

3.5 Oxygen Permeability

The oxygen permeability varied from 2.2×10^{-10} to 0.35×10^{-10} m^2. The ANOVA showed that the main factor (quartz substitution) and the interaction effect between quartz substitution and use of admixture significantly affected the permeability response. Figure 6 shows the main effect of the quartz substitution on the mean permeability. The total replacement of quartz with rubber particles increased the permeability by 168%. The replacement of coarse quartz with rubber at 30wt%, however, did not affect significantly the permeability compared to the composites with no rubber inclusions. The permeability considerably increased only when higher weight fractions of the rubber particles were used to replace equivalent quartz particulates, with a 59.5 % increase for 50wt% of rubber particles. Although the replacement of quartz fine particles corresponds only to 20wt% amount of rubber, the permeability of the composites was also increased. The replacement of coarse/medium quartz particles (total amount of 80wt%) showed also a higher permeability compared to the case related to the use of medium/fine particles (70wt%). Overall, the results indicate that the amount of rubber, rather than the particle size, affects in a negative way the permeability, as the increase in permeability has a quasi-linear correlation with the wt% of rubber (Figure 7).

Figure 8 shows the plot of the interaction effect between the quartz particles replacement and the use of the admixture on the average values of the permeability. The superplasticizer admixture decreased the oxygen permeability in all the mixtures, except for those composites fabricated with coarse/medium and medium/fine rubber particles. This behaviour can be attributed to the packing configuration of the mutual rubber/quartz system.

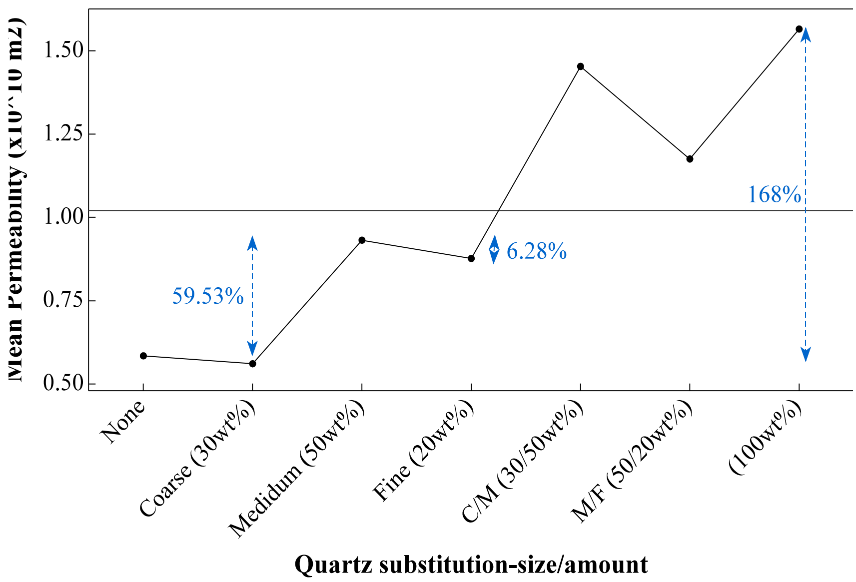

Figure 6. Plot of the main effect given by the substitution of quartz particles upon the mean values of the oxygen permeability

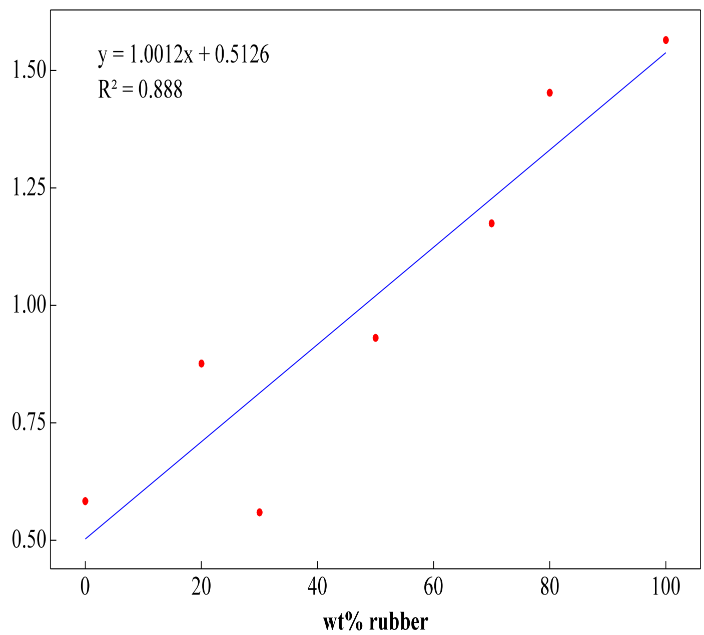

Figure 7. Permeability of the composites as a function of the rubber percentage in the mixtures

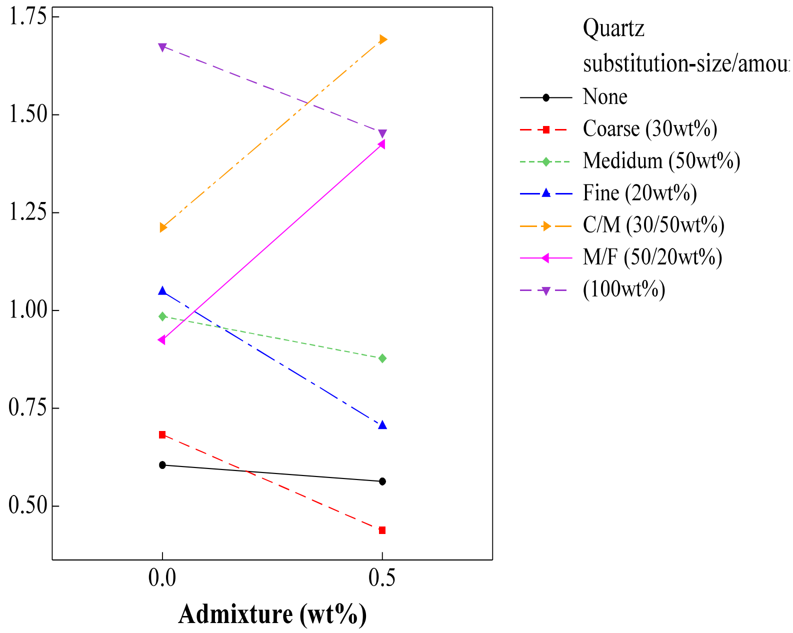

Figure 8. Plot of the interaction effect between substitution of quartz and use of admixture on the mean oxygen permeability

3.6 Compressive strength

The compressive strength varied from 0.14MPa to 22.60MPa and was significantly affected not only by the main factors, but also by two interactions of the second order (see Table 4). Therefore, only the interaction effect plots are presented in this work. The lowest values of compressive strength belong to composites produced with the lowest w/c ratio and highest percentage of rubber particles; those are unsuitable to structural engineering applications. Figure 9 shows the interaction effect between the quartz replacement and w/c ratio upon the mean compressive strength. A higher mechanical strength was reached when the composites were manufactured using a w/c ratio of 0.5 and 100% of quartz particles. The substitution of quartz with rubber at fine, coarse and medium particle sizes reduced the strength by 90%, 156% and 369% respectively. The substitution of two particle size ranges (C/M and M/F) and 100wt% of rubber gave compressive strength values lower than 3.6MPa, which is usually considered very low even for non-structural applications. Higher compressive strength was achieved when a large amount of water was considered (0.5). This behaviour implies again that the lower level of w/c ratio used (0.4) was not able to provide fully compaction of the composites (possibly also affecting the hydration of cement), therefore jeopardising the mechanical strength of the rubber composites.

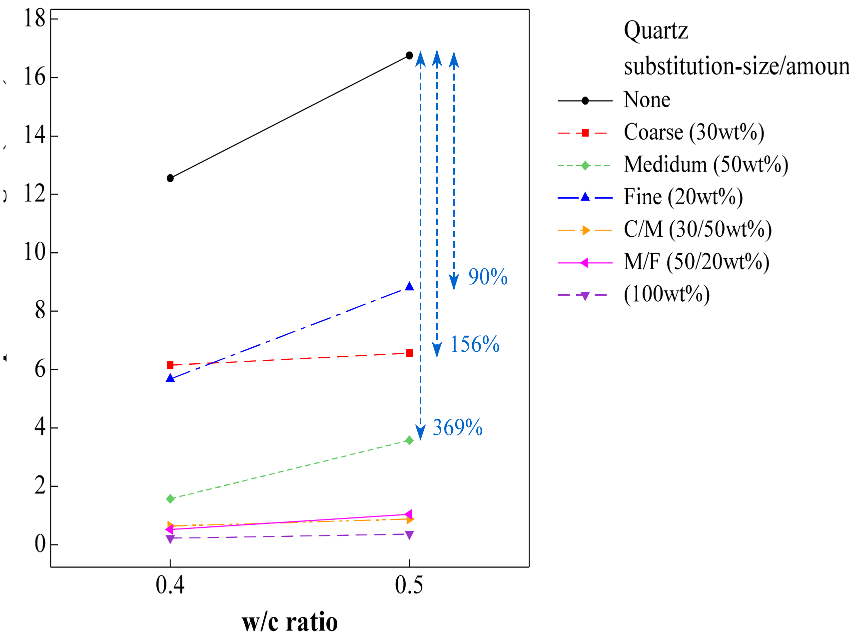

Figure 9. Plot of the interaction effect between quartz substitution and w/c ratio on the mean compressive strength

Figure 10 shows how the compressive strength was affected by the employment of rubber particles at the presence of a superplasticizer admixture. The inclusion of the superplasticizer increased the mechanical strength, mainly when higher amounts of quartz were used, to a limit of. 67.63% when 100wt% of quartz was presented in the composites. The superplasticizer did not affect the rheology of the system when large amount of rubber particles are embedded.

3.7 Modulus of Elasticity

The modulus of elasticity (E) of the composites varied from 1.48 MPa to 2.95GPa. The residuals calculated from the data did not respect the conditions of normality and homogeneity required to validate the ANOVA, and therefore a natural logarithm function (ln) was used to make the data suitable for the statistical analysis. Similarly to the compressive strength, extremely low values of E corresponded to samples at the extreme end of the design envelope, thus not suitable to any structural engineering application. The mean of the logarithm of the Young's modulus was significantly affected by the cross-interaction between quartz replacement, water to cement ratio and the use of the admixture. Figure 11 shows a slight increase of the ln(E) when the w/c ratio rises from 0.4 to 0.5, except for composites consisting of 100wt% of quartz particles. The admixture was more effective especially in those composites made from 100wt% of quartz particles. Figure 11 also indicates a slight positive effect of the superplasticizer on the stiffness when a 0.5 w/c ratio is considered.

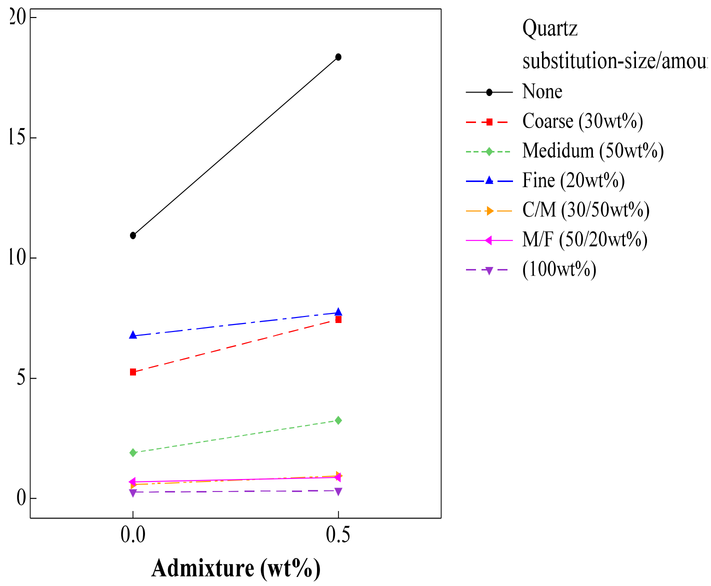

Figure 10. Plot of the interaction effect between quartz substitution and admixture on the mean compressive strength

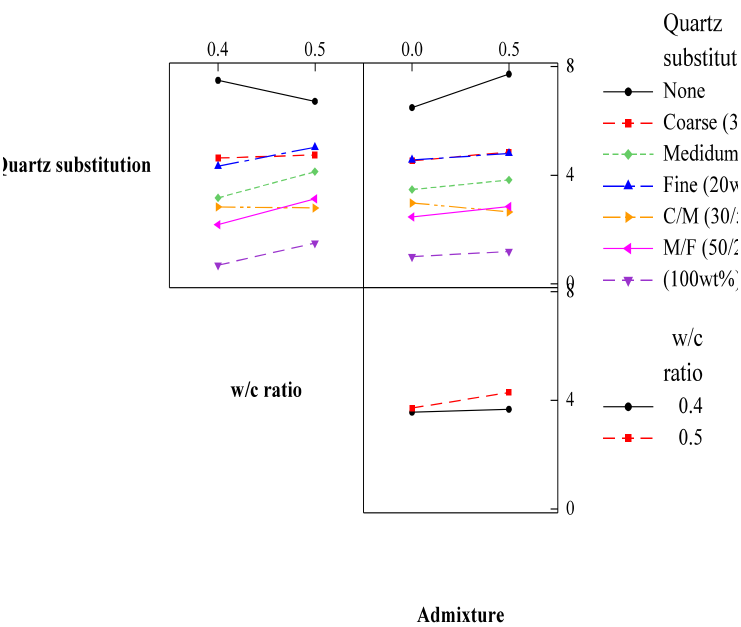

Figure 11. Plot of the interaction effect between quartz substitution, w/c ratio and admixture on the mean ln(E)

3.8 Microstructural Analysis

SEM images obtained from a Hitachi T3000 bench top microscope were used to visually analyse the microstructure of some composites. The micrographs shown in Figure 12 and 13 were obtained under the same conditions of contrast, colour intensity and 50× of magnification. Figure 12 shows the microstructure of the C3 and C4 composites manufactured with 100wt% of quartz, w/c ratio = 0.5, with no admixture (Fig. 12a) and 0.5% of admixture (Fig. 12b). Figure 12a reveals a microstructure containing slightly larger pores. The lower porosity in C4 composites can be attributed to the superplasticizer effect.

Figure 13 shows the microstructure of composites C27 and C28, consisting of 100wt% of rubber, w/c ratio = 0.5. The C27 material had no admixture (Figure 13a), while the C28 had superplasticizer amount of 0.5% (Figure 13b). In general, the pore sizes found in these two composites are larger than those observed in systems made of 100wt% of quartz (see Figure 12). The total substitution of quartz particulates with rubber shows evidence of affecting the properties of the composites, not only by increasing the porosity (Figure 5) but also by reducing the compressive strength (Figure 10). The presence of the admixture (Figure 13b) appears to improve the compaction of the composites using higher amounts of rubber particles.

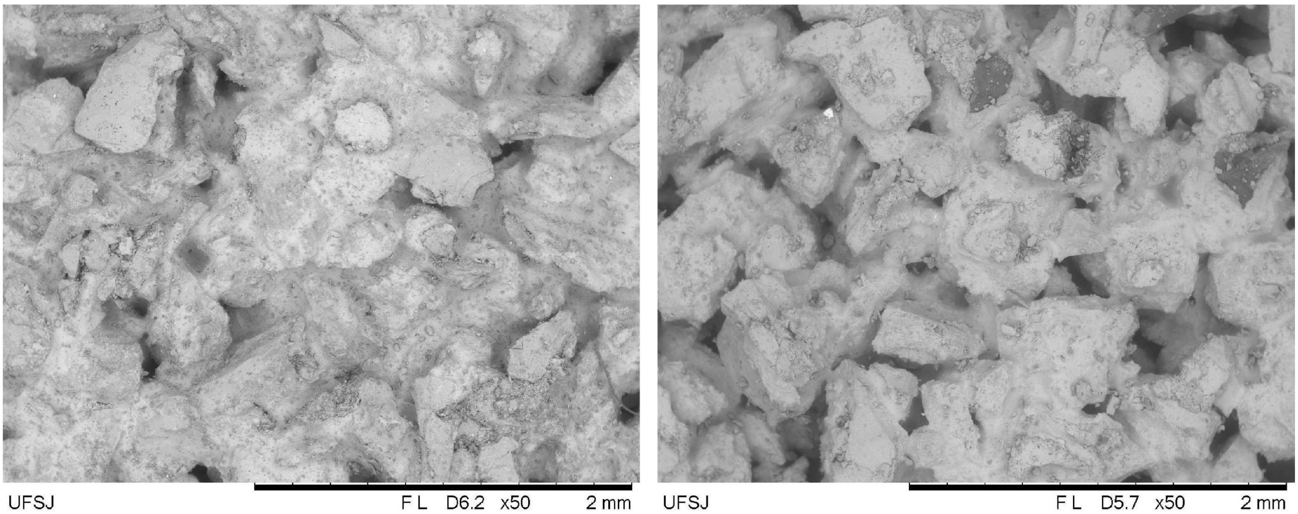

Figure 12. SEM images at a magnification of 50 X (a) C3: 100wt% quartz, w/c 0.5, no admixture and (b) C4: 100wt% quartz, w/c 0 5, with admixture

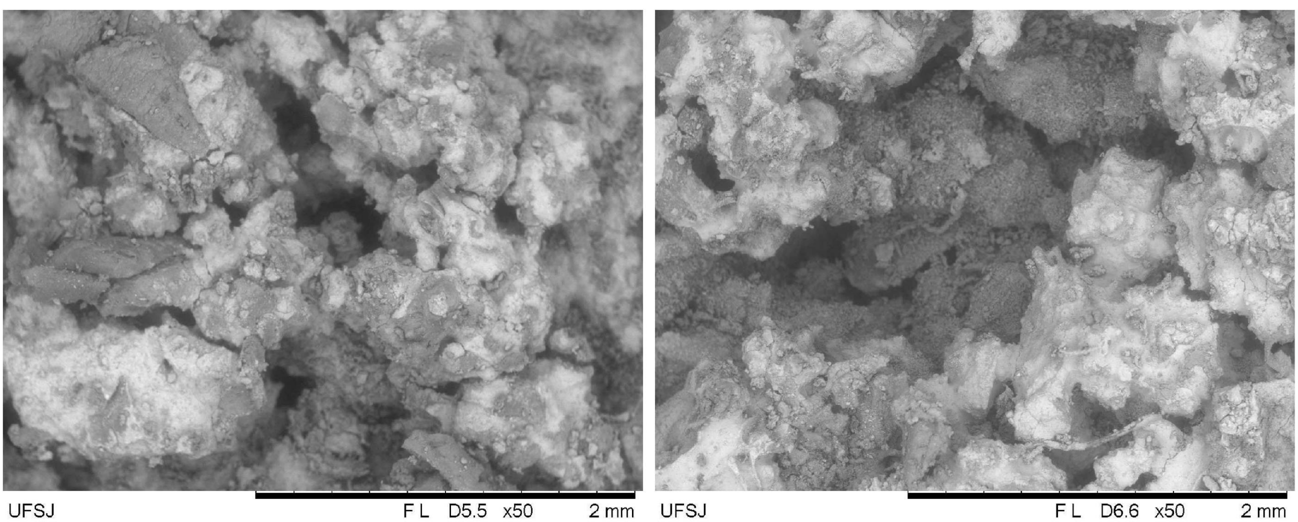

Figure 13. SEM images at a magnification of 50 X (a) C27: 100wt% rubber, w/c 0.5, no admixture and (b) C28: 100wt% rubber, w/c 0 5, with admixture

4. Conclusions

This work investigated the effect of substituting quartz with recycled rubber particles cementitious composites, also taking into account the contribution of the water/cement ratio and the presence of a superplasticizer in the manufacturing of the composites. The replacement of quartz particles with rubber provided a general decrease of the stiffness, strength and bulk density, the latter being also negatively affected by the increase of the water to cement ratio. In general, any decrease of the workability of the mortar mixes due to the replacement of the quartz particles with the recycled rubber could be offset by the use of a superplasticizer, which provides also an increase in the compressive strength of the cementitious composites. A particular type of cementitious composite (C8) with 30wt% of coarse particle substitution, w/c = 0.5 and 0.5% admixture showed low porosity, low water absorption and permeability, with relatively high compressive strength and modulus of elasticity. This particular composite configuration may represent a promising material configuration to introduce rubber from scrap tyres in mortars for civil engineering applications.

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References

Aiello, M. A., & Leuzzi, F. (2010). Waste tyre rubberized concrete: Properties at fresh and hardened state. *Waste Management, 30*(8-9), 1696-1704. http://dx.doi.org/10.1016/j.wasman.2010.02.005

ANIP (Associação Nacional da Indústria de Pneumáticos). (2011). *ANIP em números.* Retrieved from http://www.anip.com.br

ASTM. (2011). C144: Standard Specification for Aggregate for Masonry Mortar, USA.

ASTM. (2012a). C780: Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry, USA.

ASTM. (2012b). C1329/C1329M: Standard Specification for Mortar Cement, USA.

ASTM. (2013). C642: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, USA.

Batayneh, M. K., Marie, I., & Asi, I. (2008). Promoting the use of crumb rubber concrete in developing countries. *Waste Management, 28*(11), 2171-2176. http://dx.doi.org/10.1016/j.wasman.2007.09.035

Cabrera, J. G., & Lynsdale, C. J. (1988). A new gas permeameter for measuring the permeability of mortar and concrete. *Magazine of Concrete Research, 40*(144), 177-182. http://dx.doi.org/10.1680/macr.1988.40.144.177

Correia, S. L., Partala, T., Loch, F. C., & Segadães, A. M. (2010). Factorial design used to model the compressive strength of mortars containing recycled rubber. *Composite Structures, 92*(1), 2047-2051. http://dx.doi.org/10.1016/j.compstruct.2009.11.007

Ling, T. C. (2011). Prediction of density and compressive strength for rubberized concrete blocks. *Construction and Building Materials, 25*(1), 4303-4306. http://dx.doi.org/10.1016/j.conbuildmat.2011.04.074

Ling, T. C., Nor, H. M., & Lim, S. K. (2010). Using recycled waste tyres in concrete paving blocks. *Waste and Resource Management, 163*(1), 37-45. http://dx.doi.org/10.1680/warm.2010.163.1.37

Mavrolidou, M., & Figueiredo, J. (2010). Discarded tyre rubber as concrete aggregate: a possible outlet for used tyres. *Global Nest Journal, 12*(4), 359-367.

Meshgin, P., Xi, Y., & Li, Y. (2012). Utilization of phase change materials and rubber particles to improve thermal and mechanical properties of mortar. *Construction and Building Materials, 28*(1), 713-721. http://dx.doi.org/10.1016/j.conbuildmat.2011.10.039

Mujal-Rosas, R., Marin-Genesca, M., Orrit-Prat, J., Rahhali, A., & Colom-Fajula, X. (2011) Dielectric, mechanical, and thermal characterization of high-density polyethylene composites with ground tire rubber. *Journal of Thermoplastic Composite Materials, 25*(5), 537-559. http://dx.doi.org/10.1177/0892705711411344

Nacif, G. L., Panzera, T. H., Strecker, K., Christoforo, A. L., & Paine, K. A. (2013). Investigations on cementitious composites based on rubber particle waste additions. *Materials Research, 16*(2), 259-268. http://dx.doi.org/10.1590/S1516-14392012005000177

Pacheco-Torgal, F., Ding, Y., & Jalali, S. (2012). Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. *Construction and Building Materials, 30*, 714-724. http://dx.doi.org/10.1016/j.conbuildmat.2011.11.047

Pelisser, F., Barcelos, A., Santos, D., Peterson, M., & Bernardin, A. M. (2012). Lightweigth concrete production with low Portland cement consumption. *Journal of Cleaner Production, 23*(11), 68-74. http://dx.doi.org/10.1016/j.jclepro.2011.10.010

Sienklewicz, M., Kucinska-Lipka, J., Janik, H., & Balas, A. (2012). Progress in used tyres management in the European Union: A review. *Waste Management, 32*(10), 1742-1751. http://dx.doi.org/10.1016/j.wasman.2012.05.010

Turgut, P., & Yesilata, B. (2008). Physico-mechanical and thermal performances of newly develop rubber-added bricks. *Energy and Buildings, 40*(1), 679-688. http://dx.doi.org/10.1016/j.enbuild.2007.05.002

WRAP (Waste and Resources Action Programme). (2007). *Tyres: Reuse and recycling.* Banbury, UK.

Wu, J. C. F., & Hamada, M. (2000). *Experiments: planning, analysis, and parameter optimization.* John Wiley & Sons, New York, USA.

Yesilata, B., Bulut, H., & Turgut, P. (2011). Experimental study on thermal behaviour of a building structure using rubberized exterior-walls. *Energy and Buildings, 43*(1), 393-399. http://dx.doi.org/10.1016/j.enbuild.2010.09.031