COMPLETE CHARACTERISITC CURVE OF CONCRETE AND RUBBERIZED CONCRETE

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The complete stress-strain curve, also known as characteristic curve, of brittle materials is difficult to get due to sudden failure of the testing sample shortly after the peak load. The need for a full stress-strain curve is of paramount importance especially since all of today's FEA packages employ such information in their analysis. Concrete is by far the most widely used construction material worldwide. It is inherently brittle and its complete characteristic curve is, to some extent, not yet available. The paper presents the experimental results that led to obtaining all the data required for tracing a full stress-strain curve of traditional concrete. Furthermore, the information is compared to that obtained for rubberized concrete where fine aggregates were replaced by rubber crumbs resulted from tire recycling. The rubberized concrete exhibited a more ductile behavior after peak load but with a penalty on the ultimate strength. The higher the percentage of aggregate replacement, the more ductile the behavior but with smaller compressive strength. Additionally, a decrease in the slope of the linear elastic range of the stress-strain curve was observed. The experimentally obtained curves were compared with the theoretical ones from the existing scientific literature. It was concluded that even though a close match was found, there is room for improvement in the consideration of the post-peak behavior of concrete.

Keywords: stress-strain curve, rubberized concrete, post-peak behavior

INTRODUCTION

The solid waste disposal is a major environmental concern of our days. Considerable amounts of non-biodegradable materials are annually stockpiled in landfills because there are no specific regulations regarding their recovery or because their recycling is not considered an economic alternative (Toma *et al.*, 2013).

Waste generation from post-consumer tires in the EU countries is estimated to stand over 3.5 million tons per year (ETRA, 2010). Only a third of this amount is actually recycled and a similar proportion is incinerated for energy recovery in cement kilns (Siddique and Naik, 2004). However, the remaining waste tires disposed in landfills are an important source of pollution especially when fires break out producing significant air and water pollution.

The use of waste automobile tires in civil engineering applications dates back to the very early ages when automobiles were first invented. Waste tires became natural candidates for construction materials, such as landfills and cushion materials. However, large scale recycling of waste tires in civil engineering applications did not happen until recently. Material recycling tends to be considered all over the world as an alternative solution instead of waste tires disposal. More than 36% of post-consumer tires are recycled in the EU countries and the recycled tire materials are used in more than fifty industries. Less than 10% is used for tire manufacturing.

Compared to their applications in asphalt paving mixtures, the use of recycled tires in Portland cement concrete has been limited (Azizian *et al.*, 2003). The size of waste tires used in concrete ranges from rubber chips (25 mm to 50 mm) to crumb rubber (1 mm to 8 mm) to powders (0.075 mm to less than 1 mm). Waste tire materials replace part of coarse or fine aggregates. The addition of waste tire rubber significantly alters the properties of the concrete (Liu *et al.*, 2013). Due to the hydrophobic nature of rubber, the bond between the untreated rubber particles and hydrated cement is weak, resulting in significant reduction of both compressive and tensile strength of rubber concrete (Topcu, 1995; Huang *et al.*, 2004). On the other hand, concrete becomes more ductile, as illustrated by higher post failure toughness (Li *et al.*, 2004).

Several analytical and laboratory based experimental studies have been performed lately in order to evaluate the mechanical performances of concrete mixes obtained by replacing the mineral (fine or coarse) aggregates with various volume fractions of rubber particles (Ganjian *et al.*, 2009). Generally, a reduction of compressive strength has been observed, but the increase of the ductility recommends the rubberized concrete mix for the construction of highly deformable, but strong enough structural elements (Son *et al.*, 2011). However, a massive replacement of aggregate with rubber particles (more than 15-20%) is not indicated due to the significant reduction of compressive strength (Khaloo *et al.*, 2008).

The obtained results reported in the literature showed that the use of the rubber crumb in construction applications can be a viable solution for post-consumer tires recycling (Pacheco-Torgal *et al.*, 2012).

The paper presents the experimental results that led to obtaining all the data required for tracing a full stress-strain curve of traditional concrete. Furthermore, the information is compared to that obtained for rubberized concrete where fine aggregates were replaced by rubber crumbs resulted from tire recycling. The rubberized concrete exhibited a more ductile behavior after peak load but with a penalty on the ultimate strength.

MATERIALS AND EXPERIMENTAL SET-UP

Materials

The cement used was a type I, 42.5R cement, with rapid hardening. It is a general purpose cement being suitable for all uses in works requiring high strength values at early ages. The target concrete strength class was C28/35, normally used for screeds.

The aggregates consisted of river gravel, having rounded edges. The aggregates were used in two different sorts based on their size: 4-8 mm and 8-16mm. For the rubberized concrete, 10% volume fraction of the sand (0-4mm) was replaced by rubber crumbs resulted from tire shredding process and subsequent sieving. The rubber crumbs were inspected for the presence of steel beads and traces of textile materials that were part of the original tire but the samples provided by the manufacturer were clean of those impurities. The mix proportions considered at this stage of the research are presented in Table 1.

Experimental Set-Up

A total number of 120, 100×200 mm, cylinders were cast for the two mix proportions shown in Table 1. After demoulding, the cylinders were kept in water until the day of testing, in accordance with SR EN 12390-2 (2009) specifications. Prior to testing, each cylinder was measured and weighed in order to determine the hardened density of normal and rubber-concrete.

The mechanical and elastic properties of concretes made with the mix proportions shown in Table 1 were determined as follows: the uniaxial compressive strength was determined on 30 specimens following the recommendations of SR EN 12390-3 (2009) code, the static modulus of elasticity was determined on 29 of the 30 cylinders used for uniaxial compression according to BS EN 12390-13 (2013) recommendations, the splitting tensile strength was determined on 20 cylinders in accordance with SR EN 12390-6 (2010) code. The complete stress-strain curve was determined on the remaining 10 cylinders.

Figure 1 shows the equipment used to assess the modulus of elasticity in compression, whereas Figure 2 presents a typical load-displacement curve used to evaluate the modulus of elasticity.

Table 1. Mix proportions for normal and rubberized concrete

Mix name	Cement	Sand	Aggregates		Rubber	Water	W/C ratio	Superplasticizer
			4-8 mm	8-16mm				
	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[l/m^3]	-	[l/m^3]
Ref.	335	847	491	532	-	185	0.55	3.35
Mix10%	335	830.87	491	532	16.13	185		

Figure 1. Measuring modulus of elasticity in compression

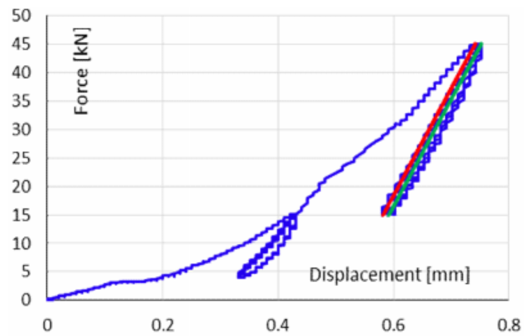

Figure 2. Load-displacement curve according to BS EN 12390-13 (2013)

The complete stress-strain curve was determined by using a special patented device (Negoita *et al.*, 1980), the purpose of which is to transform a force-controlled testing procedure into a displacement-control. The latter is a more suitable testing method in case in brittle materials, especially when the post-peak behavior is of interest.

RESULTS AND DISCUSSIONS

Strength and Elastic Characteristics

Table 2 presents the mechanical characteristics of the considered mix proportions. It can be observed that by replacing the sand with rubber crumbs leads to a penalty in terms of both compressive and splitting tensile strength by 7.38% and 15.64%, respectively. The obtained results are in line with the ones obtained on similar mix proportions and reported in the scientific literature (Issa and Salem, 2013). The traceability of the experimental results is quite good considering that the values of the coefficient of variation (COV) is below 10% and the number of data entries used for the statistical processing was at least 30.

Figure 3 shows the evolution of the modulus of elasticity as function of the curing age of the cylinders. It can be observed that in the case of the reference mix, the modulus of elasticity reaches its prescribed value for the corresponding concrete class at the age of 14 days and remains almost constant until the age of 28 days.

Table 2. Mechanical characteristics of normal and rubberized concrete

Mix name	Density [kg/m^3]	COV [%]	Compressive strength, f_{ck} [N/mm^2]	COV [%]	Splitting tensile strength, f_t [N/mm^2]	COV [l/m^3]
Ref.	2435	0.63	33.46	6.2	2.75	8.91
Mix10%	2350	1.05	30.99	5.4	2.32	6.33

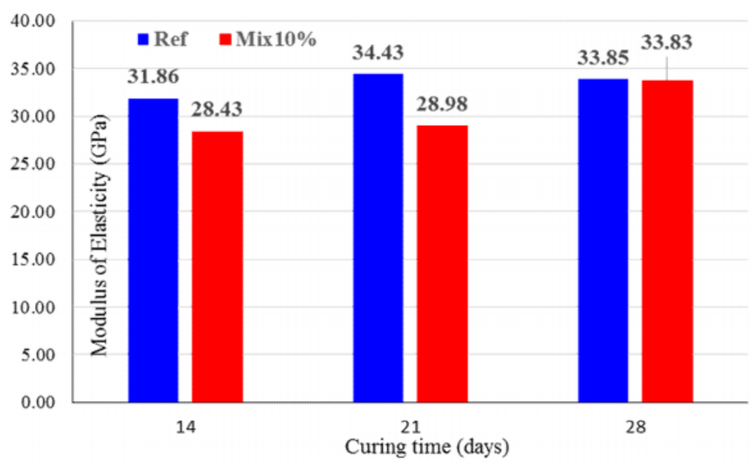

Figure 3. Modulus of elasticity as function of curing time

The rubberized concrete, however, exhibits a continuously increasing trend in the values for the modulus of elasticity from 14 to 28 days, reaching a similar value to the reference mix.

Based on the obtained results it can be concluded that the influence of rubber addition on the elastic properties of concrete is significant only during the early stages of curing when the concrete is not completely hardened. Once the hardening process is complete, the influence of rubber upon the modulus of elasticity is very small. This is, however, valid for small percentages of rubber crumbs taking into account that in this case the rubber content is less than 4%, volume fraction, of the total volume.

Stress-Strain Curve

The complete stress-strain normalized curves of normal and rubberized concrete are shown in Figure 4. As expected, the rubberized-concrete is able to dissipate more energy, especially in the post-peak region. The strain energy stored in the samples made of rubberized concrete is 10.5% larger than the ones stored in the cylinders made from the reference mix. This means that structural elements made of rubberized concrete can dissipate more energy compared to their counterparts made of traditional concrete. More energy dissipation would improve seismic safety of concrete structures such as bridges and buildings. Similar results were reported by Xue and Shinozuka (2013).

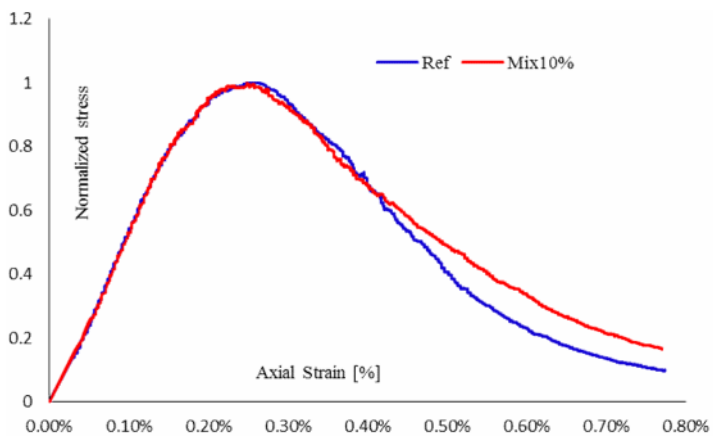

Figure 4. Normalized stress-strain curves for concrete and rubberized concrete

CONCLUSIONS

The ever-increasing volume of rubber waste in landfills from the disposal of used tires has grown into a serious environmental problem. For both environmental and economic reasons, there is renewed interest in developing alternatives to disposal. The paper presents preliminary findings, from a long series of experimental investigations, on the complete stress-strain curve of normal and rubberized concrete as well as their mechanical properties. Based on the obtained results, the following conclusions can be drawn:

The addition of rubber particles, in small percentages, does not seem to significantly alter the compressive strength and the modulus of elasticity at the age of 28 days. The latter has a continuously increasing trend compared to the one obtained for the reference mix which exhibits an almost constant value between 14 days and 28 days. The splitting tensile strength, however, decreases by as much as 15% for rubberized concrete.

The real benefit from adding tire rubber crumbs comes in the form of decreased density and a 10.5% higher energy dissipation capacity. More energy dissipation would improve seismic safety of concrete structures such as bridges and buildings.

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