Pergamon

Cement and Concrete Research 32 (2002) 1587–1596

CEMENT AND CONCRETE RESEARCH

Static and dynamic behaviour of recycled tyre rubber-filled concrete

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Received 8 January 2002; accepted 16 April 2002

Abstract

The paper summarises the experimental results of mechanical behaviour under static and dynamic loads of specimens made of concrete filled with small volumetric fractions of crushed tyre rubber and polypropylene short fibres, at 7 and 28 days. The experimental results are compared with results of concrete specimens of similar features without fibres or tyre. The results of a microscopic study (SEM) of the interface cement–rubber fiber are included in order to analyze their compatibility. Compression, indirect tension and bending static tests and compression dynamic tests have been performed. The results of the dynamic tests have been used to calculate the complex modulus and the capacity of this material to dissipate elastic energy due to low-frequency dynamic actions. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: SEM; Mechanical properties; Waste management; Rubber-filled concrete

1. Introduction

Concrete pavements are scarce both in Spain and in Europe, as a general rule. Nevertheless, there exists increasing interest in its application for traffic pavements, mainly promoted by the cement industry.

The most important difficulties for this application are the rigid behaviour of the concrete slabs and its easy-to-crack characteristic at early ages due to plastic shrinkage. Concrete pavements are noisy in highroad mainly due to its high Young modulus and low viscous damping. The plastic cracking can be avoided with the addition of a very small volume fraction of short polypropylene (PP) fibres (0.1%), but the rigid behaviour of compacted rolled concrete remains as an important problem.

A lot of expensive solutions can be proposed to increase the damping properties of concrete pavements: the addition of bituminous or elastomeric products, for instance. In this paper, another nonexpensive solution, and quite interesting from an ecological point of view, is explored: the addition of short fibres of crumbed waste tyres to the fresh concrete, in different volume fractions.

The important contaminant effect of tyres waste is well known. Some people propose to use it as fuel material for the cement industries. Other construction products are based on rubber powder obtained from the cryogenic milling of tyres, mixed with asphalt or bituminous materials.

Some papers presented partial results of the mechanical behaviour of the concrete filled with small volumetric fractions of crumbed tyre rubber (also called rubberised concrete) [1–5], but few of them contained dynamic experimental results [6]. In this paper, some dynamic results with different volume fractions of fiber, frequencies and temperatures are presented. The results of the dynamic tests were used to calculate the complex modulus and the capacity of this material to dissipate elastic energy due to low-frequency dynamic actions.

Linked to this research, an experimental traffic road was built in a residential area in Gudino, near Salamanca (Spain), made of concrete filled with small volumetric fractions of crumbed tyre rubber. After 3 years of heavy use (cars and trucks), it still shows a very good performance [7].

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PII: S0008-8846(02)00833-5

2. Materials

The materials used in the performance of the specimens have been selected in accordance with the concrete manufacturer company, PAS. The composition correspondent with a set of nine cylindrical specimens (15 × 30 cm) was:

Cement CEM I-42.5 R	20.6 kg
Water	8.414 l
Coarse aggregate, 12/18 mm	63.164 kg
Sand, 3/6 mm	40.052 kg
Fine aggregate, 0/3 mm	11.06 kg
Superplasticizer (Sikament 500)	411 g
Retarder (Bettoretard)	60 g
PP	51.5 g
Rubber (3.5 vol.%)	2.051 kg

In the concretes with 5 vol.% rubber concrete, only the amount of rubber was changed, maintaining the proportion of all the other materials. It must be noted that fiber proportions always refer to volumetric fraction.

The company PAS (Salamanca, Spain) nsupplied the aggregates from their own quarries. The PP was provided by FIBERMESH (Chattanooga, USA). It is a meshed fiber, MD Code 6891, 100% virgin. It was composed of short fiber plane sheaf, between 12 and 19 mm long. This presentation eased its mixture with concrete and avoided the development of balls during the process. This fiber is chemically passive and is not affected by water and cement hydration reactions. Its main function was to prevent cracking of fresh concrete due to plastic shrinkage, between the fourth and the eighth hours after the beginning of the setting process. Due to the small amount of PP introduced in the composition, no influence in the mechanical features could be expected. The properties of the PP fiber are:

Density	0.91 g/cm^3
Water absorption	None
Flammable temperature	590 °C
Tension strength	Between 560 and 770 MPa
Young modulus	3500 MPa

Rubber crumbed fiber came from used truck tyres castaway after a second recapping. Strip process produced short fibres between 0.85 and 2.15 cm long, with an average of 1.25 cm. Their surfaces were rough and damaged due to the cutting process. They contained 4% of fine dust particles, retained by the 1.6 mm sieve, that acted as airing particles. The apparent density of rubber fiber was 0.84 g/cm^3 and they had a water absorption coefficient of 25%, with a natural humidity of 6.25%. The fiber contained iron impurities with a maximum value of 0.05% of weight. The fiber-softening point temperature was determined at 175 °C and combustion occurred at 200 °C.

Other nominal properties of crumbed truck tyre rubber are [8]:

Young modulus	
at 100%	1.97 MPa
at 300%	10 MPa
at 500%	22.36 MPa
Tension strength	28.1 MPa
Strength at failure	590%
Resilience	
at 23 °C	44%
at 75 °C	55%

3. Rubber–hydrated cement interaction

Simultaneously with mechanical tests, a microscopic study (SEM) was performed. It was carried out at the Microscopy Laboratory of the Interdepartmental Research Service of the Universidad Autónoma de Madrid, on samples extracted from the 5 vol.% of rubber fiber-bending specimens. EDAX analysis of the samples (cement and the surface of the fiber) was also performed (Fig. 1).

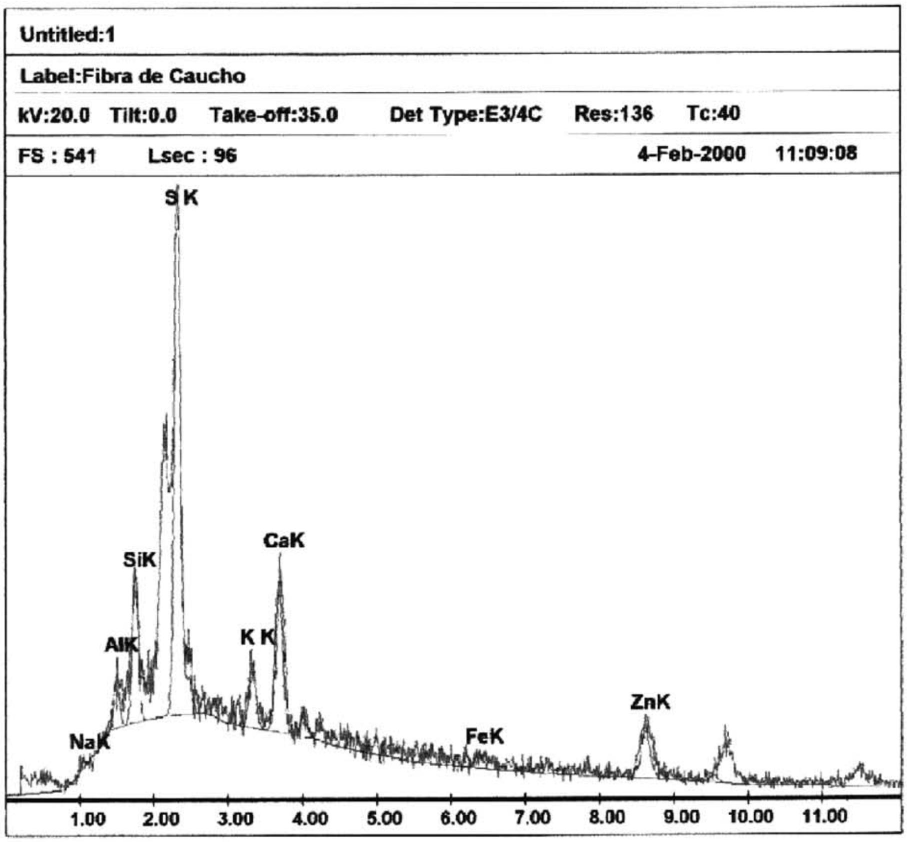
In the first micrography (Fig. 2), the perfect adherence between rubber and cement matrix can be observed. The EDAX analysis of the cement reported standard values.

The second micrography (Fig. 3) shows in detail the surface of the fiber in contact with the cement matrix. A high concentration of calcium oxide crystals on the surface and the presence of silicon and aluminium oxides were observed. It meant that there was a perfect bond between rubber and hydrated cement products, producing an interface different from both components that creates an adequate joint between them. No different damage was observed.

4. Mechanical static test results

The results of the compression, indirect tension and bending tests on specimens with and without fiber at 7 and 28 days of age are described. These values were obtained after performing 16 mixtures, half with fiber and the other half without it, corresponding with 18 sets of three specimens each. Cylindrical (15 × 30 cm) specimens were manufactured for compression and indirect tension tests. Two types of specimens, 10 × 10 × 40 cm and standard 15 × 15 × 60 cm, were performed for bending tests. A statistical study of characteristic bending strength was carried out with the standard specimens. An analysis of crack control capacity of the rubber fiber was developed with the nonstandard specimens, using compositions with fiber (3.5 and 5 vol.%) and without it.

The results of the sets of specimens tested under compression (Fig. 4) show that short rubber fiber-filled concrete had a characteristic compressive strength 23 MPa, while in



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
NaK	2.85	4.58	0.0088	1.0189	0.3030	1.0029
AlK	5.17	7.08	0.0255	1.0132	0.4818	1.0093
SiK	10.53	13.84	0.0637	1.0425	0.5736	1.0118
S K	37.04	42.67	0.2776	1.0392	0.7179	1.0046
K K	5.05	4.77	0.0391	0.9950	0.7692	1.0117
CaK	12.80	11.80	0.1057	1.0176	0.8092	1.0028
FeK	2.71	1.79	0.0248	0.9279	0.9584	1.0293
ZnK	23.85	13.47	0.2118	0.8989	0.9882	1.0000
Total	100.00	100.00				

Fig. 1. EDAX spectrum of rubber–concrete matrix interface.

plain concrete it was 36 MPa. The average compression values were 29 and 40 MPa, respectively.

The results of the sets of specimens tested under indirect tension, Brazilian method (Fig. 5), showed that rubber fiber-filled concrete had a characteristic strength at 28 days and 95% confidence of 2.3 MPa, while in plain concrete it was 2.8 MPa. The average values were 3 and 3.4 MPa, respectively.

The results of the sets of specimens experimented under standard bending tests (Fig. 6) showed that rubber fiber-filled concrete had a characteristic strength at 28 days and 95% confidence of 4 MPa, while in plain concrete it was 5.4 MPa. The average values were 5.2 and 6.1 MPa, respectively.

In the graphics stress–strain of the 10 × 10 × 40 cm bending specimens, with and without fiber (Fig. 7), a clear difference on the behaviour when maximum strength was overcome could be observed. When there was no fiber, a brittle failure occurred, while the addition of fiber produced a slight decrease of strength but without the separation of the crack edges.

5. Dynamic compression test results

When a periodic load is applied, in this case a compressive load, on a material that shows relaxation, as what

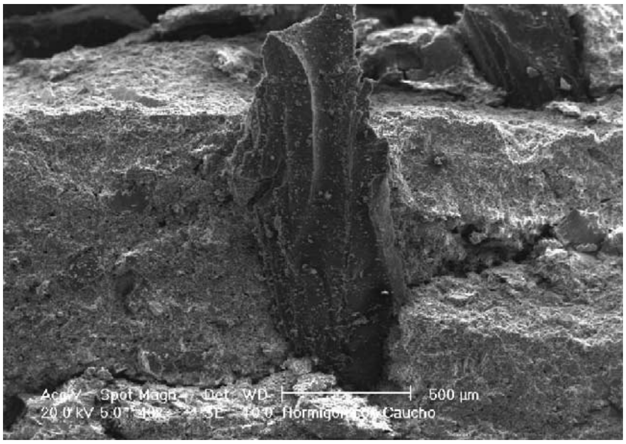


Fig. 2. Micrography of rubber particle inside the concrete matrix.

happens on rubber fiber-filled concrete, the strain effect appears delayed with regard to the moment when the load is applied. This delay on the deformation is a direct consequence of the internal nature of the material, partially polymeric. It can be described by a phase shift coefficient associated with the temporal dependence of stress and strain, in the way it will be described, according to the tests performed [9].

Expressing the periodic compressive stress in a complex way, we have (Eq. (1)):

$$\sigma^* = \sigma_0 e^{i\omega t} \tag{1}$$

where σ_0 is the amplitude of the compressive stress and ω is the angular frequency (rad/s) of the applied load. The unitary complex deformation would be (Eq. (2)):

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \delta)} \tag{2}$$

where ε_0 is the maximum amplitude of the unitary deformation and δ is the phase shift coefficient that expresses the delay between strain and stress. The relationship between stress and strain would be (Eq. (3)):

$$\sigma = E^*\varepsilon^* = (E' + iE'')\varepsilon^* \tag{3}$$

where E^* is the Young complex modulus (Eq. (4)):

$$E^* = E' + iE'' \tag{4}$$

and E' and E'' are the real and imaginary components, respectively. Substituting the temporal dependence (Eq. (5)):

$$\sigma_0 = E^*\varepsilon_0 e^{-i\delta}. \tag{5}$$

The modulus of this relation can be expressed in complex variables (Eq. (6)):

$$|\sigma_0| = |E^*|\varepsilon_0 \Rightarrow |E^*| = E_0. \tag{6}$$

This means that the absolute value of the Young complex modulus coincides with the value of the Young dynamic modulus, E_0. Also, from relation (7):

$$E' + iE'' = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = E_0(\cos\delta + i\sin\delta) \tag{7}$$

it can be deduced that (Eq. (8)):

$$E' = E_0\cos\delta \tag{8}$$

$$E'' = E_0\sin\delta.$$

Also (Eq. (9)):

$$\tan\delta = \frac{E''}{E'}. \tag{9}$$

The compression dynamic test allows the experimental measurement of load, strain and phase shift coefficient, and either the instant values or the stress and strain amplitudes (σ_0,ε_0), respectively. Through this mathematical deduction, experimental values of σ_0 ,ε_0 and $\tan\delta$, which are related with Young dynamic modulus $E_0 = \sigma_0/\varepsilon_0$, give a value of the real and imaginary parts of the Young complex modulus.

Experimental dynamic measurements with standard specimens (15×30 cm) at 7 and 28 days, with 3.5% and 5% of recycled truck tyres rubber fiber contents, were performed. Each group of measurements was carried out on sets of three specimens and the values recorded on the graphics are average values.

Fig. 8 shows the measured values of the Young dynamic modules, corresponding with 5, 10 and 20 Hz frequencies. A clear dependence can be observed, either the specimen characteristics or the test frequencies. Dynamic modules were lower at 7 days than at 28 days, that is, in principle, obvious due to the endurance process of the concrete matrix, enlarging the stiffness of the material. Concrete with 5% of rubber in its composition had, in all cases, a lower dynamic

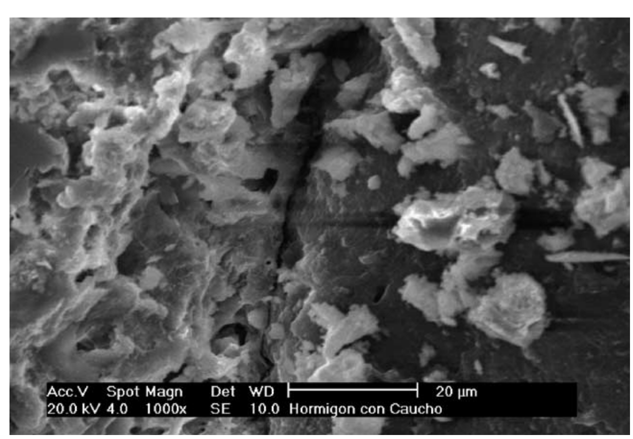


Fig. 3. Micrography of rubber–concrete matrix interface.

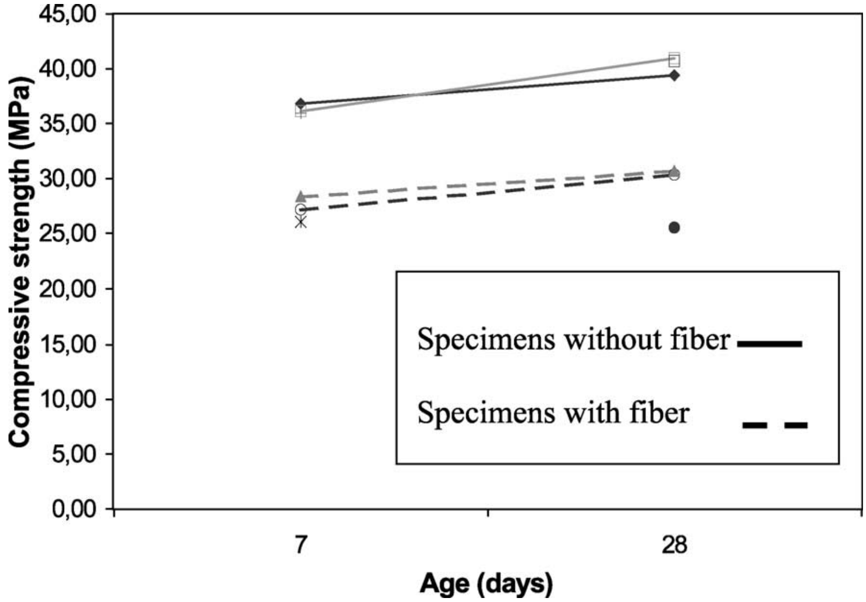


Fig. 4. Compressive strength at 7 and 28 days.

modulus than 3.5% rubber fiber concrete. This result is maintained with age (at 7 and 28 days). Finally, Young dynamic modulus was sensitive to the load application frequency. It increased slightly with the increase of frequency.

The energy dissipated by this material, in viscoelastic regime and under compressive dynamic load, is another aspect to analyze. This material is able to dissipate elastic energy, without damage. Dynamic tests were performed by applying a load in the viscoelastic range of concrete, so that the amplitude of stress did not overcome 30% of the compressive elastic limit of concrete.

For determining the dissipated energy, calculations are presented. W can be defined as the elastic energy absorbed by a specimen in a quarter of cycle—from $t=0$ to $t=(1/4)(2\pi/\omega)$—in the compressive dynamic test:

$$W = \int_0^{\frac{\pi}{2\omega}} \sigma \frac{d\varepsilon}{dt} dt. \tag{10}$$

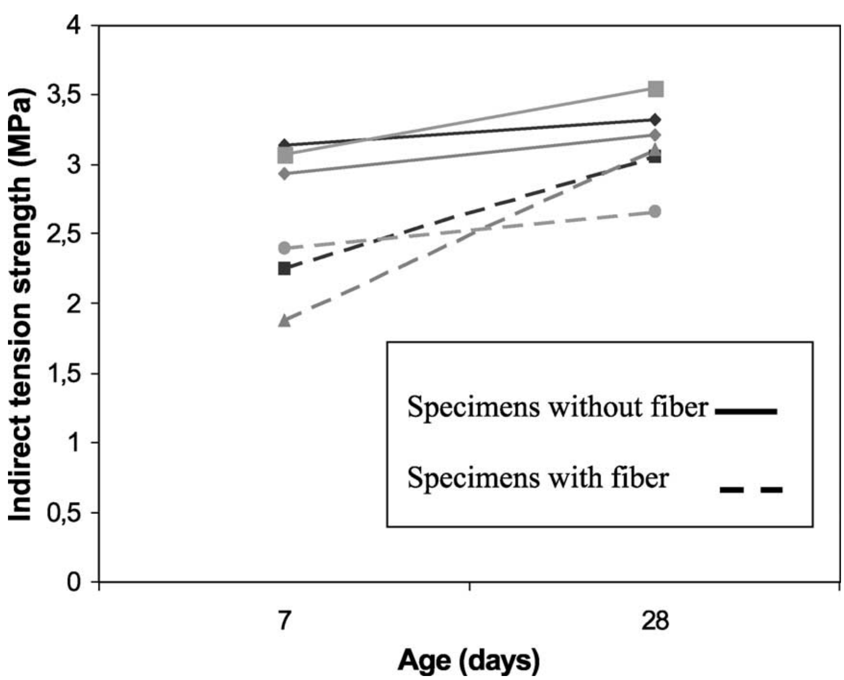


Fig. 5. Indirect tension strength at 7 and 28 days.

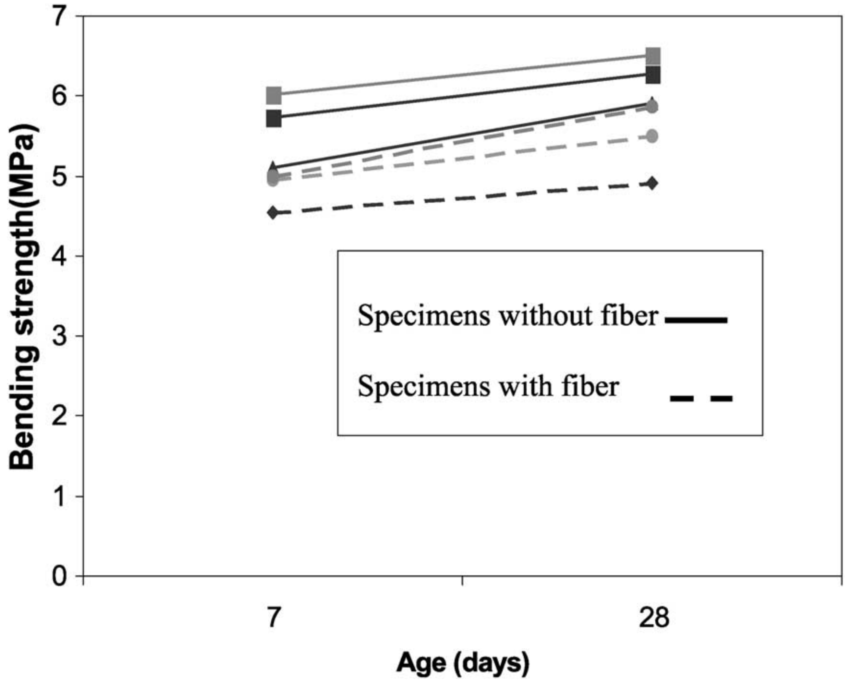


Fig. 6. Bending strength at 7 and 28 days.

Substituting $\sigma = \sigma_0 \mathrm{sen}(\omega t)$, $\varepsilon = \varepsilon_0 \cos(\omega t - \delta)$, the following can be obtained:

$$W = \sigma_0 \varepsilon_0 \left[\frac{\cos\delta}{2} + \frac{\pi \sin\delta}{4} \right]. \quad (11)$$

The expression in brackets in Eq. (11) is the density of mechanical energy dissipated in a quarter of cycle. If $\delta = 0$ disappears, this expression is null. $\sigma_0 \varepsilon_0$ corresponds with the maximum density of elastic energy stored in the specimen in that quarter of cycle. When a whole cycle is taken into account, the elastic energy stored is null, evidently. But, designating as ΔW the elastic energy dissipated in a cycle and as W_a the maximum density of elastic stored energy (it would correspond with the first half of the cycle: the load stage), Eq. (12) can be obtained:

$$\frac{\Delta W}{W_a} = 2\pi \tan\delta. \quad (12)$$

It can also be expressed in the next form (Eq. (13)):

$$\Delta W = \pi \sigma_0 \varepsilon_0 \sin(\delta) = \pi \varepsilon_0^2 E''. \quad (13)$$

The relation $\Delta W / W_a$ is denominated as specific loss.

Fig. 9 presents the values of $\Delta W / W_a$ for the tested specimen sets under dynamic compressive load. It shows the percentage of the dissipated energy with regard to maximum elastic energy stored under load. A clear dependence on age, frequency and fiber volumetric fraction can be observed. Younger specimens dissipated more energy than older ones, due to the increase of stiffness with age. Under 20 Hz of frequency, dissipated energy was larger than under 5 or 10 Hz. Specimens with higher fiber volumetric fraction (5%) dissipated more energy than lower contents of fiber (3.5%). In all cases, the high percentage of the specific energy dissipated (between 23% and 30%), which makes this material with high contents of recycled tyre rubber an optimal candidate for absorbing and dissipating energy under dynamic actions without damage, can be highlighted.

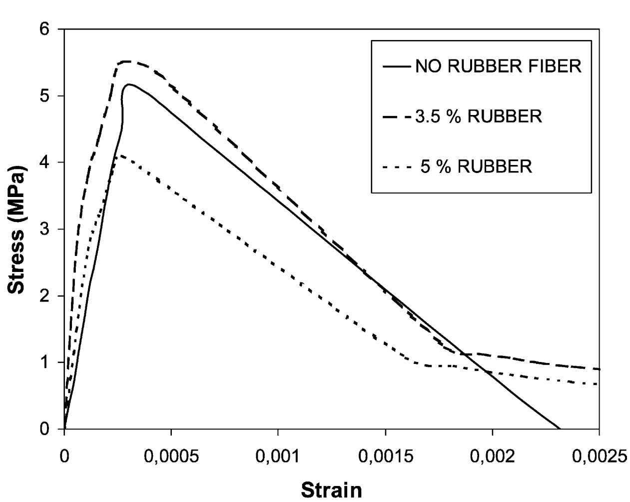


Fig. 7. Static bending tests. Stress–strain graphics with different compositions.

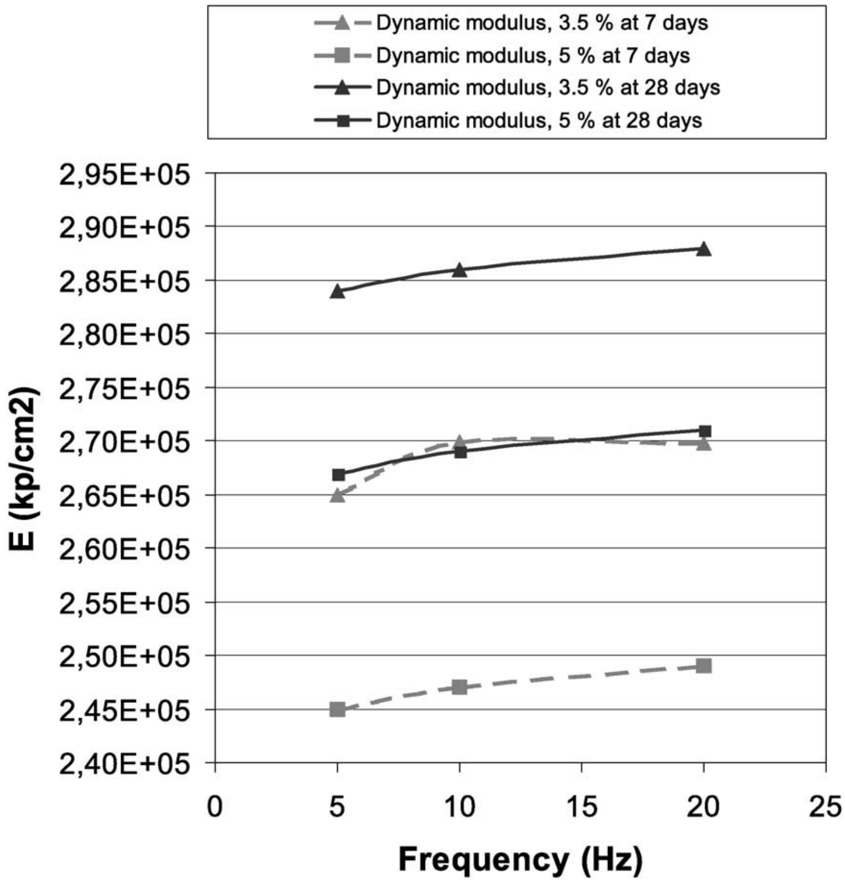


Fig. 8. Young dynamic modulus as function of frequency, age and rubber volumetric fraction.

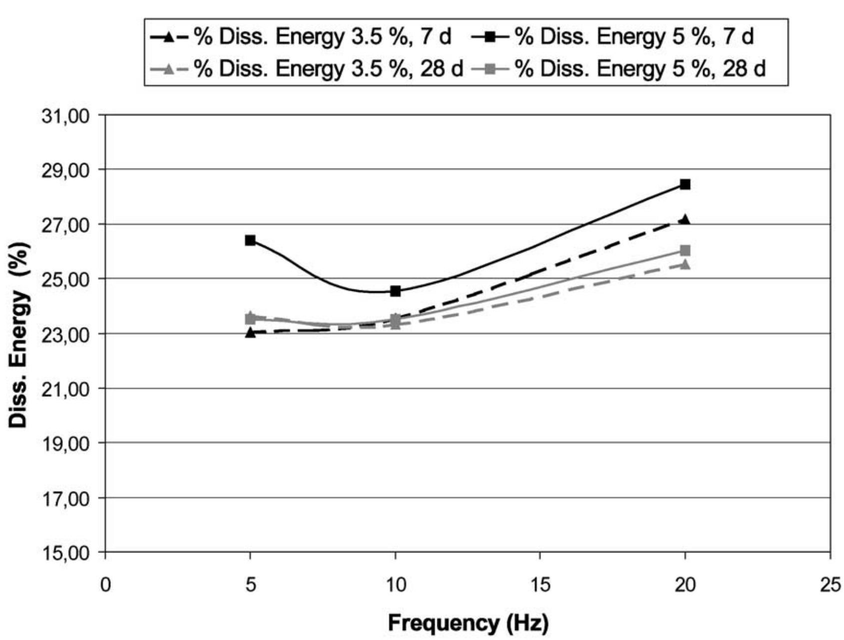


Fig. 9. Dissipated energy as function of frequency.

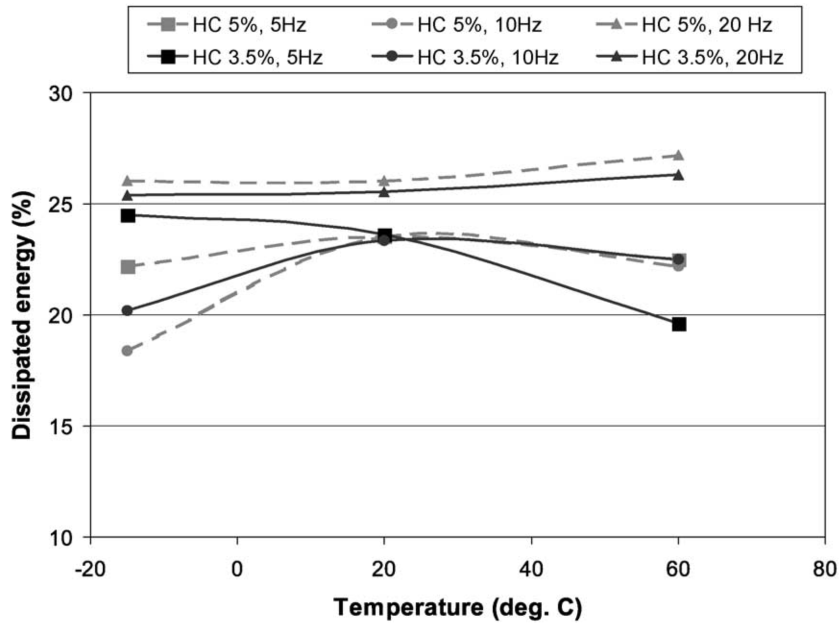


Fig. 10. Dissipated energy as function of temperature.

5.1. Temperature influence

Dynamic compression tests were performed on cylindrical 3.5 and 5 vol.% rubber short fiber-filled concrete specimens at -15, 20 and 60 °C, at 28 days. Specific dissipated energy, tanδ, Young dynamic modulus and real and imaginary Young complex modulus components were measured or calculated. The results are represented in graphics (Figs. 10 and 11).

Fig. 10 presents the variation of the dissipated energy percentage as a function of the testing temperature. It can be observed that maximum dissipation occurred under higher frequencies (20 Hz) and it was low thermal sensitive. Once again, specimens with higher rubber content (5 vol.%) showed larger dissipated energy percentages than lower rubber content ones (3.5 vol.%). Dissipated energy was slightly lower under lower frequencies. It can be emphasised that there was a coincident result at 20 °C under 5 and 10 Hz, whatever the rubber content was. At high temperature (60 °C), maximum energy dissipation occurred under higher frequencies (20 Hz) and higher rubber contents. At low temperature (-15 °C), there was a larger scatter of results and an inverse behaviour with regard to frequencies: higher dissipation happened at lower frequencies and, at each frequency,

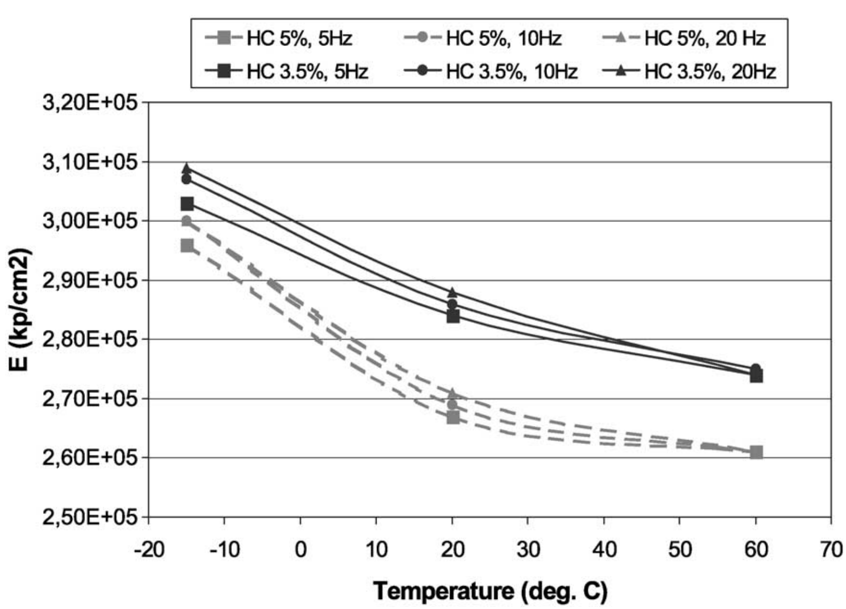


Fig. 11. Young dynamic modulus as function of temperature.

dissipation was larger as rubber content decreased. This behaviour was inverse than at high temperature. This result should be confirmed with more tests in order to extract general conclusions.

The variation of Young dynamic modulus with temperature (Fig. 11) showed a characteristic behaviour. At 60 °C, there was low scatter of results, increasing as temperature decreases. At − 15 °C, 3.5% and 5% rubber fiber volumetric fraction results were quite similar, although, as temperature increased, rubber volumetric fraction determined the behaviour of the composite material.

6. Discussion

The statistical study of compressive, indirect tension (Brazilian method) and four point-bending strength on standard specimens with and without fiber reinforcement concrete at 7 and 28 days showed an admissible dispersion of results, taking into account the nature of the material. The result distributions of the tested specimen sets fit in the majority of the cases with normal patterns of distribution.

In general, rubber fiber-filled specimens show larger result dispersions than sets without fiber, and the Gauss distribution is wider in the first case than in the second. It means that rubber fiber-filled concrete is less reliable than concrete without fiber and maximum compressive strength decreases slightly. Density drops also when rubber fiber is included in the composition with regard to plain concrete density.

Results obtained under three-point static bending load showed small differences either of elasticity modulus or maximum bending strength at the ages and fiber volumetric fractions tested. The largest difference appeared in the stress–strain plot, after maximum stress (cracks growing inside concrete matrix), where the graphic continues if concrete contains fiber. In concrete without fiber, the first crack propagated immediately, provoking instant failure, although in rubber fiber-filled concrete, fiber maintained the sides of the crack together, allowing the material to retain a part of the load at large displacements.

The behaviour of short rubber fiber-filled concrete under dynamic compressive load responded to typical concrete parameters. It means that, with fiber volumetric fractions tested, rubber fiber had no significant influence on the composite material response under compressive dynamic load. Due to the high stiffness of the material, the delay between load application and strain response of the material recorded was quite reduced. It implies that complex compressive modulus is very similar to dynamic compressive modulus. The imaginary component of complex modulus was around 20 times less than the real component because it depends on the sine of the phase angle. The variations of dynamic modulus with regard to temperature, age and rubber fiber volumetric fraction indicated that the behaviour of the composite material is quite similar to that of plain concrete. It can be said that the elastic branch of the stress–strain curve is directly related with the concrete matrix mechanical characteristics. In all cases, the high percentage of the specific energy dissipated (between 23% and 30%), which makes this material with high contents of recycled tyre rubber an optimal candidate for absorbing and dissipating energy under dynamic actions without damage, can be highlighted.

7. Conclusions

The addition of crumbed tyre rubber volume fractions up to 5% in a cement matrix does not imply a significant variation of the concrete mechanical features, either maximum stresses or elastic modulus.

Analyzing the variations on the modules experimentally obtained either under static or dynamic load, it can be observed that they increase with age and decrease as the fiber content or temperature increases. It can be concluded that the elastic branch of the plot stress–strain refers to the concrete matrix. In fact, the inclusion of fiber implies defects in the internal structure of the composite material, producing a reduction of strength and a decrease of stiffness. But when maximum strength is overcome, fiber collaborates with concrete, avoiding the opening of the cracks and therefore increasing the energy absorbed by strain (toughness) and the breaking of concrete. This feature of the composite can be assigned to the stiffness difference (modulus of elasticity) of the compounds (30 GPa for the concrete matrix and 10 times less for the rubber).

The microscopic study about the rubber–cement interface shows the crystallisation of calcium compounds on the surface of the rubber fiber. The spectrum records a high concentration of calcium oxides on the surface coming from hydration products of cement (rubber has no calcium in its composition). Therefore, it can be said that hydrated cement reacts with the rubber fiber exterior surface and a diffusion of the hydrated products happens, specially the ones with high calcium oxides content.

Acknowledgments

The authors want to acknowledge the human and technical support supplied by PAS, and also J. García Carretero of the Roads Laboratory of CEDEX and E. Salvador of SIDI, UAM. Some of the results presented correspond to a project partially supported by CDTI.

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