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Positive synergy between steel-fibres and rubber aggregates: Effect on the resistance of cement-based mortars to shrinkage cracking

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Abstract

Cement-based materials suffer from their low tensile strength and their poor straining capacity: they are sensitive to cracking, particularly shrinkage cracking. Enhancing the cracking resistance of cementitious materials is the challenge of a broad ongoing research programme. In this regard, the aim of the present work was the design of a cement composite exhibiting a high straining capacity before macrocracking localisation. It was assumed that incorporation of aggregates with low elastic modulus could be a solution. Actually rubber aggregates obtained from shredded non-reusable tyres were used, conferring an environmental interest on the study.

After a previous contribution focusing on the basic mechanical properties of rubberised mortar, the purpose of this paper is to present the influence of rubber aggregates on the load–deflection relationship of mortar in flexure. The synergy between rubber aggregate substitution and metal–fibre reinforcement was also investigated. Despite the low strength and high shrinkage length change of rubberised mortars, ring-tests showed that the composite materials exhibited an enhanced resistance to shrinkage cracking. In this regard, a positive synergy effect between rubber aggregates and steel-fibres was evidenced: shrinkage cracking was delayed and when it occurred, multiple cracking with thinner crack openings was observed.

Keywords: Rubber aggregates; Fibre reinforcement; Mechanical properties; Tensile properties; Shrinkage

1. Introduction

The brittleness and low tensile strength of cement-based materials are detrimental to their durability. Such materials, the prominent construction materials, are sensitive to cracking. They particularly suffer from shrinkage cracking, especially when the shrinkage is restrained. A typical example is the one of large area structures such as slabs on grade. Are also affected: toppings, linings and cement-based overlays. Their cracking induces debonding, the latter being the main cause limiting their durability [1–4]. Common solutions, such as reinforcement by fibres or steel bars, remain imperfect since they do not prevent cracking but restrain the crack openings. Sawed joints are also used to mask disorders by localising the cracking. However they can be the starting point of future distress. In such conditions a perfect solution would be to design cement-based materials exhibiting an enhanced capacity for deformation before cracking. In the present work, it was hypothesised that incorporating aggregates with low elastic modulus would provide this material performance.

Rubber aggregates obtained from shredded non-reusable tyres were chosen, conferring a second facet to the work: an opportunity to recycle rubber tyres, thus helping to meet the demand for a clean environment. It is an opportune coincidence that a French law prohibiting the dumping of scrap tyres came into force in December 2002, a year for which, of a total of 390,000 tons of used tyres produced in France, about 25% were disposed of without control.

2. Materials studied

The cement-based material studied was a mortar; the composition of the control mix is presented in Table 1. CEM

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Table 1
Control mix composition, 0R0F (values in kg/m^3)

Cement	Sand	Water	Colloidal admixture	Superplasticiser
500	1600	250	0.8	3

I 52.5R Portland cement and dried natural river sand aggregates were used. Rubberised mortars were obtained by partly replacing a volume of sand by the same volume of rubber aggregates. Two substitution rates, 20 and 30% of the total volume of aggregates, were investigated. The limitation of rubber aggregate substitution to 30% will be justified later with regard to the impact on the mechanical performance of the composite. Sand and rubber aggregates have a similar maximum grain size of 4 mm. Due to their lower specific gravity, 1.2, rubber aggregates are highly sensitive to gravitational segregation. Thanks to a colloidal admixture designed to increase the mix cohesion, such segregation was prevented. In order to eliminate the colloidal admixture's effects from the analysis, it was also used in all mixes without rubber aggregates. A melamine formol based superplasticiser was also used to control workability.

Concerning the fibre reinforcement, two contents, 20 and 40 kg/m^3 were investigated. Straight steel wire fibres, 13 mm in length and 0.20 mm in diameter, developed for concrete and mortar, were used. Their tensile strength was 2600 MPa and a copper coating, applied as a lubricant for wire drawing, gave them a bright aspect.

The different mixes will be designated using their level of rubber aggregate substitution and fibre content. The letters R and F refer to Rubber and Fibres respectively. For instance 30R or 40F designates 30% rubber aggregate content or an addition of 40 kg/m^3 of fibres.

3. Previous findings on basic mechanical properties of rubberised mortars

Previous studies [5,6] to determine the basic mechanical properties (compressive and tensile strengths, σ_c and σ_t; and compressive and tensile elastic moduli, E_c and E_t) are summarised in Table 2.

Such results confirm well known tendencies [7–12]: rubber aggregate incorporation is highly detrimental to compressive and tensile strengths, and rubberised composites exhibit a reduced elastic modulus. For instance, results in Table 2 show that 30% rubber substitution induces a drop of about 80%, 60% and 65% respectively in compressive strength, tensile strength and elastic modulus.

It is clear that the low compressive strength of cement-based materials incorporating rubber aggregates is a major handicap to some civil engineering applications. However niches applications may exist where reduced compressive strength would be tolerable if high strain capacity and improved resistance to shrinkage cracking could be realized. Such applications include repair, resurfacing or lining, sidewalk and in some cases of slabs on soil.

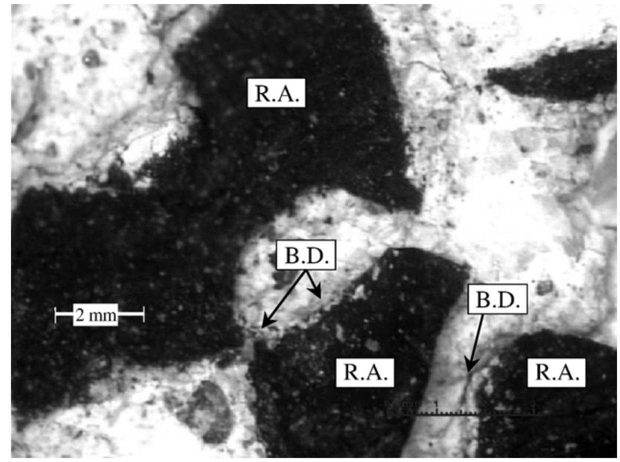

Fig. 1. Bond defect (B.D.) between rubber aggregates (R.A.) and cement matrix.

The detrimental effect on the composite strength can be explained in different ways notably by the low stiffness of rubber aggregates. However, the statement classifying rubber aggregates as large pores [10] is quite misleading since the bulk modulus of vulcanised rubber is about 1 GPa. Further, rubber aggregates, unlike pores, contribute to the transfer of stresses when an external load is applied to rubberised composites.

Bond defects between rubber aggregates and the matrix are often proposed to explain the low strength of the material. To confirm such assertion, we examined a specimen cured for 28 days at 20 °C and at 100% R.H. After curing the specimen was sawn under wet conditions and we observed the obtained surface using a Keyence video microscope. The results confirmed such bond defects (photograph in Fig. 1).

A few researchers have proposed to improve the rubber–cementitious matrix bond [9], notably by a treating the rubber particles with an NaOH aqueous solution [12]. However, the results they obtained showed that the strength benefit due to the rubber treatment was small.

In other aspects it is well documented that a significant difference in Poisson's ratio of a material (such as rubber) and a cement-matrix encourages premature cracking [13].

4. Straining capacity

The straining capacity was evaluated through four-point flexure tests using prismatic specimens (85 × 50 × 420 mm) that

Table 2
28-day mechanical characteristics (in MPa) of the mortars studied

Mix	0R0F	20R0F	30R0F	0R20F	20R20F	30R20F	0R40F	20R40F	30R40F
σ_c	38	16	8	33	18	7	32	14	9
σ_t	3.0	1.8	0.9	1.8	1.8	0.9	2.8	1.6	1.1
E_c	20200	12450	8250	22350	12000	9650	22800	17800	9050
E_t	24550	12950	5500	22300	11000	5550	20400	12725	6000

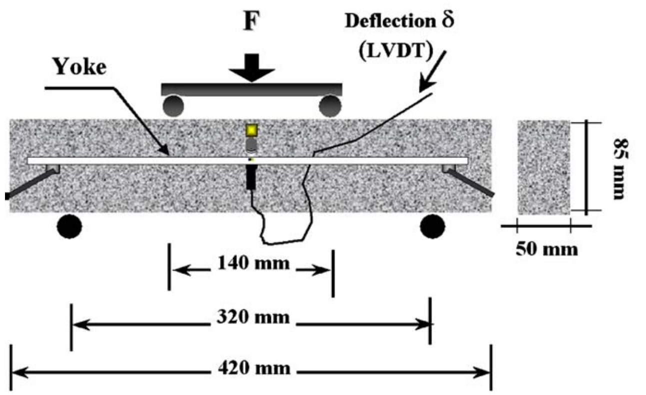

Fig. 2. Experimental set-up for evaluation of straining capacity.

had been continuously cured at 20 °C and 100% R.H. The testing set-up is presented in Fig. 2. The tests were carried out at 28 days. The deflection, δ, of the specimen was measured with a yoke by reference to the specimen itself. The tests were controlled by this deflection, δ, at the rate of 50 µm/min. The load F and the deflection δ were automatically and continuously recorded by a data acquisition system.

It is well known that flexure crack initiation occurs significantly before peak load. SEM observations have shown this occurring at about 60% of the ultimate load [14]. However, microcrack coalescence, and subsequent macrocrack localisation does not occur at strains below the peak load, Fmax. The deflection δ_{Fmax} corresponding to the peak load (or if necessary, the end of the maximum load plateau), is thus a pertinent indicator of the straining capacity.

The load versus deflection curves in Fig. 3 are typical of the results of the tests. Table 3 gives the average values (from four tests) of the peak load (Fmax), straining capacity (δ_{Fmax}) and stiffness (K) of the specimens. The latter is quantified by the slope ($\Delta F/\Delta\delta$) of the linear branch of the ascending curves, between 0 and 2 kN.

Table 3
Quantifying parameters of the specimen behaviour in four-point flexure tests

Mix	0R0F	30R0F	0R40F	30R40F
Fmax (kN)	4.9	3.3	6.9	3.1
δ_{Fmax}	0.08	0.20	0.11	0.21
K (kN/mm)	83	27	87	28

In accordance with the effect of rubber on the compressive and tensile strengths, the curves in Fig. 3 show that rubberised mortars, whether fibre reinforced or not, exhibit a lower flexural load bearing capacity (Fmax). The low elastic modulus of rubberised mortar induces a low stiffness (K) but, in turn, the straining capacity (δ_{Fmax}) is significantly increased. For instance, it becomes about 2.5 times greater when the volume fraction of rubber aggregates is increased from 0% to 30%. We explain such behaviour by the effect of rubber aggregates on the cracking kinetics. Indeed rubber aggregate acts like a drilling at the crack tip, the simplest way for arresting crack propagation [15,16]. It decreases the stress concentration and removes the geometric singularity caused by the crack tip. Thus, when the first microcracks run into the rubber–matrix interface, the resulting stress relaxation prevents further propagation and delays microcrack coalescence. In this regard, rubber aggregates act as microcrack arresters. Moreover, instead of a sharp peak load which characterises the control mix, rubber aggregates and rubber aggregates combined with a fibre reinforcement give rise to a pronounced quasi plateau. Results also demonstrate that rubber substitution does not affect the residual post-peak bearing capacity provided by fibre reinforcement.

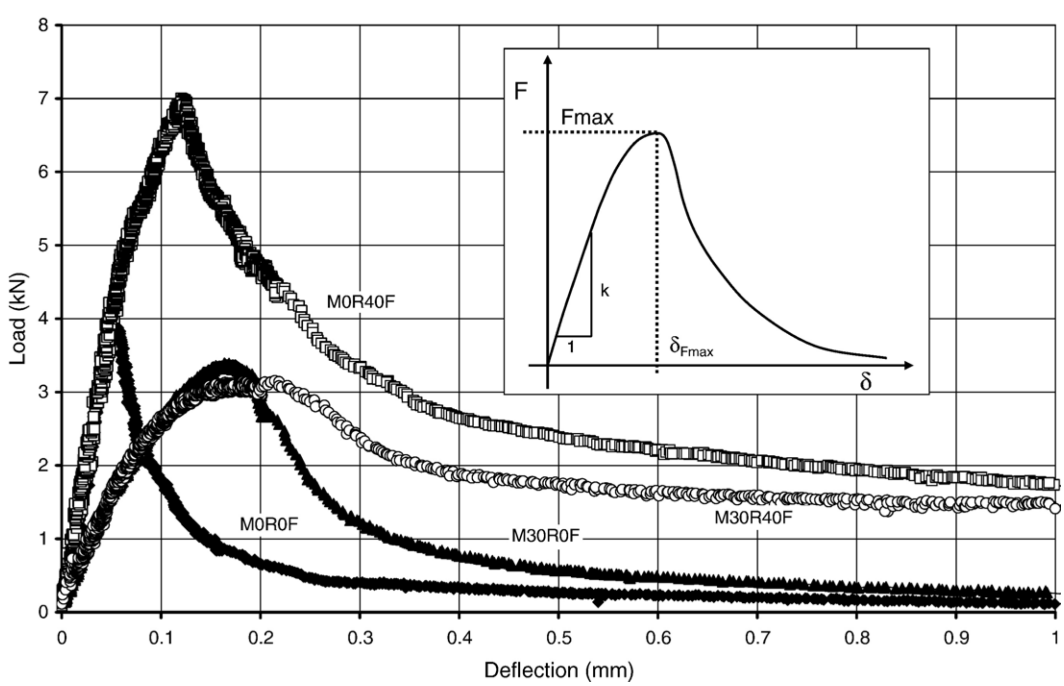

Fig. 3. Load vs. deflection in four-point flexure tests, effects of rubber aggregate incorporation and of fibre reinforcement.

5. Resistance of rubberised cement-based mortars to shrinkage cracking

5.1. Shrinkage cracking

Shrinkage is a major factor concerning cracking; particularly when the shrinkage is restrained. This is the case, for example, for slabs, pavements and bonded cement-based repairs. It is expected that the presence of less stiff aggregates should reduce the internal restraint and thus increase the resulting shrinkage length change [17,18]. In a previous study [5], free shrinkage tests were conducted in accordance with NF P 15-433 French standard. Specimens (40×40×160 mm prisms) were continuously exposed to drying conditions, 20 °C and 50% R.H. and the higher free shrinkage length change which was measured with the presence of rubber aggregates confirmed expectations. In such conditions the benefit of the higher straining capacity of rubberised cement-based composites could be offset by their higher shrinkage length change. To evaluate the sensitivity of rubberised cement-based composites to restrained shrinkage cracking, ring-tests were performed.

5.2. Ring-tests

The principle of the ring-test is well documented and such tests are widely used to assess the propensity of cement-based composites to shrinkage cracking [19–21]. Fig. 4 illustrates the testing set-up used. 35 mm thick and 140 mm wide mortar rings were cast around a 25 mm thick stainless steel ring. The external diameter of the steel ring was 250 mm. Two steel semi-cylindrical shells that could be easily dismantled and reused were used as outer mould. The steel ring and the mould were concentrically fastened onto a stainless steel base. The outer mould was removed 24 h after casting and the specimens were immediately placed in a 21 °C and 50% R.H. environment for the remainder of the experiment. A silicone seal was used to prevent drying from the upper face of the mortar ring. Generally, it is assumed that the shrinkage along the height of the specimens is uniform when the height is more than four times the thickness [20]. As shown in Fig. 4, this condition was fulfilled.

A video microscope was used to detect cracks from their initiation, to monitor their propagation and eventually, to measure their opening. The tests were continued for 55 days (no significant event was observed after this time) and typical examples of results are presented in Fig. 5a to d. For each mix tested, the crack pattern on two diametrically opposite views (side A and side B) is shown. The extent of the shrinkage cracking is illustrated by photographs at a constant magnification. Table 4 summarises the information.

With regard to the resistance to shrinkage cracking, the results demonstrate the benefit of rubber aggregate incorporation. On the one hand, shrinkage cracking is delayed; on the other hand, when it occurs, multiple cracking with thinner crack opening is observed (30R0F). For that matter, 30% of rubber aggregate substitution seems more efficient than 40 kg/m^3 of fibre reinforcement, for which a crack crossing the whole height

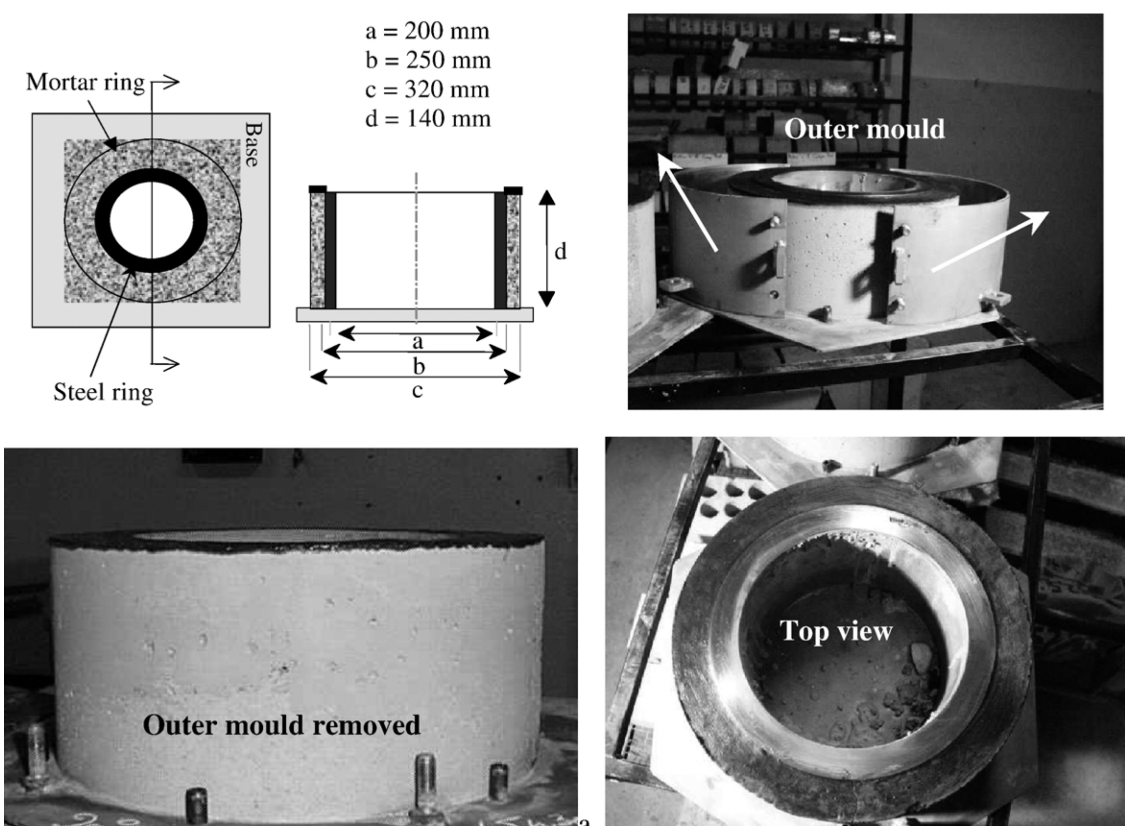

Fig. 4. Ring-test set-up.

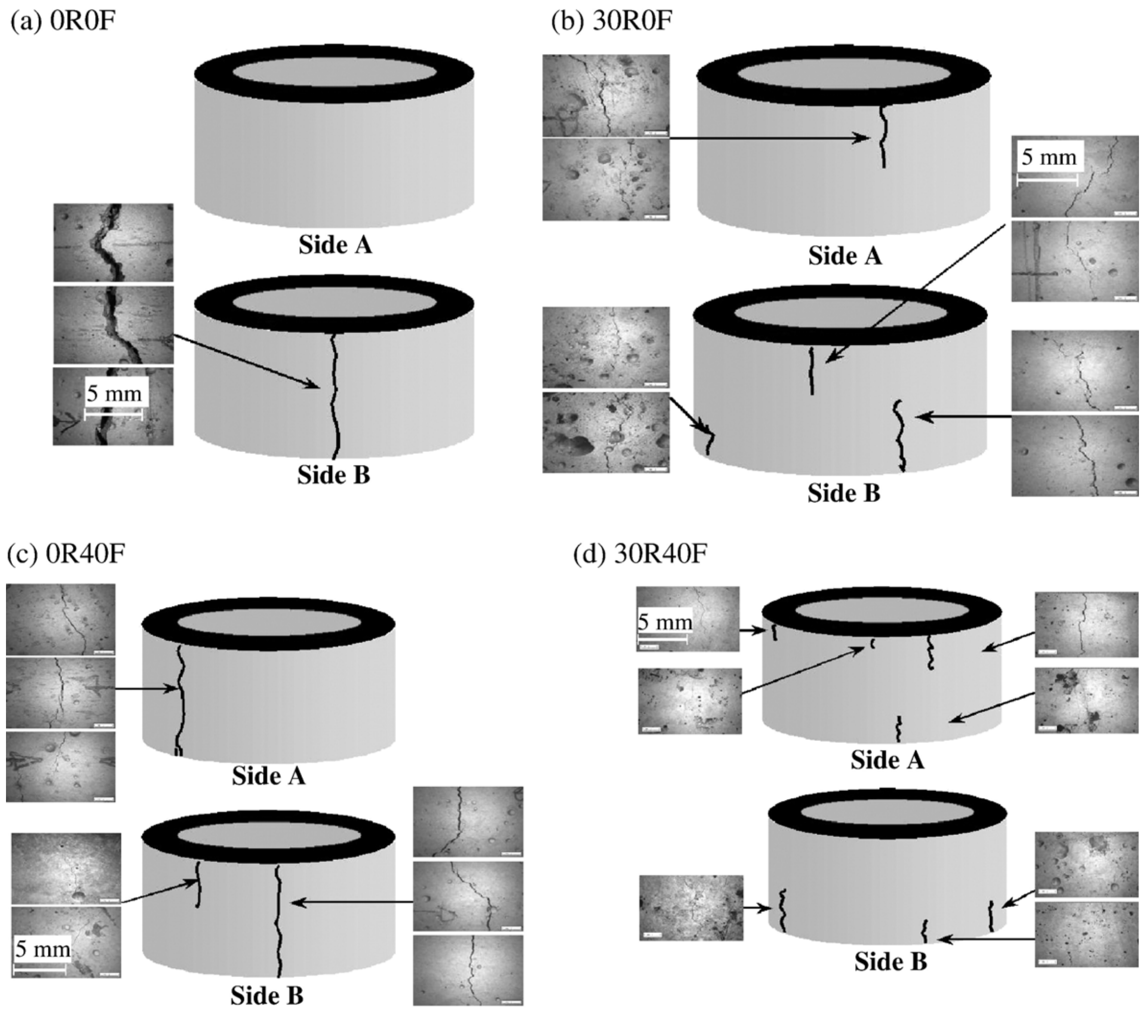

Fig. 5. Shrinkage cracking pattern after 55 days.

occurred (0R40F). However this multiple cracking aspect is pronounced when rubber aggregate substitution is combined with metal–fibre reinforcement (30R40F). The behaviour resulting from such a positive synergy effect contrasts with the behaviour of the control mortar (0R0F) where a single, early and wide crack cut the specimen along its full height.

6. Conclusions

The results presented here show that the incorporation of rubber aggregates obtained from shredded non-reusable tyres in cement-based mortars is a suitable solution to limit their brittleness. Despite some drawbacks, such as the large decrease in tensile and compressive strengths, and the significant increase of free shrinkage length change; the tests demonstrated that rubberised mortars exhibited an interesting increase in their straining capacity.

Flexural tests showed that the deflection corresponding to the ultimate load increased with rubber aggregate incorporation.

With regard to the resistance to shrinkage cracking, ring-tests were carried out to make sure that the additional shrinkage length change did not offset the straining capacity gain. Results showed a clear benefit from rubber aggregate incorporation: the propensity for shrinkage cracking is highly reduced and this benefit is enhanced when a rubberised mortar is fibre reinforced. Such behaviour is promising for the improvement of structure durability particularly when resistance to cracking due to imposed deformation is a priority.

Table 4
Ring-tests: synthesis of results

Rubber substitution (%)	0	30	0	30
Fibre dosage (kg/m^3)	0	0	40	40
Mix designation	(0R0F)	(30R0F)	(0R40F)	(30R40F)
Age at first crack initiation (days)	6	17	17	18
Number of cracks after 55 days	1	4	3	7
Main crack length (mm)	140	90	140	70
Maximum crack opening (mm)	1.10	0.11	0.13	0.06

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