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Workability, mechanical properties, and chemical stability of a recycled tyre rubber-filled cementitious composite

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The workability and mechanical properties of mortar containing shredded automobile and truck tyres were evaluated. Two different shapes of rubber particles were used as constituents of mortar: (1) granules about 2 mm in diameter, and (2) shreds having two sizes which were, nominally, 5.5 mm × 1.2 mm and 10.8 mm × 1.8 mm (length × diameter). As expected, the geometry of the rubber particles influenced the fracture behaviour of rubber-containing mortar. The addition of rubber led to a decrease in flexural strength and plastic shrinkage cracking of mortar. The crack width and crack length due to plastic shrinkage were reduced for mortar containing the 10.8 × 1.8 mm rubber shreds compared with a mortar without shreds. The rheological properties of the mortar containing rubber shreds were comparable to those of a mortar without rubber and yielded lower plastic viscosity than a mortar containing 25.4 mm × 15 μm (length × diameter) polypropylene fibres. The alkaline stability of rubber in mortar was also evaluated by immersing rubber shreds in NaOH and $Ca(OH)_2$ solutions for 4 mon and the results showed that there is less than 20% change in stress and strain value. The findings of the research suggest that automobile and truck tyres can be recycled by shredding and incorporating them into mortar and probably concrete for certain infrastructural applications. © *1998 Chapman & Hall*

1. Introduction

Disposal of used rubber tyres is a global problem. Each year, the United States produces about 279 million tyres (3 million metric tons), resulting in a significant solid waste dilemma [1]. The practice of disposing of scrap tyres in landfills is becoming difficult because of the rapid depletion of available sites for waste disposal. Proposed alternatives include recycling the tyres as fuel for cement kilns, as feedstock for producing carbon black, as reefs in marine environments, and in paving asphalt [2–4]. Using tyres as fuel is technically feasible but not economically attractive because of the high initial capital investment [4, 5]. The use of rubber tyres in carbon black eliminates shredding and grinding costs but the carbon black from tyre pyrolysis is more expensive, and gives inferior carbon black than that from petroleum oils [2]. On the other hand, the use of comminuted tyres in asphalt in concrete for paving is technically feasible and can be economically attractive. However, the asphalt industry can currently absorb only 30%–40% of the scrap tyres generated [6]. Furthermore, automobiles when driven on asphalt are 16% less efficient as compared to concrete [7]. The addition of rubber particles from scrap tyres into concrete is the subject of current investigation. Possible uses of the rubber-constituted concrete could be in sub-bases for highway pavements, highway medians, sound barriers and other transportation structures where high strength is not of prime importance [8]. Until now, most of the research on uses of rubber particles in concrete has been conducted using granular rubber [9–16]. Particle sizes have ranged from 0.06–16 mm diameter. The results have shown that the compressive and flexural strengths of concrete decreased on addition of granular rubber, while other properties such as freeze–thaw resistance and impact resistance increased [8]. Concrete with fibrous rubber showed increased crack resistance and noise attenuation compared with conventional concrete [7]. The process employed for comminution of rubber tyres dictates the particle shape and size distribution [17]. Therefore, it is worth investigating the effect of geometry of shredded rubber on the properties of the rubber-containing concrete.

In previous work, it was shown that the compressive strength of mortar specimens (cylinders and

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cubes) containing 10.8 mm × 1.8 mm rubber shreds was higher than mortar containing granular rubber [18]. It is well known that the use of fibres (such as environmentally-unsafe asbestos fibre, moisture-sensitive cellulosic fibre, chemical-resistive polypropylene fibres, and polyacrylonitrile-based carbon fibre) in concrete can produce concretes that are less prone to brittle failure and to plastic shrinkage cracking [19–21]. The intent of the present research is to explore the usefulness of incorporating shredded rubber (granular or fibrous rubber) in concrete by studying the workability, mechanical properties of recycled tyre rubber cementitious composites.

In this investigation, the influence of the shape of rubber particles on flexural strength of mortar was examined by using rubber granules of about 2 mm diameter (designated GR 2), and two sizes of rubber shreds, one being about 5.5 mm long and about 1.2 mm diameter (FR 2.36), and the other being about 10.8 mm long and about 1.8 mm diameter (FR 4.75). In this exploratory study, mortar was used instead of concrete because it is easier to work with mortar.

As expected, this study confirmed the findings of previous work that rubber addition decreases the flexural strength of the mortar. However, an encouraging discovery was that the severity of plastic shrinkage cracking can be reduced by the addition of shredded rubber. Also, it was found that shredded rubber retained its structural integrity when exposed to highly alkaline environments for up to 4 mon. A study of alkaline environment on rubber shreds will provide preliminary information about the effect of aggressive environments (namely alkali hydroxide and alkaline hydroxide) surrounding the rubber shreds in rubber-constituted mortar.

2. Experimental procedure

2.1. Materials and specimen preparation

Table I summarizes the characteristics and proportions of the materials used in the specimen preparation. The geometry of the rubber particles varies considerably depending on the grinding process and the source of rubber tyre [17]. The dimensions of mechanically ground rubber particles were determined by measurements under a light microscope. The rubber shreds were received in bulk and separated into two size fractions by sieving using standard sieves (ASTM E11) [22]. The cross-section of the rubber shreds was not uniform along the axial direction. Table II summarizes the lengths and diameters of the two sizes of rubber shreds. The reported values are the average of measurements on 20 randomly selected rubber shreds. The two types of rubber shred obtained from sieving the shredded rubber tyre are:

(i) rubber shreds that passed through the 4.75 mm sieve (no. 6) and were retained by the 2.36 mm sieve (no. 8); these were designated FR 4.75;

(ii) rubber shreds that passed through the 2.36 mm sieve (no. 8) and were retained by the 1.18 mm sieve (no. 16); these were designated FR 2.36.

This rudimentary method of separation into two sizes was deemed adequate for an exploratory study. GR 2 represents granular rubber of approximately 2 mm diameter. Fig. 1 shows the rubber and polypropylene fibres used for comparison in the study.

TABLE I Materials and mixture proportions

Material	Type/source	Ratio by mass of cement
Cement	Portland cement ASTM Type I–II	1
Sand	Graded sand ASTM C 778	2.75
Water	Distilled water	0.485
Rubber		
Granules (2 mm diameter)	Baker Industries, Indiana	0%, 1%, 2.5%, 5%, 10%, 15%
Shreds	Rouse Rubber, Mississippi (see Table II)	0%, 1%, 2.5%, 5%, 10%, 15%
Polypropylene fibres	W.R. Grace and Co. 25.4 mm long, 15 μm diameter	1%

TABLE II Dimensions of rubber shreds (circular in cross-section)

Type of rubber particles	Average diameter at the centre[a] (mm ± S.D.)	Average length[a] (mm ± S.D.)	Average aspect ratio
FR 2.36	1.2 ± 0.6	5.5 ± 2.2	4.6
FR 4.75	1.8 ± 0.8	10.8 ± 4.5	6.0

[a] Measurements of 20 shreds.

Mortar batches were prepared as described in ASTM C 109 [23]. The water-to-cement and sand-to-cement ratios were kept constant as indicated in Table I. (Such an identification does not imply recommendation/endorsement by the National Institute of Standards and Technology and Howard University nor does it imply that instruments or materials identified are necessarily the best available for the purpose.) The rubber was added at the end of the standard mixing cycle, and the mortar was mixed for an additional 2 min. For flexural strength specimens, the moulded specimens were covered with wet paper towels and cured in a chamber at 100% RH and room temperature (23 ± 2)°C for 24 h. After demoulding; the specimens were cured in lime-water for 7 d before flexural strength testing. For the plastic shrinkage cracking tests, the moulded specimens were placed immediately in a drying chamber (section 2.2.2) for at least 3 h.

2.2. Test methods

2.2.1. Flexural strengths

The specimens for flexural strength measurements were 25 mm × 25 mm × 279 mm (1 in × 1 in × 11 in) beams. For each mixture, the batches included seven beams. The flexural strength of the beams was measured using one-third point loading as described in ASTM C 78 [24]. The tests were performed on an 810 Materials

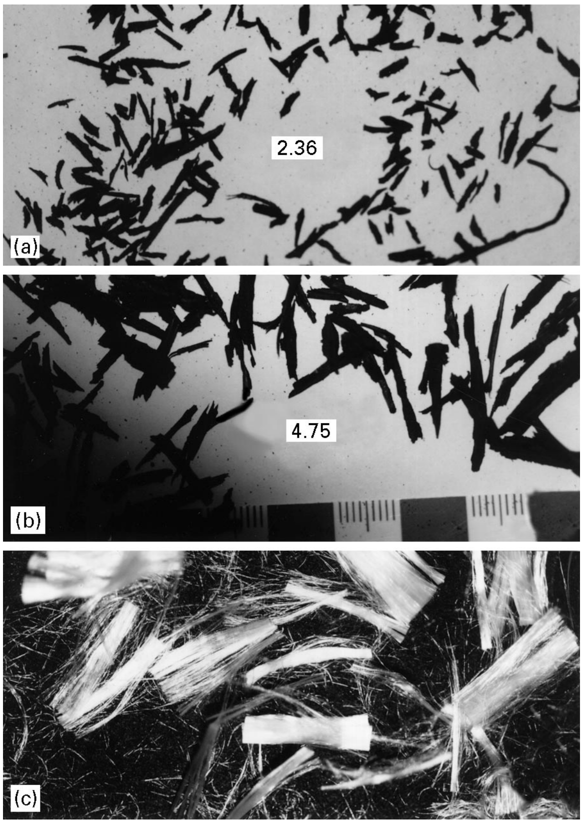

Figure 1 Pictures of the fibres used: (a) FR 2.36 rubber; (b) FR 4.75 rubber; (c) polypropylene.

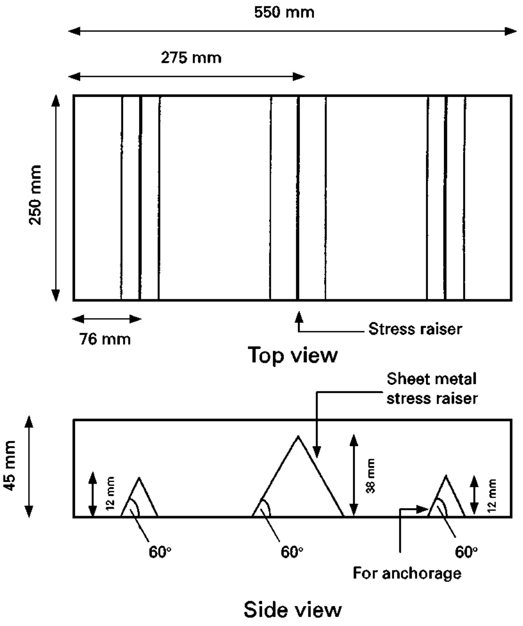

Figure 2 Schematic drawing of the mould used for the determination of plastic shrinkage cracking.

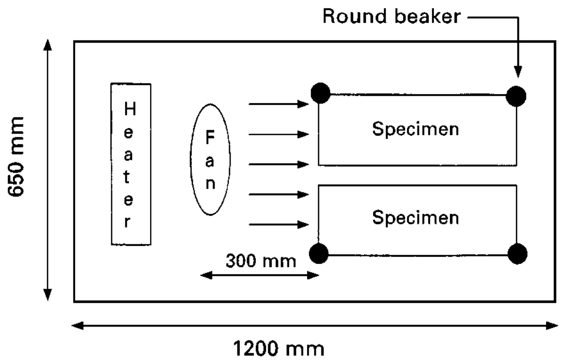

Figure 3 Schematic drawing of the mould placement in the drying chamber for plastic shrinkage cracking measurements.

Testing System (MTS) machine. The data were recorded at 1 s intervals.

2.2.2. Plastic shrinkage cracking

Fig. 2 is a sketch of the mould used to prepare specimens to evaluate resistance to plastic shrinkage cracking. The mould dimensions were one-half of those described in the draft protocol currently under review by the ASTM subcommittee on fibre-reinforced concrete [21]. The moulds include sheet metal triangular inserts to anchor the ends of the specimens and act as stress riser to provide for stress concentration at the centre of the specimen. A laboratory hood was used as a drying chamber. The moulds along with the specimens (immediately after moulding) were placed in the hood for 3 h. Fig. 3 shows the placement of the plastic shrinkage moulds within the hood. A heater and fan were used to control the evaporation rate within the chamber. Four beakers containing known amounts of water were placed as shown in Fig. 3. The evaporation rate was determined by the loss of water mass during the 3 h drying test. During the tests, the temperature and the air-flow rate of the chamber were adjusted to attain a surface evaporation rate of 1150–1180 $\mathrm{g\,m^{-2}\,h^{-1}}$. The exact times at which the first crack appeared on the top surface of the specimen were noted, and crack length as well as crack width was measured periodically. The crack length was determined by placing a string along the crack and measuring the length of the string. The crack width was measured using a crack width comparator (CTL, crack width compactor, 1988). The crack length reported represents the sum of the lengths of the cracks detected along the stress-riser region, and the crack width is the average of three measurements for each specimen. The crack length and crack width were determined on control mortar, mortar with polypropylene fibres, and mortar with fibrous rubber. The mass fraction of rubber ranged from 1%–15% cement by mass, while the content of polypropylene fibres was 1% cement by mass.

2.2.3. Workability

The workability of the mortar was measured using a VeBe test [25]. The mould dimensions were one-half of those described in the original mould [18]. The apparatus is intended to be used for mortar mixtures where specimens are compacted by vibration. The workability was determined on control mortar, mortar with polypropylene fibres, and mortar with rubber shreds. The polypropylene fibres were added to the mortar mixture during processing in the same way as the rubber shreds were added to the mortar. The mass fraction of rubber shreds was 1%–15% cement by mass, while the content of polypropylene fibres was 1%. The mortar mixture was formed in the conical mould inside the cylindrical container. The cone was removed and a circular plate, whose diameter was slightly less than that of the cylindrical container, was placed on the top of the mortar cone. The vibrating table was turned on and the initial time was recorded. The time was recorded when the bottom of the transparent circular plate was completely covered with mortar. The reported results are averages of two or three repeated tests on different batches with the same mixture proportions. The time difference, the "VeBe" time, is a measure of the plastic viscosity of the mixture. A shorter VeBe time represents a lower plastic viscosity of the mixture.

2.2.4. Chemical stability of rubber shreds in an alkaline environment

Pore solution in mortar usually contains alkali hydroxide [26] and is strongly basic (pH $\cong$ 13); therefore, experiments were designed to study the aggressive environment surrounding rubber shreds in mortar by exposing rubber shreds to various solutions with pH between 10 and 13. FR 4.75 shreds were immersed in a sodium hydroxide solution of pH 10, a calcium hydroxide solution of pH $\sim$ 12.5, and a simulated pore solution of pH $\cong$ 13 [27] at room temperature (23 ± 2)°C for 4 mon. At the end of the test period, the shreds were retrieved from each solution and allowed to equilibrate with deionized water. The process of equilibration was repeated with fresh deionized water to recover alkali-free rubber sample. The rubber was air dried to a constant mass. Tensile tests were performed on untreated and chemically treated shreds. At least 10 shreds were selected from each batch (as-received and treated in NaOH, in $Ca(OH)_2$ and in pore solution) and tested. Care was taken to choose long shreds of uniform diameter by measuring the cross-sectional areas at several locations. The diameter of the shred was measured using a digital low-pressure caliper. The ends of the shred were attached to mounting tabs. The tabs were clamped to the tensile grips so that the tested shred was aligned perpendicular to the direction of grip. The test was performed on an Instron 5500 R (Model 1122) testing machine with a cross-head speed of 7 mm min^{-1}. Maximum stress and per cent strain at peak of both untreated and treated shreds were recorded.

3. Results and discussion

3.1. Flexural strength

Fig. 4 shows the individual flexural strengths of the beams from different mortar batches. The within-batch coefficients of variation varied from 1.4%–7.6%. Fig. 4 shows that increasing the content of rubber decreased the flexural strength of mortar. To examine whether there were statistically significant differences in the average flexural strengths due to the type of rubber or combination of the amount and type of rubber, an analysis of variance (ANOVA) and a post-hoc (Scheffé method) test was used. A Datadesk software package was used to determine the confidence level (probability) at which the mean flexural strengths of mortar containing granular rubber and rubber shreds were different. Any confidence level lower than 95% was equivalent to no statistically significant difference. The results of the analysis indicated that overall, FR 4.75 showed a smaller reduction in mortar flexural strength than GR 2. Table III indicates that with the addition of mass fraction of 1% rubber, the mean difference in flexural strength between mortars containing FR 4.75 and GR 2 was statistically significant. However, at mass fractions of 5% and 10% rubber, the differences in the mean flexural strengths of mortar containing FR 4.75 and GR 2 were not statistically significant. In summary, the results of the flexural strength tests appear to indicate that FR 4.75 may perform a little better than GR 2. However, because there were insufficient replicate batches, this conclusion should be viewed with caution.

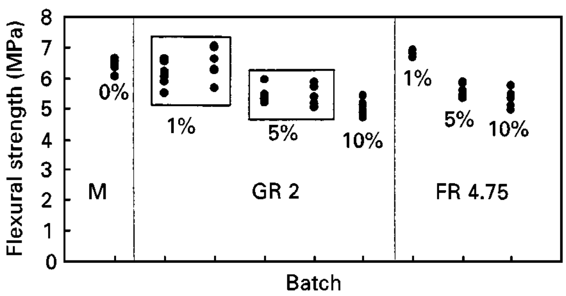

Figure 4 Flexural strengths of mortar and rubber-containing mortar beams.

TABLE III Differences in mean flexural strength of mortars with rubber type GR 2 and FR 4.75 (the data are provided in Fig. 4) GR 2 = Granular rubber 2 mm diameter, FR4 = Fibrous rubber 4.75. Values for rubber percentage are shown in parentheses

Rubber type and composition	Flexural strength difference (MPa)	Standard error (MPa)	Confidence level[a] (%)
GR 2 (1)–FR4 (1)	– 0.52[b]	0.17	99
GR 2 (5)–FR4 (5)	– 0.24	0.16	[c]
GR 2 (10)–FR4 (10)	– 0.33	0.19	[c]

[a] Confidence level at which the two samples are different (Scheffé's method)

[b] GR 2 (1)–FR4 (1) = the difference in the mean flexural strengths of 1% GR 2 and 1% FR4

[c] No significant difference between means

The mortar specimens with rubber shreds were able to withstand additional load after they were cracked. The specimens did not physically separate into two pieces under flexural loading because of bridging of cracks by rubber. Fig. 5 shows a fractured mortar specimen containing rubber shreds. It can be seen that the mortar matrix failed, while the rubber shreds bridged the crack and prevented catastrophic failure of the specimen during the test. Specimens with granular

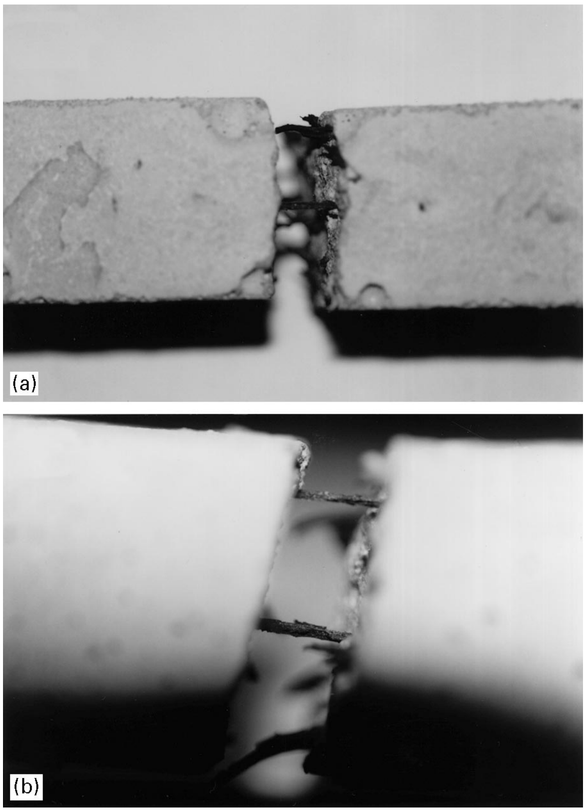

Figure 5 Fractured beam of fibrous rubber-mortar: (a) as-obtained, (b) after stretching the two parts (close view of the rubber).

rubber broke in two when the peak load was attained. Therefore, the post-crack strength is improved by switching from granular rubber to rubber shreds.

Fig. 6 is a light micrograph of fractured granular rubber mortar. Microscopic observations of the specimens showed that fracture occurred at the rubber-to-cement interface for the granular rubber inclusion. The pull-out characteristics of the granular rubber particles from the mortar matrix are consistent with poor interfacial bonding. It was not unexpected, because similar results have been reported in the literature [9–14].

3.2. Plastic shrinkage

Fig. 7 shows plastic shrinkage specimens with mass fraction of 0%, 5%, 10% and 15% rubber shreds and mass fraction of 1% polypropylene fibres in mortar. All specimens cracked within the first 3 h exposure, except those with 1% polypropylene fibre. The specimens with polypropylene fibres had minimal or no plastic shrinkage cracking. In the cracked specimens, the cracks always occurred over the central stress raiser. The use of rubber shreds was found to be effective in allowing multiple cracking to occur over the width of the specimen compared with a single crack in the mortar without rubber shreds. In spite of multiple cracking, the total crack area in the case of rubber-filled mortar, appears to decrease with an increase in the rubber mass fraction. Apparently, crack propagation was arrested several times by the rubber shreds. The rubber shreds, despite the weak bonding of rubber, provided sufficient restraint to prevent the shorter cracks from propagating.

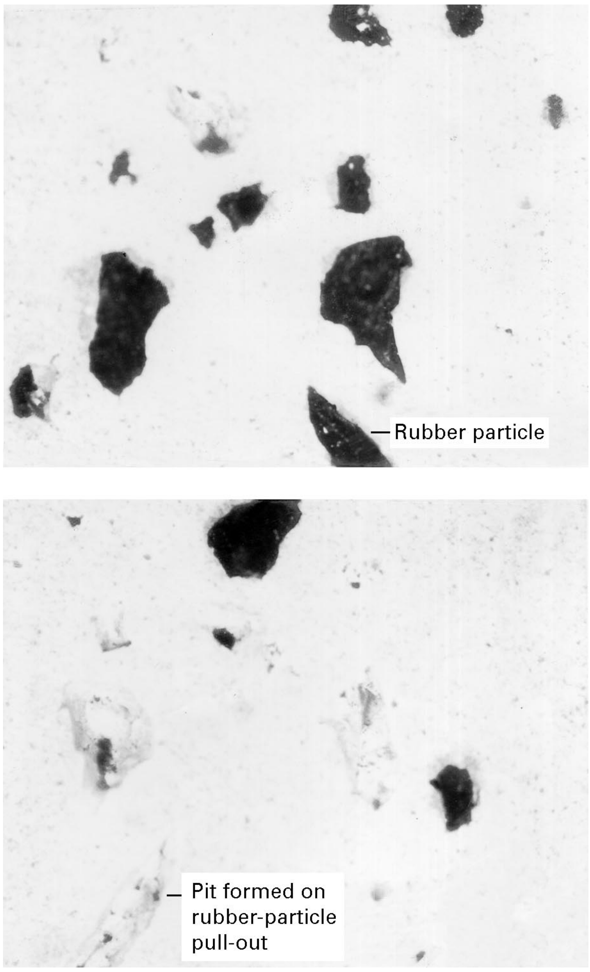

Figure 6(a, b) Light micrographs of fractured beam with granular rubber-mortar.

Because the specimen geometry and testing configuration were constant for all the mixtures, the parameter that best describes the performance of different mixtures is the crack width at the central stress raiser. The width of the cracks for all the mixtures was measured at 1, 2 and 3 h in the drying chamber. The results are summarized in Table IV. After 3 h, the plain mortar specimen (control) developed a crack having an average width of about 0.9 mm, while the average crack width for the specimen with mass fraction of 5% rubber shreds was about 0.4–0.6 mm. The crack width reported is the average of three measurements for each mixture. It was found that the onset of cracking was delayed by the addition of rubber shreds: the mortar without rubber shreds cracked within 30 min, the specimen with mass fraction of 5% FR 4.75 rubber cracked within 30 min, while the specimen with mass fraction of 15% FR 4.75 rubber cracked after 1 h. The content of rubber shreds in the mortar affected the onset time of cracking, the crack length, and the crack width. Although additional studies are necessary to confirm these observations, it appears that the addition of rubber shreds could be beneficial for reducing plastic shrinkage crack development of mortar and probably concrete.

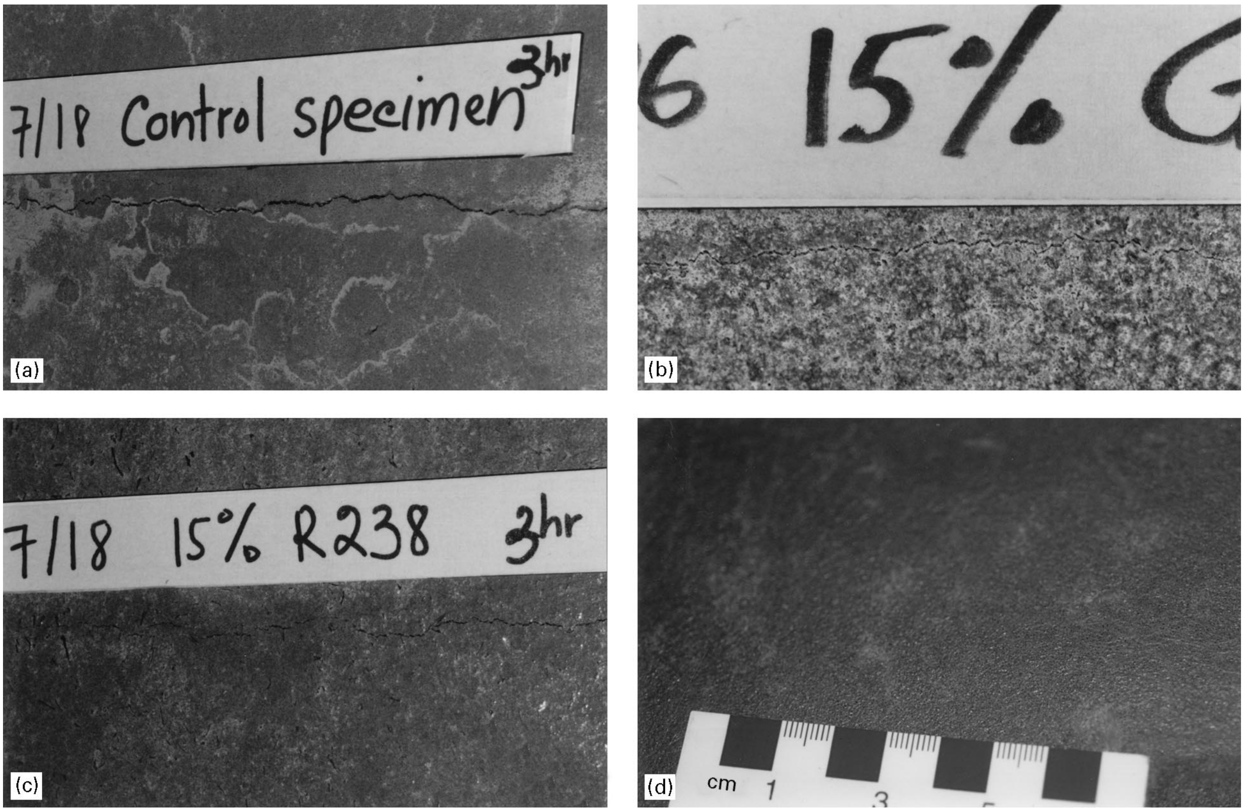

Figure 7 Pictures of the specimen after testing for plastic shrinkage: (a) plain mortar; (b) 15% granular rubber-mortar; (c) 15% fibrous rubber-mortar; (d) 1% polypropylene fibre-mortar.

TABLE IV Plastic shrinkage cracking results of mortars

Fibres added to the mortar	Amount (% by mass of cements)	Number of cracks	Crack length (mm)			Average crack width (mm)			Time of first crack (min)
			1 h	2 h	3 h	1 h	2 h	3 h	
None	0	1	158	212	246	0.3	0.6	0.9	2
Polypropylene	1	0	0	0	0	0	0	0	No cracks
FR 4.75	5	2	174	212	212	0.2	0.4	0.6	30
	10	2	156	203	203	0.2	0.2	0.4	60
	15	4	103	142	178	0.2	0.3	0.4	60
FR 2.36	15	4	163	181	203	0.2	0.3	0.3	35
GR 2	15	3	107	204	219	0.2	0.2	0.4	45

3.3. Workability

Table V summarizes the results of workability measurements. The mortars containing rubber shreds showed workability comparable to or better than mortar without rubber particles. The mortar containing 25.4 mm long and 15 mm diameter polypropylene fibre showed poor workability. It is believed that the effects of the polypropylene fibres in preventing the free flow of the mixture are attributable to their greater number and higher aspect ratio.

TABLE V Workability measurements of fresh mortars

Material added to the mortar	VeBe time [s]	
	1%	10%
	mass fraction of cement	
Plain (control)	55 ± 1	–
Polypropylene	241 ± 8	–
GR 2	40 ± 2	58 ± 3
FR 2.36	36 ± 1	50 ± 4
FR 4.75	26 ± 1	44 ± 3

3.4. Chemical stability of rubber shreds in an alkaline environment

Fig. 8a and b show the tensile strength and strain at peak stress of untreated and rubber shreds exposed to an alkaline environment. Tensile strength of shreds tend to vary within a batch. The tensile strength of the shred is governed by the number and size of flaws in the specimen. Therefore, 10 shreds were tested to obtain reliable strength and strain data. From a

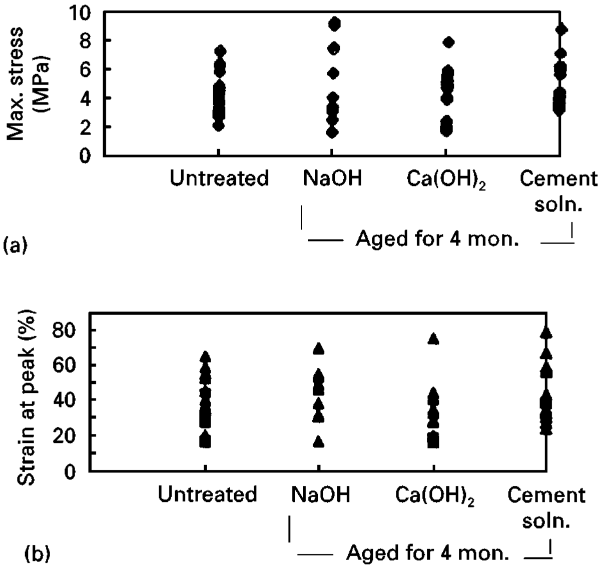

Figure 8 Tensile test results of alkaline-treated and untreated rubber shreds: (a) tensile strength, and (b) strain at peak stress.

comparison of the average strengths, it was concluded that the rubber shreds retained their strength even after 4 mon exposure to a highly alkaline medium. The rubber shreds did not undergo chemical degradation, suggesting that the shreds may not be seriously attacked by the alkaline environment in mortar. The results are in agreement with the reported minimal reduction in mass of rubber shreds, small change in pH of the leachate and the retention of the rubber texture as determined by scanning electron microscopy upon ageing for 4 mon [28]. Of course, additional long-term studies are needed to confirm this observation over a longer time period.

4. Conclusions and recommendations

Rubber-filled mortar was prepared using various proportions of granular rubber or rubber shreds obtained from shredding rubber tyres. For comparison, some tests were done with plain mortar and mortar containing polypropylene fibres. The following conclusions were drawn from this study:

1. The addition of rubber particles resulted in a reduction of flexural strengths of the mortar mixes. The decrease in strength was dependent on the content of rubber granules or shreds and the shape of the shredded rubber.

2. Preliminary results appear to show that the addition of rubber shreds to mortar reduces the severity of the plastic shrinkage cracking compared with the control mortar. The crack length, the crack width, and the time of cracking of the rubber-containing mortar were dependent on the content of rubber shreds. The rubber shreds bridged the cracks and provided restraint to crack widening. The addition of polypropylene fibres to plain mortar resulted in no plastic shrinkage cracking.

3. The fractured specimens of mortar containing rubber shreds exhibited crack bridging by the rubber particles. Even though the matrix was completely fractured under flexural load, the rubber particles held the specimen together. The rubber shreds continue to carry stress beyond matrix cracking, which helps maintain structural integrity in the material. For mortar specimens containing granular rubber, the rubber particles pulled out from the matrix, resulting in complete separation of the cracked specimens. The granular rubber-filled mortar failed in a catastrophic mode. This study confirmed the findings of previous work that rubber adhesion to mortar is poor [12–14]. For improvement in the interfacial properties, bonding between cement and granular rubber is beneficial.

4. The mortar containing up to a mass fraction of 10% rubber shreds showed rheological properties comparable to that of plain mortar, while the mortar containing a mass fraction of 1% polypropylene fibres showed high plastic viscosity.

5. Rubber shreds appear to undergo minimal ageing, if any, under highly alkaline medium. The strength measurements of as-received and alkali-treated rubber showed less than 20% change in stress value over 4 mon alkaline exposure.

For any application, if improvement in plastic shrinkage properties in mortar is judged to be important at the expense of the strength of mortar, future work should include the influence of the source of rubber, the comminution process to produce the rubber shreds, the bonding agent to improve the interface between rubber and cement and the optimum geometry of the rubber shreds for preventing plastic shrinkage cracking without causing large reductions in the compressive and flexural strengths of the mortar, as well as concrete mixes. Because alkaline studies on rubber were performed only for 4 mon no definite conclusions about the long-term stability of shredded rubber can be drawn, and additional long-term tests are required. The studies should also be extended to concrete.

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