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An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes

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HIGHLIGHTS

- An experimental investigation of unconfined CRC with 2 grading mixes is presented.
- Replacement >3.5% of aggregates with crumb rubber decreased compressive strength.
- Using silica fume did not improve the compressive strength up to 28 days of age.
- 3 Layers of FRP confinement improved CRC compressive strength by 186%.
- This has promising implications for the use of FRP confined CRC in seismic zones.

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ABSTRACT

Due to the known loss of compressive strength experienced by crumb rubber concrete (CRC) compared with conventional concrete, there have been few applications explored to date for the structural use of these materials. This paper describes experimental work conducted to explore the possible future use of CRC for structural columns by evaluating the use of fibre reinforced polymer (FRP) confinement as a means of overcoming the material deficiencies (decreased compressive strength). The results indicated that the use of FRP to confine rubberized concrete effectively negates the decrease in strength, and retains the advantages of increased ductility that arise from rubberized concrete. This indicates promising potential for structural column applications, particularly in seismic zones.

1. Introduction

Crumb rubber concrete (CRC) is similar to conventional concrete but uses shredded scrap tyre rubber as a partial substitution for mineral aggregates. Scrap tyres are among the largest and most problematic sources of waste of modern societies, due to their durability and the huge volumes of discarded tyres every year. When tyres are dumped to landfill they can cause numerous environmental problems, such as becoming breeding grounds for mosquitoes and other pests. In addition, when such tyre dumps catch fire it is notoriously difficult and costly to extinguish [1]. The recycling of used rubber conserves valuable natural resources and reduces the amount of rubber entering landfill [2]. Extensive previous research has been undertaken on CRC that shows a common problem, namely that replacing mineral aggregates in concrete with rubber aggregates results in compressive strength losses of up to 85% depending on the rubber size and content [3]. Moreover, CRC has lower tensile strength and modulus of elasticity compared with equivalent conventional concrete [3–11]. However, compared to conventional concrete, CRC has higher energy dissipation, ductility, durability, damping ratio, impact resistance, and toughness [12–16]. These characteristics make CRC an ideal potential candidate for concrete members subjected to dynamic loading conditions such as columns in earthquake zones.

Recently, a new type of concrete column consisting of concrete segments encased in fibre reinforced polymer (FRP) tubes has been developed (e.g. [17,18]). The FRP tube in this structure acts as a stay-in-place structural formwork, shear reinforcement, and confining reinforcement. This segmental column is able to resist lateral forces without experiencing significant or sudden loss of strength. In addition, the damage is very minor which indicates low energy dissipation compared to a traditional reinforced concrete column [17].

Researchers have recently shown that confining conventional concrete using FRP increases its axial capacity and ductility [19].

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Combining the advantages of concrete filled fibre tube (CFFT) and CRC may therefore result in a new type of bridge column that has adequate strength, higher energy dissipation, higher damping ratio, and higher ductility. To date there has been very limited investigation of the behaviour of CRC encased in FRP tubes. A measure called confinement effectiveness, defined as the ratio between ultimate confined and unconfined strengths, has been used to determine the improved strength gained by confining the concrete in FRP tubes. Li et al. [7] showed that FRP encased CRC had confinement effectiveness 23% higher than that of FRP-confined conventional concrete. Moreover, the ultimate axial strain of the FRP-confined CRC cylinders was double that of the reference CRC cylinders.

This paper investigates the mechanical properties of 12 CRC mixes. In addition, the behaviour of 18 concrete cylinders consisting of CRC or conventional concrete encased in FRP tubes having different thicknesses was investigated. These data will provide additional information necessary to support the further development of the proposed bridge columns that are the subject of future work by the authors.

2. Experimental program

In this research the performance of concrete mixes incorporating 0%, 5%, 10%, and 20% of crumbed scrap tyre rubber as a partial volume replacement of fine aggregates was experimentally investigated. The effects of rubber content, rubber pre-treatment, and silica fume (SF) additives on concrete workability, compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio were examined by testing 101 standard concrete cylinders. In addition, 18 concrete cylinders encased in FRP tubes having different thicknesses were subjected to uniaxial compression to determine the difference in behaviour, if any, between the confined CRC and conventional concrete.

2.1. Materials

Table 1 summarises the different components of all concrete mixes used in this study. The mixture code used starts with the letter "L" or "M" indicating limited rubber-sizes (poorly-graded) or multiple rubber-sizes (well-graded), respectively. This letter is followed by the rubber content (expressed in terms of the per cent of sand volume replaced by rubber) and then the letter "P" or "N" standing for pre-treated rubber or non-treated rubber, respectively. Finally the letters SF are used for mixes where silica fume was included.

General purpose cement, in accordance with Australian Standard (AS) AS 3972 [20], was used as the binder material in the concrete mixes. Densified SF with specific gravity of 2.2 was used as a partial replacement of concrete cement (10% by weight) in three mixes (M0-SF, M10-P-SF, and M20-P-SF) aiming to increase the compressive strength of CRC. Dolomite stone having nominal maximum sizes of 10 mm and 20 mm was used as coarse aggregate. River sand with a maximum aggregate size of 5 mm was used as fine aggregate. The crumb rubber used during the course of this study had two different grading categories, namely poorly-graded and well-graded. The poorly-graded type had only two particle sizes of 1.18 and 2.36 mm, while the well-graded type had particle sizes that ranged between 0.15 and 2.36 mm. Both rubber types were used as a partial replacement of sand by volume (Table 1). The sieve analyses for all aggregates used are shown in Fig. 1. The specific gravity, unit weight, and fineness modulus were 2.72, 1570 kg/m^3, and 6.02 respectively for dolomite; 2.65, 1630 kg/m^3, and 2.36 respectively for sand; 0.85, 530 kg/m^3, and 4.53 respectively for poorly-graded rubber, and 0.85, 530 kg/m^3, and 3.51 respectively for the well-graded rubber. Polycarboxylic ether type superplasticizer (SP) with a specific gravity of 1.08 was added to the concrete mixtures to achieve the required concrete workability.

Unidirectional carbon FRP sheets with a nominal thickness of 0.13 mm and two-part epoxy resins were used during the course of this study. According to the manufacturer's data, the ultimate strength, elastic modulus, and failure strain were 4900 MPa, 230 GPa, and 2.1%, respectively for the carbon FRP sheets; and 30 MPa, 4.5 GPa, and 0.9%, respectively for the epoxy resin.

2.2. Concrete mixes design

The concrete mixes were designed according to Australian Standard AS 1012.2 [21]. Two groups of concrete mixes were used with target compressive strengths of 50 MPa (group L) and 60 MPa (group M). Group L was designed with a constant water to cement (W/C) ratio of 0.35, SP of 0.5% (by cement weight), and cement content of 425 kg/m^3. The fine/coarse aggregate ratio was 1/2. Group M was designed to achieve a slump of 130–150 mm. In group M, the W/C ratio and cement content were held constant at 0.5 and 350 kg/m^3, respectively. However, the SP dosage was varied to achieve the required slump (Table 1). The fine/coarse aggregate ratio was 1/1.2. The mixing procedure for the control mixes was as follows: mix dry sand and gravel for 1 min.; add half of the water and mix for 1 min.; rest for 2 min.; add cementitious materials, water, and admixtures, and then mix for 2 min. The same procedure was followed for the CRC mixes, except that the rubber aggregate was first mixed with dry cementitious materials for 1 min in an external container, aiming to increase the rubber–cement interface adhesion, which is one of the main factors impacting on CRC strength.

2.3. Pre-treatment of rubber

Some studies have shown that pre-treatment of rubber particles can play an important role in improving the rubber/cement interface adhesion. The poor adhesion of rubber particles to cement is attributed to the existence of zinc stearate which is present in tyre formulation during manufacturing. This zinc stearate migrates and diffuses to the rubber surface creating a soap layer that repels water. In addition, rubber has low hydraulic conductivity and a smooth surface which both result in poor adhesion of the rubber to the cement [6,8,22,23]. Pre-treatment of rubber by using a Sodium Hydroxide (NaOH) solution removes the zinc stearate layers from the rubber surface [24]. The NaOH solution is able to eliminate the additives on the rubber surface leaving voids on the rubber outer surface that lead to a relatively rough and porous surface, compared with non-treated rubber. Because of the eroding effect of this acid solution on rubber particles, the surface of these particles is scraggy, which can improve the cohesion strength between rubber particles and cement [25]. In addition, it increases the hydraulic conductivity, rubber/cement water transfer rate, and hydration at the interface which improves the rubber/cement adhesion [3,4,26–31].

Table 1
Proportions of concrete mixes.

Group	Mix code	*Rs* (%)	*Rt* (%)	Pre-treatment of rubber	W/C	Mix proportions (kg/m^3)					Rubber	Water	SP.
						Cement	SF	Sand	Dolomite				
									10 mm	20 mm			
L	L0	0	0	–	0.35	425	–	628	1257	–	–	148.8	2.125
	L5-P	5	1.75	NaOH	0.35	425	–	597	1257	–	10.2	148.8	2.125
	L10-P	10	3.5	NaOH	0.35	425	–	565	1257	–	20.4	148.8	2.125
	L20-P	20	7.0	NaOH	0.35	425	–	502	1257	–	40.8	148.8	2.125
	L20-N	20	7.0	–	0.35	425	–	502	1257	–	40.8	148.8	2.125
M	M0	0	0	–	0.5	350	–	866	311	727	–	175	6.30
	M5-P	5	2.37	NaOH	0.5	350	–	823	311	727	13.8	175	6.30
	M10-P	10	4.75	NaOH	0.5	350	–	779	311	727	27.7	175	6.37
	M20-P	20	9.5	NaOH	0.5	350	–	693	311	727	55.5	175	6.65
	M0-SF	0	0	NaOH	0.5	315	35	865	311	727	–	175	8.40
	M10-P-SF	10	4.75	NaOH	0.5	315	35	778	311	727	27.7	175	8.90
	M20-P-SF	20	9.5	NaOH	0.5	315	35	692	311	727	55.5	175	9.45

Rs: Per cent of sand volume replaced by rubber.
Rt: Per cent of total aggregate volume replaced by rubber.
W/C: Water to cement ratio.
SP: Superplasticizer dosage.