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Behaviour of rubberised concrete members in asymmetric shear tests

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HIGHLIGHTS

- Assessment of rubberised concrete behaviour under asymmetric four-point loading.
- Tests on fifteen prismatic members using conventional and rubberised concrete.
- Detailed measurements of the crack width and evaluation of the ultimate behaviour.
- Complementary numerical simulations with focus on shear-governed failure modes.
- Comparative assessments and definition of expressions for the shear resistance.

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ABSTRACT

This paper deals with the experimental behaviour of rubberised concrete members subjected to asymmetric four-point shear loading. A detailed account of tests on 15 prismatic members using conventional concrete as well as rubberised concrete, with relatively high replacement ratios of both fine and coarse mineral aggregates with rubber particles, is given. The results enable direct assessment of strength and complete deformation characteristics including the post-peak response for ultimate behaviour governed both by shear and mixed-mode tensile-shear. After describing the material properties, mix designs and member details, the main observations from detailed measurements of the crack kinematics through a digital image correlation monitoring system, with focus on members developing shear-governed response, are reported. Complementary numerical studies are undertaken using nonlinear finite element procedures which are validated against tests developing shear-governed failures. In order to provide further insight into the key response characteristics, particularly those related to ultimate strength, a number of numerical sensitivity studies employing various constitutive parameters are also carried out. Moreover, comparative assessments in terms of shear resistance, toughness and force transfer across the cracked interfaces are performed and discussed. The detailed test measurements, coupled with the results obtained from the numerical simulations, permit the definition of expressions for representing the shear resistance as a function of the rubber content and concrete compressive strength.

1. Introduction

The management of waste rubber resulting from end-of-life tyres has involved various solutions including their use in asphalt mixtures for road constructions, reuse of ground tyre in plastic and rubber products [1], incineration of tyres for the production of steam or energy and in rubberised Portland cement concrete [2,3]. Early studies on the use of rubber particles in concrete materials have focused on the basic properties of rubberised concrete by replacing various portions of aggregates with rubber particles. Since aggregates represent the major part of the concrete mixture, their properties and mix ratio affect the properties of the material [2,4–6]. Amongst other parameters, the geometry of the aggregates determines the fresh properties of concrete while the mineralogical composition influences its mechanical properties such as strength, elastic modulus, and ductility [7].

Rubberised concrete mixtures show relatively lower compressive and tensile strengths, indicating a lower elastic energy capacity compared to normal concrete [2]. On the other hand, rubberised concrete mixtures exhibit a more ductile post-peak behaviour that shows the ability to absorb a larger amount of plastic energy under compressive and tensile loads in comparison with conventional concrete [4]. The reductions in compressive strength, elastic modulus and axial crushing strain are all functions of the increase of rubber content, as well as the lateral crushing strain and energy

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Nomenclature

Greek letters

δ	displacement (mm)
δ_{Pu}	displacement at failure (mm)
ε	strain (mm/mm)
$\varepsilon_{rc,el}$	strain proportionality limit (mm/mm)
ε_{rc1}	uniaxial crushing strain (mm/mm)
ε_{cru}	ultimate compressive strain (mm/mm)
ε_{u}	ultimate tensile strain (mm/mm)
λ	mineral aggregate size factor (-)
σ	stress (MPa)
σ_{pu}	cement matrix strength (MPa)
ρ_{vr}	rubber replacement ratio (-)
τ	shear stress (MPa)
τ_{res}	residual shear strength (MPa)
τ_{u}	shear resistance (MPa)
τ_{res}	residual shear strength (MPa)
ψ	dilation angle (degrees)
ϵ	potential eccentricity (-)

Lowercase latin letters

d_i	damage parameter (-)
$d_{g,repl}$	size of the replaced mineral aggregate (mm)
$d_{g,\mathrm{max}}$	maximum aggregate size (mm)
f_c	cylinder concrete compressive strength (MPa)
f_{ct}	tensile concrete strength (MPa)
f_{rct}	tensile rubberised concrete strength (MPa)
f_{rc}	compressive rubberised concrete strength (MPa)
f_{c0}	compressive reference concrete strength (MPa)
l_m	mesh size (mm)
l_s	shear bandwidth (mm)
s	crack slip (mm)
s_{lim}	slip limit (mm)
w	crack width (mm)
w_{bot}	crack width at the bottom notch (mm)
w_{top}	crack width at the top notch (mm)
$w_{max,0}$	maximum crack size for normal concrete (mm)
$w_{max,r}$	maximum crack size for rubberised concrete (mm)

Uppercase latin letters

A_f	area of the critical section (mm^2)
E_{rc}	elastic modulus of rubberised concrete (MPa or GPa)
K_c	factor for the shape of the deviatoric plane (-)
G_{cl}	total crushing energy (N/mm)
P_2/P_1	load ratio (-)
P	load (kN)
P_{cr}	cracking load (kN)
P_u	maximum load (kN)
$P_{u,num}$	numerical ultimate strength (kN)
$P_{u,test}$	test ultimate strength (kN)
T_s	toughness (N/mm)

dissipation that may be enhanced by the presence of rubber particles [8].

Although, the quantity of rubber in concrete has a notable influence on the rubberised concrete mechanical properties, this has less detrimental effect on the reinforcement – rubberised concrete bond properties, with bond coefficients exhibiting largely constant trends irrespective of the rubber content up to replacement ratios of 60% [9].

Recent applications have focused on the use of rubberised concrete in structural members. These applications have varied from unconfined and FRP confined columns [10,11], rubberised-concrete filled steel tubes [12,13], push-off specimens provided with shear studs replicating composite beams [14], flexural RC beams [15], standard wall panels used as exterior cladding on building systems [16], and wall panels under near-field blast load and ballistic impact [17,18]. It is, however, important to note that previous studies have focused on the axial and bending behaviour of rubberised concrete materials and members, with less attention given to shear behaviour despite its importance as a possible governing the failure mode under various loading situations [19–21]. Although some studies have examined the impact behaviour of rubberised concrete at the material level [18,22,23] investigations on rubberised concrete under direct shear are lacking.

To obtain an insight into the shear behaviour of rubberised concrete, this paper describes an experimental programme carried out on members subjected to asymmetric four-point loading. A full account of 15 prismatic members made of conventional concrete, as well as rubberised concrete with 20%, 45% and 60% replacement of both fine and coarse mineral aggregates with rubber particles, is given. To capture crack kinematics and crack patterns at failure, a digital image correlation monitoring system is used to track the member displacements throughout the tests. After characterising the members according to their failure modes, a detailed analysis is carried out on members developing shear-governed failures, with focus on the influence of the rubber content on the shear capacity and resistance to cracking. The main observations related to the shear transfer across the cracked interfaces are also discussed. Additionally, complementary numerical simulations and parametric investigations are performed in order to assess the shear resistance for a wider range of constitutive configurations. Finally, representative expressions are proposed in order to relate the shear resistance to the rubber content and the mechanical properties of concrete.

2. Experimental programme

A total of 15 specimens were prepared to assess the shear behaviour of normal concrete as well as rubberised concrete with various replacement ratios of both fine and coarse aggregates in equal quantities. Two normal concrete types (C35 Grade and C70 Grade) and three rubberised concrete mixes (with the volumetric replacement ratios varying in the range of $\rho_{vr} = 0–0.6$) were considered.

2.1. Materials

The coarse and fine aggregates used in the rubberised concrete mixes were obtained from natural deposits with various mineral compositions [24]. The fine aggregates had sizes up to 5 mm with the specific gravity of 2.65 and initial moisture content of 5%, whilst the coarse aggregate had sizes of 5–10 mm with the specific gravity of 2.65 and moisture content of 3%. The rubber particles used in the rubberised concrete mixes were acquired from two sources. Smaller rubber particles with diameters between 0–4 mm and 4–10 mm, were manufactured from recycled car tyres [25]. As illustrated in Fig. 1a, larger rubber particles with a size range of 10–20 mm were obtained from shredded truck tyres [26]. The results of a sieve analysis carried out for both mineral aggregates and rubber particles are presented in Table 1. The proportions employed in the rubberised concrete mixes were optimised for balancing the workability and strength loss in a previous study carried out by Raffoul et al. (2016) [8] as part of a wider European research project [27].

2.2. Mix design and sample details

The rubberised concrete mixes prepared for assessment of shear behaviour, are referred to herein as R20, R45 and R60, representing 20%, 45% and 60%, respectively, in terms of volumetric replacement of both fine and coarse aggregates. As described in Table 2, the mix details were derived from reference high strength concrete mixes. From the total quantity of binders reported in the table, 80% was CEM I 52,5 [28], 10% was EN 450–1 [29] fineness category S fly ash and 10% was Grade