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Performance of rubberised reinforced concrete members under cyclic loading

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ABSTRACT

This paper presents an experimental investigation into the cyclic behaviour of reinforced concrete members incorporating a significant proportion of recycled rubber particles as a replacement for mineral aggregates. Tests were carried out on thirteen large scale members of circular cross-section, with and without external confinement, and with different proportions of rubber content and axial loads. The specimens were subjected to inelastic lateral cyclic displacements and predefined levels of co-existing axial loading. After describing the testing arrangement and specimen details, the main results and observations are provided and discussed. The test results enable a direct comparative assessment of the key response characteristics of the specimens, with focus on stiffness properties and strength interaction, as well as ductility and energy dissipation. It is shown that rubberised reinforced concrete members can offer a good balance between bending capacity and ductility in comparison with conventional reinforced concrete members, particularly for low levels of axial loads. In the presence of relatively high axial loading and when a significant proportion of rubber content is used, external confinement such as through FRP sheets as employed in this study, can be adopted to recover the required capacity and to provide highly stable hysteretic response. The implications of the findings on the use of rubberised reinforced concrete members in practice, and procedures that can be used to determine the main design parameters, are also highlighted within the discussions.

1. Introduction

In addition to the environmental benefits of using rubber as replacement for mineral aggregates in concrete, the presence of rubber particles can also offer other merits in terms of structural performance. In recent years, several investigations considered the combination of rubber particles resulting from tyre recycling with cementitious materials in various applications including crash barriers [1–4], floors and pavements [5–8], blast panels [9,10], amongst others. These studies focused primarily on the response of combined rubber and concrete materials at the constitutive level through detailed studies including their fresh and hardened properties [11–21], durability [22,23], rubber-cement matrix interactions [10,24–26], sound absorption [27,28], as well as thermal and dynamic characteristics [29–33].

The above-noted previous studies showed that the embedded rubber particles modify the fresh and hardened properties of the concrete as a function of the percentage of rubber replacement and grain size, with only a marginal effect arising from the type of rubber used. The relatively low specific gravity of rubber leads to a reduction in the unit weight in comparison with conventional concrete. The presence of rubber particles also leads to a reduction in compression strength, splitting tensile strength, elastic modulus and shear resistance of rubberised concrete materials [14,34], yet it can provide improved ductility and energy dissipation characteristics. Although investigations on the behaviour of structural members incorporating rubberised concrete materials have been limited compared to studies at the material level, the potential benefits have been illustrated [35–43].

Earlier studies on members included tests on rectangular columns with varying rubber content subjected to uniaxial compressive loading [35]. These tests showed that apart from the reduction in load carrying capacity, rubberised columns were capable of undergoing up to twice the lateral deformations before buckling compared to conventional concrete columns. Other tests on reinforced concrete beam and column specimens with replacement of sand by rubber of up to 18% showed that while the material compressive strength reduced by about 31%, the reductions in the ultimate beam and column member capacities was about 6% and 12%, respectively [42]. On the other hand, tests on rubberised reinforced concrete columns, with and without external confinement using polymeric sheets, showed that high levels of energy dissipation can be obtained in comparison with conventional reinforced

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Nomenclature

Greek letters

δ	lateral displacement or deformation
δ_{cr}	lateral deformation at cracking
δ_f	lateral deformation at rebar fracture
δ_y	lateral deformation at flexural yielding
δ_u	lateral deformation at ultimate load corresponding herein to 20% decrease in capacity
ε	strain
ε_1	axial strain
ε_2	lateral strain
$\varepsilon_{c0,1}$	crushing strain of conventional reference concrete
ε_{cu}	ultimate concrete strain
ε_{cu2}	ultimate concrete strain for simplified design
ε_{c0u2}	ultimate concrete strain of reference concrete for simplified design
ε_{rcu2}	ultimate concrete strain of rubberised concrete for simplified design
ε_{2u}	ultimate lateral strain
$\varepsilon_{rc1,1}$	axial crushing strain
$\varepsilon_{rc2,1}$	lateral strain at crushing
ε_{rcc1}	axial strain for confined rubberised concrete
ε_{rcc2}	lateral strain for confined rubberised concrete
ε_{rccu}	ultimate strain for confined rubberised concrete
ε_{sy}	steel yield strain
θ	slope
λ	factor for the size of mineral aggregate replaced
λ_k	assessed stiffness parameter
$\lambda_{k,test}$	test stiffness parameter
μ_ψ	rotation ductility
ν	axial load ratio
ρ_l	flexural reinforcement ratio
σ	stress
τ	plastic hinge parameter
Δ_y	drift at yielding
ψ	rotation
ψ_y	rotation at yielding
ψ_p	plastic rotation
ψ_u	ultimate rotation

Lowercase latin letters

d_b	longitudinal rebar diameter
e	eccentricity
f_{c0}	cylinder reference concrete strength
f_c	cylinder concrete strength
$f_{c,cube}$	cube concrete strength
f_{ct}	concrete splitting strength
f_{cc}	confined concrete strength
$f_{c,top}$	cylinder concrete strength above the rubberised region
f_{rc}	rubberised concrete strength
f_{rcc}	confined rubberised concrete strength
f_t	fracture strength of the longitudinal steel
f_{tw}	fracture strength of the transverse steel
f_y	yield strength of the longitudinal steel
f_{yw}	yield strength of the transverse steel
h_f	footing depth
$k_{cr,test}$	test member inelastic stiffness
$k_{el,calc}$	assessed member elastic stiffness
l_f	footing length
l_{rub}	length of the rubberised concrete region
l_{conf}	length of the externally confined region
s_w	stirrup spacing

Uppercase latin letters

D	column diameter
E_d	energy dissipation
E_s	steel elastic modulus
E_{rc}	rubberised concrete elastic modulus
EI_{el}	elastic cross-sectional stiffness
L	moment length
L_{pl}	plastic hinge length
$L_{pl,test}$	test assessed spread of plasticity
L_{tot}	total member length
M	bending moment
M_y	bending moment at yield
M_u	bending moment at ultimate
N	axial load
N_{max}	maximum axial capacity of the member
Ø	diameter
P	applied lateral load
V	shear force
V_{cr}	cracking lateral force
V_{max}	maximum lateral force
V_y	yielding lateral load

concrete members [37]. Other tests in which thin steel tubes were infilled with rubberised or normal concrete indicated only a marginal influence from the type of concrete infill on the inelastic behaviour of the members [41].

Although previous tests have demonstrated the viability and potential benefits of using rubberised concrete materials in structural elements, available experimental results have been limited to member configurations in which relatively small proportions of total aggregate replacement, typically well below 20%, have been employed [36,37]. In general, there is a need for further research on the inelastic performance of structural members, especially for cases in which relatively large proportions of rubber particles as a replacement for mineral aggregate are incorporated. In this respect, an earlier study by the authors on rubberised concrete materials showed that the loss of strength is significant up to replacement levels of 10–15%, but the rate of reduction decreases with higher replacement ratios [14]. It was also shown that the rubber content has a less detrimental influence on the bond properties in comparison with its influence on the uniaxial compressive strength, with bond coefficients exhibiting largely constant trends irrespective of the rubber content up to replacement ratios of 60% [44]. This suggests that higher replacement ratios may offer an improved balance between the environmental benefits of using rubber as well as enhanced ductility, energy dissipation, and reliable bond behaviour on the one hand, and the loss in concrete strength on the other hand.

This paper describes a detailed experimental study on reinforced concrete member specimens subjected to inelastic lateral cyclic displacements and different levels of co-existing axial loads. The test series includes specimens that employ concrete materials incorporating rubber particles representing relatively large replacement proportions of mineral aggregates up to 60%. A detailed account of the test results from thirteen large-scale tests on 350 mm and 250 mm diameter circular reinforced rubberised concrete members, with or without external confinement through FRP sheets, is given. Based on the test results and observations, key response characteristics including stiffness properties and strength interaction, as well as ductility, spread of plasticity and energy dissipation, are assessed and compared, and the main