Construction and Building Materials 154 (2017) 884–898

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Bond-slip response of deformed bars in rubberised concrete

D.V. Bompa, A.Y. Elghazouli *

Department of Civil and Environmental Engineering, Imperial College London, UK

HIGHLIGHTS

- Assessment of complete bond-slip behaviour of deformed bars in rubberised concrete.
- Fifty-four pull-out tests on cylindrical specimens using two reinforcement sizes.
- Direct evaluation of confinement effect and its influence on failure modes.
- Examination of key bond parameters and detailed interfacial behaviour.
- Proposed representations for bond characteristics and associated failure modes.

ARTICLE INFO

Article history:
Received 26 May 2017
Received in revised form 2 August 2017
Accepted 4 August 2017
Available online 10 August 2017

Keywords:
Bond-slip
Bond strength
Rubberised concrete
Recycled rubber
Deformed bars

ABSTRACT

This paper is concerned with examining the complete bond-slip behaviour between deformed reinforcement bars and concrete incorporating rubber particles from recycled tyres as a partial replacement for mineral aggregates. An experimental study consisting of fifty-four pull-out tests on cylindrical rubberised and normal concrete specimens, in conjunction with two reinforcement sizes with short embedment lengths, is described. In addition to a detailed assessment of the full bond-slip relationship, the test results offer a direct interpretation of bond behaviour under practical levels of confinement and its influence on the failure modes. Particular emphasis is given to the characteristic bond behaviour of rubberised concrete in terms of maximum bond strength and splitting strength as well bond stiffness and slip parameters. The detailed test measurements and observations provided in this study enable the definition of key bond parameters depicting the interfacial behaviour between rubberised concrete and deformed bars. The findings also permit the development of modified approaches for reliable representation of the failure modes and bond capacities for the concrete materials considered in this investigation.

1. Introduction

In addition to its sustainability-related merits, the use of recycled rubber in concrete has potential structural performance benefits, particularly in terms of enhanced energy dissipation under dynamic loads. The mechanical properties of rubberised concrete have therefore been investigated in many previous studies, with a particular focus on the compressive strength properties e.g. [1–16]. In order to use such modified concrete materials in structural applications there is, however, a need for a reliable characterisation of the bond interaction with the embedded reinforcement bars. The bond behaviour is governed not only by the mechanical strength of concrete but also by its microstructure [17]. In rubberised concrete, the interface behaviour between steel and concrete may be significantly altered by the replacement of mineral aggregates with recycled rubber in terms of the stiffness, strength and overall characteristics of the bond-slip relationship.

In normal concrete, the bond strength between deformed bars and concrete is developed by chemical adhesion and steel-concrete friction followed by the mechanical interlocking of the rebar ribs [18,19]. The mechanical bond resulting from the rebar ribs-concrete keys interaction produces ring/burst forces and splitting cracks which may produce failure by splitting or pull-out [20–24]. The bond behaviour is typically examined using conventional pull-out type tests [25,26]. In such tests, premature splitting failures can be arrested through confining action by stirrups [27,28] or external devices [29–31]. Tests showed nonetheless that the bond strength exhibits an upper bound, since there is a limit of confining pressure which forces bond failure due to shearing of the concrete keys between the rebar ribs [26,29].

Previous studies on deformed bars showed that the governing parameters in bond behaviour are those related to mechanical bond, rather than chemical adhesion and friction [31]. Under

---

* Corresponding author.
E-mail address: a.elghazouli@imperial.ac.uk (A.Y. Elghazouli).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.016

Nomenclature

Greek letters

α	bond stiffness parameter
γ_b	bond coefficient
δ	displacement
Δs	relative slip
ε	strain
ε_u	ultimate tensile strain
η_2	bond parameter for splitting strength
λ	rubber replacement ratio parameter
λ_{sp}	splitting parameter
ρ_{rv}	rubber replacement ratio
σ	stress
$\sigma_{l,cc}$	lateral confinement force
τ	bond stress
$\tau_{b,f}$	residual bond strength
$\tau_{b,max}$	maximum bond strength
$\tau_{b,test}$	maximum test bond strength
$\tau_{b,y}$	yield bond strength
$\tau_{bu,sp}$	splitting strength

Lowercase latin letters

c_{min}, c_{max}	concrete covers
d_b	bar diameter
d_{col}	column diameter
d_{bw}	stirrup diameter
$d_{g,repl}$	size of the replaced aggregate
$d_{g,max}$	maximum aggregate size
f_c	cylinder compressive concrete strength
$f_{c,cube}$	cube compressive concrete strength
$f_{ct,sp}$	concrete material splitting strength
f_y	steel yield strength
f_u	steel ultimate tensile strength
f_R	relative rib area
l_b	embedded bond length
s_i	slip parameters
s	slip
s_R	rib spacing
u	bar perimeter

Uppercase latin letters

A_b	bar cross-sectional area
F_b	bond force
$F_{b,max}$	maximum bond force
G_b	bond post-peak energy
Ø	diameter

confinement conditions that prevent splitting failure, enhanced bond strengths are obtained from higher relative rib areas [32,34–36] independently of the specific combination of rib height and rib spacing [37], whilst rib inclination and angle have minimal influence on the bond behaviour [38]. Previous studies have reported an increase in bond strength with increase in confining pressure [20,28,27,37,39], yet it tends to level off at ratios of $\sigma_{l,cc}/f_c$ of between about 0.25 and 0.30, where $\sigma_{l,cc}$ is the lateral confining stress and f_c is the concrete strength.

Limited information exists on steel-concrete bond behaviour in rubberised concrete, whilst tools to assess bond parameters are lacking. Tests on 20 mm rebar pull out resistance were performed on plain and self-compacting rubberised concrete samples with rubber replacement ratio of 18% and 14%, respectively, in equal quantities of both coarse and fine aggregate with pre-coated crumb rubber [40]. These tests showed lower maximum bond strength $\tau_{b,max}$ but higher bond coefficient γ_b, assessed as the ratio between $\tau_{b,max}$ versus square root of the concrete compressive strength $f_c^{1/2}$, compared to normal concrete, resulting in reduced slip displacement at maximum bond strength. Although, in actual values, $\tau_{b,max}$ decreases as the mineral aggregates are replaced by rubber, the bond coefficient γ_b follows an inversely proportional relationship with the rubber content. Additionally, the reduced slip displacement $\tau_{b,max}$ is directly related to the higher bond stiffness for rubberised concrete tests in comparison to the normal concrete tests.

Another study on replacements of fine and coarse aggregates with crumb rubber and tyre chips in ratios ranging from 0–30% in 5% increments showed that the bond strength for 16 mm rebars was lower by up to 40% compared with normal concrete for the highest rubber content [41]. Other tests on 10 mm rebars in cylindrical samples with a replacement of fine and coarse aggregates up to 40% by weight also showed a consistent decrease of up to 60% [42]. This was attributed to a reduction in shear strain at the steel-concrete interface resulting from the low modulus of rubber which allows greater absorption of kinetic energy [40,41]. The friction between the rebars and rubberised concrete seems to be relatively low, primarily due to the weak interfacial bond between rubber particles and cement paste which allows premature cracking to develop [43]. However, as noted before, the bond behaviour is not only governed by concrete properties, but also by reinforcement geometry. Surface properties and rib configuration may increase the bond strength by up to two folds [21]. The compaction level and concrete porosity can also have an influence on interface behaviour. Details of rebar geometry are however not reported in previous studies [40–42], hence restricting appropriate assessment.

As noted above, in normal concrete the bond behaviour depends on the mechanical properties of the concrete, its microstructure, rebar configuration, concrete thickness and level of confinement. The presence of rubber particles in concrete modifies its microstructure, which directly influences the interlocking behaviour between rebar ribs and concrete keys and consequently the splitting and crushing actions near the interface region. Additionally, the mechanical properties of rubberised concrete under external confinement are strongly modified for high rubber replacements [44–46], hence the bond behaviour of deformed bars in confined rubberised concrete is also expected to change. Although some information exists on rebar-rubberised concrete interface behaviour, it is limited to bond strengths rather than the full bond-slip behaviour, whilst the influence of confinement has not been investigated. Also, procedures to predict the bond-slip response including the maximum bond strength between deformed rebars and rubberised concrete are lacking.

In this paper, 54 pull-out tests in which deformed rebars embedded in concrete cylinders of normal and rubberised concrete, with up to 60% aggregate replacement, are described. The experimental investigation focused on examining the bond strength and the complete bond-slip relationship, as well as on evaluating the influence of bar diameter and controlled external confinement on the bond behaviour. After describing the test configuration and specimen details, comparative assessments in terms of peak strength and bond-confinement interaction are carried out in order to quantify the influence of rubber content on the bond characteristics. Complementary material tests, including the complete stress-strain response of the concrete and steel materials considered, are also reported. The detailed test measurements