Construction and Building Materials 180 (2018) 519–530

Contents lists available at ScienceDirect

Construction and Building Materials

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

Influence of lightweight aggregates concrete on the bond strength of concrete-to-concrete interfaces

H. Costa[a], R.N.F. Carmo[a,*], E. Júlio[b]

[a] CERIS and Polytechnic Institute of Coimbra, Rua Pedro Nunes – Quinta da Nora, 3030-199 Coimbra, Portugal
[b] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

HIGHLIGHTS

- Evaluation of the bond strength of LWAC/NDC and LWAC/LWAC interfaces.
- Significant differences between experimental results and the predictions according to EC2 and fib MC2010.
- The binding matrix strength and the type of aggregate have a major influence in the interface strength.
- It is presented expressions to predict the coefficients of cohesion and friction based in the roughness parameter Rpm.
- There is no advantage, in terms of strengths at interfaces, to increase the surface roughness above a certain limit.

ARTICLE INFO

Article history:
Received 23 February 2018
Received in revised form 14 May 2018
Accepted 1 June 2018

Keywords:
LWAC
Bond strength
Concrete-to-concrete interface
Roughness

ABSTRACT

An experimental study carried out to characterize the bond strength of lightweight aggregate concrete (LWAC) to normal density concrete (NDC) and LWAC-to-LWAC interfaces is presented, also including NDC-to-NDC interfaces as reference. A single NDC mixture, with a compressive strength of 50 MPa, and three LWAC mixtures, with density range between 1500 and 1900 kg/m^3 and compressive strength between 45 and 75 MPa, were adopted. Slant shear and splitting tests were conducted to evaluate the interface bond strength, considering different methods to increase the surface roughness of the substrate. Results were analysed and compared with predictions according to Eurocode 2 (EC2) and *fib* Model Code 2010, and showed significant differences, mainly for rough surfaces. It was found that the role of the binding matrix strength and of the type of aggregate, in the interface strength, is dependent of the roughness of the substrate; the coefficients of cohesion and friction exhibited a good correlation with the roughness parameter “mean peak high”, R_{pm}, being the cohesion also influenced by the matrix strength of the added concrete. It was also concluded that there is no advantage, in terms of shear and tensile strengths of interfaces with LWAC, to increase the surface roughness above a certain limit.

1. Introduction

In the last decades, with the development of the concrete production technology, it became possible to produce structural concrete with density values well below 2000 kg/m^3, called lightweight aggregate concrete (LWAC). This is obtained by replacing current aggregates by artificially produced aggregates, with reduced density, but keeping adequate mechanical performance and durability [1–7]. LWAC represents an interesting solution, not only for new structures, including precast structures, where the reduction of the self-weight plays an important role, but also for strengthening existing structures, for the same reason. In both cases the result is a composite member comprising a LWAC layer and a normal density concrete (NDC), or a LWAC, substrate. Therefore, it is fundamental to check if design expressions in current codes, empirically formulated for NDC-to-NDC interfaces, still apply for LWAC-to-NDC and LWAC-to-LWAC interfaces, or if adjustments or corrections are required.

Research on the bond strength of concrete-to-concrete interfaces started in the 1960s, mostly oriented for precast reinforced concrete (RC) members with cast-in-place parts. The most important contribution in this scope is the ‘shear-friction theory’, presented in 1966 by Birkeland and Birkeland [8]. The latter assumes that the shear strength of the concrete-to-concrete interface is mobilized through a relative slip between both concrete parts. Due to the surface roughness, this also originates a relative normal displacement (dilatancy), inducing tensile yielding stresses

---

* Corresponding author.
E-mail address: ricarmo@sapo.pt (R.N.F. Carmo).

https://doi.org/10.1016/j.conbuildmat.2018.06.011
0950-0618/© 2018 Elsevier Ltd. All rights reserved.

on the reinforcement crossing the interface. As a reaction, the interface develops compressive stresses and resists slippage by friction.

During the last 50 years, different researchers have proposed several modified versions of the shear friction theory [9–14]. A comprehensive literature review of most relevant studies on this subject can be found in [15]. In 1997, Randl [16] proposed a design expression that considers the interface shear strength as the sum of three different effects: cohesion, friction and dowel action. Cohesion is related with adhesion and aggregates interlock; friction results from the relative slippage between concrete parts and is influenced by the surface roughness and the normal stress (applied and/or caused by reinforcement tensile stress combined with dilatancy) at the interface; and dowel action refers to the specific localized deformation of rebars crossing the interface due to slippage; all these effects oppose to slippage and thus contribute to the interface shear strength.

Few of the approaches cited in [15] have been adopted in design codes. In [17], a comparison between results obtained with some design codes' expressions, as well as with both experimental and numerical results, is presented. In Table 1, the expressions adopted in: (i) the International Federation of Concrete model code, *fib* MC 2010 [18], (ii) the European design code, EC2 [19], (iii) the North American design code, ACI [20], and (iv) the Canadian design code, CAN/CSA [21], are presented.

It should be highlighted that both cohesion and friction coefficients depend on the roughness of the interface and have a major influence on the bond strength. These were typically assessed with a qualitative approach in all codes. To overcome this clear disadvantage, Santos and Júlio [22] developed a method and equipment, the latter named 2D Laser Roughness Analyser, to measure the interface surface roughness and, based on this, to compute both cohesion and friction coefficients. Following this, the *fib* MC 2010 [18] adopted a new approach, linking the traditional qualitative characterization of the interface surface roughness with the quantitative characterization of the latter.

2. Main goals and research significance

Most studies on the bond strength of concrete-to-concrete interfaces focused on normal density concrete (NDC). Similarly, in codes, the influence of concrete density either is not considered or is addressed in a simplified way. More specifically, as shown in Table 1, both ACI 318 [20] and CAN/CSA A23.3 [21] present a parameter λ that depends on the concrete density, but this does not consider all the aspects related with the shear strength between concretes with different densities. In fact, very few studies addressed this topic. One of these studies [23] was performed to study the strength of interfaces in lightweight aggregate concrete (LWAC) bridge girders, another study [24] was performed to study the influence of different lightweight aggregates in the interface shear transfer and another one [25] was conducted aiming at examining the applicability of both ACI 318 and PCI Design Handbook specifications for different types of LWAC. Those studies [23–25] concluded that codes provide conservative design approaches (through the λ parameter) when LWAC is used. Therefore, the major goal of the study herein presented is to help filling the gap regarding the shear strength of the interface between LWAC-to-NDC (Fig. 1) and LWAC-to-LWAC.

A recent study [13] addressed parameters not considered in codes but that can also influence the bond strength of NDC-to-NDC interfaces, such as: (i) concrete curing conditions of both the overlay and the substrate, (ii) differential shrinkage, and (iii) differential stiffness. Regarding LWAC-to-NDC interfaces, it can be stated that both curing conditions and differential shrinkage are expected to have a less significant influence on the interface bond strength, due to the improved internal curing and reduced shrinkage of LWAC, resulting from the extended hydration of the binder matrix ensured by the water stored inside the lightweight

Fig. 1. Interface between LWAC-to-NDC.

Table 1
Design shear strength of concrete-to-concrete interfaces, according to international, European, North American and Canadian codes.

fib Model Code 2010	Interfaces without reinforcement (rigid bond-slip behavior) $v_{rd} = c\,f_{ctd} + \mu\,\sigma_n \leqslant 0.5\nu\,f_{cd}$ Interfaces intersected by reinforcement $v_{rd} = c_r\,f_{ck}^{1/3} + \mu\,\sigma_n + \kappa_1\,\rho\,f_{yd}(\mu\sin\alpha + \cos\alpha) + \kappa_2\rho\sqrt{f_{yd}\,f_{cd}} \leqslant \beta_c\nu f_{cd}$
Eurocode 2	$v_{rd} = c\,f_{ctd} + \mu\,\sigma_n + \rho\,f_{yd}(\mu\sin\alpha + \cos\alpha) \leqslant 0.5\nu\,f_{cd}$
ACI 318	$v_{rd} = \rho f_{yd}(\mu\sin\alpha + \cos\alpha)$
CAN/CSA A23.3	$v_{rd} = \lambda\phi_c(c + \mu\sigma) + \phi_s\rho\,f_{yd}\cos\alpha$

where c is the adhesive or cohesion coefficient and is related with roughness of the interface; c_r is the coefficient for aggregate interlock effects at rough interfaces; f_{cd} is the design compressive strength of the concrete; f_{ck} is the characteristic compressive strength of concrete; f_{ctd} is the design tensile strength of the concrete with the lowest strength; f_{yd} is the design yield stress of the reinforcement; α is the angle between the reinforcement and the interface shear plane; β_c is the coefficient for the strength of the compression strut; κ_l is the interaction coefficient for tensile force; κ_2 is the interaction coefficient for flexural resistance; λ is a factor that depends on concrete density; μ is the friction coefficient (in ACI 318, this coefficient is affected by the concrete density using the λ factor); v is equal to $0.55\left(\frac{30}{f_{ck}}\right)^{1/3} < 0.55$, in *fib* MC 2010, and to $0.6\left[1 - \frac{f_{ck}}{250}\right]$, in EC2, with f_{ck} in MPa; v_{rd} is the design shear strength of the concrete-to-concrete interface; ρ is the reinforcement ratio of the reinforcing steel crossing the interface being given by A_s/A_i, A_s is the area of reinforcement and A_i is the area of the interface; σ_n is the compressive stress resulting from normal force acting on the interface; ϕ_c is the resistance factor for concrete taken as 0.65; and ϕ_s is the resistance factor for reinforcing bars taken as 0.85.