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Bonding of steel reinforcement in structural expanded clay lightweight aggregate concrete: The influence of failure mechanism and concrete composition

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HIGHLIGHTS

- The concrete–steel bond of LWC is characterized for different failure mechanisms.
- In splitting, the bond strength of LWC was 70% that of normal concrete.
- The bond strength of LWC can be more than twice that of NWC of equal compressive strength.
- It has been shown that the normative expressions proposed for LWC may be too unrealistic.
- A new approach for estimating the LWC bond strength has been suggested.

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ABSTRACT

A comprehensive experimental study on the concrete–steel bond behaviour of structural expanded clay lightweight aggregate concrete (LWC) was carried out using different compositions, types and initial wetting conditions of lightweight aggregates, anchorage lengths, reinforcement arrangements, strength classes and failure mechanisms. For splitting failure, the bond strength of LWC was about 70% that of normal weight concrete (NWC). But when the confinement is sufficient and pull-out of the reinforcement occurs, the relative performance of LWC and NWC may vary widely. The reduction of the bond strength with LWC was roughly proportional to $\rho_d/2200$, where ρ_d is the concrete dry density. The addition of silica fume had little effect on the LWC bond strength. The bond was impaired when the LWA was pre-soaked. LWC seems to be less affected by the position and orientation of the reinforcement. It is shown that the water/cemet (w/c) ratio has a greater influence on the bond strength than on compressive strength. The bond strength was higher in the lower w/c concrete, regardless of the type of aggregate. Moreover, the bond strength of LWC was more than twice that of NWC of equal compressive strength. It is shown that the application of reduction factors to the LWC bond strength, as suggested in the main standards, may be too unrealistic. A new approach for estimating the LWC bond strength is suggested.

1. Introduction

Although some studies have been carried out on the steel–concrete bond in structural lightweight aggregate concrete (LWC), particularly in the last 20 years (e.g., [1–4]), several uncertainties persist regarding the LWC bond behaviour and its normative approach, especially taking also into account high strength LWC. In the main normative documents, such as ACI 318 [5], EN 1992 [6] and MC 2010 [7], the steel–LWC bond is usually grossly estimated from the expressions defined for normal density concrete (NWC), which are multiplied by an empirical factor that takes into account the lower tensile strength of LWC [8].

It is well known that the force transfer between steel and concrete is ensured by chemical and micromechanical physical adhesion, friction, crushing strength of concrete near the steel ribs (wedge action) and by the interlocking effect of coarse aggregates [9–11]. These mechanisms are activated at different loading stages. The adhesion component should be better in LWCs since they usually have lower w/c ratios than NWC of equal compressive strength [12]. On the other hand, the micro-cracking is minimized by the better elastic compatibility between the lightweight aggregates (LWA) and the surrounding mortar, which improves the steel–concrete adhesion in LWC. The internal curing provided by LWA

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Acronyms

LWA	lightweight aggregates
LWC	lightweight concrete
LWS	lightweight sand
LWSC	lightweight concrete with lightweight sand
NA	normal weight aggregate
NWC	normal weight concrete
SF	silica fume

can also contribute to the better quality of the surrounding paste. However, the interlocking and wedge effect tend to be lower in LWC, because the LWA has lower crushing strength and is less rigid than normal weight aggregate (NA). In general, the lower strength of LWA causes LWC to have lower tensile and crushing strength than NWC. Therefore, the bonding strength of LWC, with or without confinement, should be lower than that of the NWC of equal composition [13].

However, it is not known how the bond behaviour of LWC compares with that of NWC of equal strength. There are contradictory results in the literature. Some authors consider that the bond strength of LWC is similar to or slightly higher than that of NWC of equal compressive strength [14–17] and others report that it is clearly lower [1–3,18,19]. Besides the different types of LWA, the concrete strength, the failure mechanism, the type of test and test conditions, the anchorage length, the bond stress distribution along the rebars and the concreting conditions, are some important factors that can contribute to the contradictory results reported in the literature.

Clarke and Birjandi [17] found higher bond stresses in LWC than in NWC of equal strength, concluding that the normative coefficients proposed for LWC are too conservative. However, Orangun [19] reported bonding stresses in LWC produced with fly ash LWA about 75–85% of those obtained in NWC of equal strength (≅25–40 MPa). Similar reductions, of about 10%, were obtained by Ofori-Darko [20] in pull-out failures of reinforced LWC of moderate strength (53 MPa), also produced with fly ash LWA. Shiedeler [14] and Orangun [19] also reported that the concrete quality surrounding the reinforcement tends to be lower in this type of low strength LWC.

Hossain [4] conducted pull-out tests to assess the bond performance of plain and ribbed bars embedded in low strength LWC (30 MPa) produced with pumice LWA. In general, the failure mechanism and the local bond stress–slip curves were similar in LWC and NWC, although the normalized stresses were 12% higher in NWC.

Based on pull-out tests with 19 mm bars, Mor [1] studied the steel–concrete bond of LWC with expanded shale LWA. The lower tensile strength of LWC led to splitting failures with bonding stresses 20–30% lower than those of NWC of equal compressive strength (of 63–67 MPa). Also for splitting failures, Robins and Standish [18] found 10–15% higher bonding strengths in NWC than in LWC. However, when the confinement was sufficient and pull-out failure occurred, the difference increased to about 45%. On the other hand, Esfahani and Rasolzadegan [15] reported slightly higher bonding strengths in LWC than in NWC of equal strength, even for splitting failures.

Published works on high-strength LWC are still scarce. In addition to the Mor [1] investigation, Mitchell and Marzouk [2] carried out pull-out tests with 25 and 32 mm bars embedded 6ϕ in LWC of 83 MPa. The average bond strength, normalized to $f_c^{1/3}$, was 6% to 10% lower in LWC than in NWC.

Walraven et al. [3] carried out pull-out tests on four concrete types with 30 MPa and 60 MPa, produced with normal weight aggregates and expanded clay and fly ash LWA. For short embedment lengths and pull-out failures the maximum bond stresses were always higher in NWC.

Based on the results obtained by different authors and also according to the ACI213R [13], the maximum bond stress of LWC may range from about 70% to the slightly higher values obtained for NWC. There is a great influence of the failure mechanism. The contradictory results reported in the literature show that the steel–LWC bond behaviour is not well known yet. To better understand the LWC bond behaviour, concretes of different compositions and strength levels should be analysed for each bond failure mechanism. This is the philosophy followed in the present study.

This paper aims to characterize the steel–concrete behaviour of LWC, taking into account: different types and initial wetting conditions of lightweight aggregates; different anchorage lengths, casting directions with respect to rebar orientation and strength classes; the partial replacement of normal weight sand by lightweight sand aggregate (LWS); the use of silica fume, and, most of all, different failure mechanisms.

2. Experimental programme

2.1. Materials

Two Iberian expanded clay lightweight aggregates were analysed: Leca from Portugal and Arlita from Spain. Their total porosity, P_T, particle density, ρ_p, bulk density, ρ_b, and 24 h water absorption, $w_{abs,24h}$, are indicated in Table 1. A more detailed microstructural characterization of these aggregates is presented elsewhere [21,22]. In terms of their specific properties, the selected LWA are categorized as Type A (Arlita) and Type B (Leca), which represent LWA of different porosity (Table 1). With these two very different types of LWA is possible to cover the most usual structural LWAC with compressive strengths from about 30 to 70 MPa. Normal density coarse and fine aggregates (NA) were also used. For the reference normal density concrete, two crushed limestone aggregates of different sizes were combined in order to have the same grading curve as Leca (20% fine and 80% coarse gravel). Fine aggregates consisted of 2/3 coarse and 1/3 fine sand. Their main properties are listed in Table 1. The cement Type I 42.5R and a polycarboxylate based superplasticizer (Sp) were also used.

Hot-rolled steel ribbed bars of 12 mm diameter were used in the pull-out tests described in 2.3. The reinforcement is characterized by an average yield strength, f_{ym}, of 584 MPa and an average ultimate strength, f_{um} of 714 MPa.

2.2. Concrete mixing and mixture proportions

The concretes were produced in a vertical shaft mixer with bottom discharge. In general, LWC was produced with aggregates pre-dried at 200 °C. Based on the method suggested by Bogas et al. [23], the absorption of LWA in the mix was estimated beforehand to take into account the correction of the total mix water. Pre-dried aggregates were placed in the mixer with sand and 50% of the water. After 4 min of mixing, the cement and 40% of the water were added. The SP was slowly added with 10% of water, after 1 more minute. The total mixing time was 9 min. The fresh concrete was compacted with an internal vibrator at 9000 cycles per minute.

Eleven different compositions were designed according to Bogas and Gomes [24] to take into account different types of aggregate and strength levels, the use of silica fume and the partial replacement of natural sand by LWS (Type B 0–3, Table 1). A concrete mix with Type B LWA, initially pre-soaked for 24 h, was also produced.

The compositions and their respective fresh, ρ_f, and dry, ρ_d, density are listed in Table 2. The w/c ratio is the effective water available for cement hydration. The Sp/c is the percentage of superplasticizer by cement weight. The denominations ‘NWC’, ‘A’ and ‘L’ correspond to the mixes with NA, Type A and Type B aggregate. Designation ‘L450PS’ and ‘ASF8’ appear when pre-soaked Type B LWA or 8% of silica fume by weight of cement are used. Except for mixture ‘LS’ natural sand was used in combination with coarse LWA (Type A or Type B 4–12). For ‘LS’, coarse sand was replaced by the lightweight sand indicated in Table 1 (Type B 0–3). The maximum aggregate size was 12.5 mm. In general, the slump was 160 ± 20 mm.