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Analytical and experimental investigation for bond behaviour of newly developed polystyrene foam particles' lightweight concrete

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ABSTRACT

Structural lightweight concrete (LWC) is of high importance to the construction industry, as it is cost effective and highly advantageous. A new kind of LWC was produced at the Department of Structural Engineering of Ain Shams University in 2005, which combines the advantages of normal density concrete, cellular concrete and high workability concrete through partially replacing the normal weight aggregates with polystyrene foam particles. This leads to concrete's unit weight reduction while maintaining adequate strength. The latter material can therefore be produced using standard methods familiar to the construction industry with a dry unit weight of 18.50 kN/m^3, which in turn leads to self weight reduction of 15–20% and the associated decrease in the structure's overall cost, hence, providing a feasible challenge to normal weight concrete (NWC). The bond behaviour of structural polystyrene foam lightweight concrete (PF-LWC) was investigated analytically and experimentally. The experimental program incorporated two phases. The first phase was performed on the standard pull-out specimens to compare its results with the commonly conducted bond testing and to abstract the bond slip curve of the standard pull-out test specimens. The second phase deal with a deduced beam-end specimen to assess the behaviour of bond between reinforcing bars and concrete in flexure members. Then analytical investigation of the obtained experimental results was performed to develop a model capable of assessing the structural bond behaviour of PF-LWC flexural members. The defining parameters of the bond stress–slip curve were modified for NWC and PF-LWC using the best fit technique to the experimental results in order to add the bar diameter as a variable in the bond stress–slip relationship. The defining parameters of the CEB-FIP 1990 bond stress–slip curve [1] were modified for NWC and PF-LWC using the best fitting technique.

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1. Introduction

Most of the current concrete research focuses on high performance concrete, which is a cost effective material that satisfies demanding performance requirements, including durability. LWC is of utmost importance to the construction industry that is cost effective and highly advantageous. The primary advantage of LWC is the reduction of the structural dead load, foundation loads, the sections of all structural elements, and consequently the overall cost of the structure. Furthermore, the reduced mass will reduce the lateral load that will be imposed on the structure during earthquakes, hence simplifying and reducing the lateral load carrying system. That is why the global cost of the structure may be reduced in case of using LWC rather than using NWC. The high workability of the proposed PF-LWC reduces extensively the cost of compaction. It possesses high ability to flow under its own weight, filling formwork even in the presence of congested reinforcement or complicated structure (as in most of bridge types) yet producing a dense and homogenous hardened concrete. The fluidity and segregation resistance of such type ensures a high level of homogeneity, minimal concrete voids and uniform concrete strength, providing the potential for a superior level of finish and durability to the structure.

The bond mechanism between deformed bars and concrete is highly influenced by multiple parameters such as the strength of surrounding material structure and its properties, the thickness of concrete cover, amount of confining reinforcement, development and splice length, the occurrence of splitting cracks in the concrete cover, the reinforcement steel stress, lateral pressure, direction of casting, reinforcing bar diameter and bar spacing [1]. LWC is considered more brittle than NWC, which might increase the risk of splitting cracks and de-lamination of the concrete cover.

Since 2005, an extensive experimental and theoretical research program, aiming to developing structurally and economically efficient PF-LWC as well as establishing design guidelines for all types of structural elements made using this material, is being undertaken at the Department of Structural Engineering of Ain Shams University.

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The first phase of this program resulted in a new kind of lightweight concrete, which combines the advantages of normal density concrete, cellular concrete and high workability concrete, through partially replacing the normal weight aggregates with polystyrene foam particles, hence, leading to concrete's unit weight reduction while maintaining adequate strength.

For any reinforced concrete element, there should exist a sufficient bond between the concrete and the reinforcing bars to allow for force flow between the two materials. The significance of this research appears from the ability to evaluate the bond properties of LWC with ordinary deformed steel rebars [2]. The importance of conducting an experimental and analytical investigation to identify the bond characteristic of PE-LWC is to allow for safe, reliable and efficient utilisation of PF-LWC. The full understanding of the behaviour of PF-LWC with steel rebars will encourage the confident implementation in the field by engineering community.

The objective of this experimental investigation is to evaluate the bond properties, including the bond strength, of PF-LWC with steel rebars using pullout specimens [3] and beam-end specimens [4]. The investigation focused on studying the bond of deformed, straight, unanchored steel rebars with PF-LWC in flexural members and examining the applicability of the available codes design expressions, available international bond models and some other reliable and accurate descriptive equations to PF-LWC.

2. Constituent materials and mix proportioning

Two concrete mixes were used for the specimens, the first mix was for the NWC specimens and the second mix was for the LWC specimens. In order to achieve the high workability LWC; polystyrene foam, silica fume and super plasticizer were added to the mix. The concrete mix consisted of natural sand as fine aggregate, fine crushed stone of nominal maximum size of 10 mm as coarse aggregate, fresh ordinary Portland cement and tab water. Super plasticizer was added to the LWC mix in order to achieve a common target compressive strength as that of NWC. The mix proportions for NWC and PF-LWC in addition to the target compressive strength and the resulted density are shown in Table 1.

Steel rebars of grade 240/350 and grade 400/600 were used. The mild steel smooth rebars of grade 240/350 having minimum yield strength of 240 MPa and ultimate tensile strength of 350 MPa were used for bar size of 6 and 8 mm. The high tensile steel deformed rebars of grade 400/600 having minimum proof strength of 400 MPa and ultimate tensile strength of 600 MPa were used for bar sizes of 12, 16 and 22 mm.

3. Experimental work program

The experimental program is carried out to investigate the bond behaviour of PF-LWC. The program incorporated two phases in which specimens were designed and cast to study the desired properties. The first phase is performed on the standard pullout specimens to compare the results with commonly conducted bond testing and to abstract the bond slip curve of the standard pullout test specimens. The second phase deals with a reduced beam-end specimen to assess the behaviour of bond between reinforcement bars and LWC in flexure members in both cases; confined with stirrups and unconfined [2].

3.1. Description of test specimens

3.1.1. Pullout specimens

This group consisted of 9 sets of cubes having side length of 150 mm a steel rebar embedded during casting as a standard pullout specimen according to ASTM C234 [3]. These specimens were tested in a direct pullout test to determine their bond strength and their bond stress versus slippage responses. The dimensions of the specimens were chosen according to ASTM C234 [3] specimen so that comparison with various researches is applicable. Three parameters were assessed in this investigation; the concrete type (NWC and LWC), the rebar diameter (12 mm, 16 mm and 22 mm) and the bonded length (2T, 3T and 4T). Table 2 and Fig. 1 summarise the number, details, coding and specifications of these specimens.

3.1.2. Beam-end specimens

This phase consisted of eight medium scale beam-end specimens as shown in Fig. 2. The figure first shows that the beam-end specimen had a rectangular cross-section of dimensions 150 mm × 450 mm over a total length of 700 mm representing a beam-end anchorage zone as shown in Fig. 3. These reduced specimens totally reflect the behaviour of bond between rebars and concrete in flexure members which was abstracted from ASTM A944 [4]. In this respect, specimens EL-T12 and EN-T12 had the same test bar T12 but with different concrete mixes. In addition to specimens EL-T16 and EN-T16 had the same test bar T16. Similarly specimens EL-T12CON, EN-T12CON, EL-T16CON and EN-T16CON had additional confining reinforcement. EL-T12CON and EN-T12CON had confining reinforcement of T6 with 120 mm spacing all over the specimens' length and T8 with 120 mm spacing for specimens EL-T16CON and EN-T16CON. The previous illustration clearly pronounces the parameters of the study; the concrete type through having NWC and PF-LWC mixtures, bar size through using T12 and T16, finally, the confining reinforcement through using stirrups T6 and T8 with 120 mm spacing. The coding, concrete dimensions and reinforcement details of the aforementioned specimens are also summarised in Table 3.

The steel test bars were prepared using watering hose as a bond breaker also end of test bars were threaded using lathing machine. The threaded end of the test bar was fixed to the test setup using washer and nuts.

3.2. Instrumentation

The accuracy of the measurement devices determines the reliability of the experimental program results. In this respect, accurate measurement devices were used to monitor and record the test outputs. The used LVDTs were directly connected to data acquisition; where the data is automatically collected every time interval. The time interval chosen during the tests was 0.1 s.

Table 1
Concrete mixes' proportions/m^3 and obtained properties.

Concrete mix	Cement (kg)	Silica fume (kg)	Coarse aggregate (kg)	Sand (kg)	Polystyrene foam (l)	Super plasticizer (l)	Water (l)	Obtained density (kN/m^3)	Target f_{cu} (MPa)
NWC	400	–	1200	600	–	–	230	22.5	27
PF-LWC	450	40	630	630	330	13.5	139	18.5	24