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Investigation of bond behavior between lightweight aggregate concrete and steel rebar using bending test

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Abstract. This paper investigates bond behavior of structural lightweight concrete (SLWC) and ordinary concrete (OC) comparatively using bending test called Standard Belgium Hinged Beam Test (SBHBT). For this purpose the experiments were carried out as three series on 36 beam specimens (12 specimens of SLWC and OC with 20ϕ development length, 12 specimens of SLWC with 25ϕ development length). For each series bond behavior of steel rebars with 8, 10, 12, 14 mm diameters were tested. The results indicate that bond strength of SLWC is considerable lower than OC and 20ϕ development length is insufficient for steel rebars with 12 mm and 14 mm diameters. Therefore development length of SLWC was extended to 25ϕ, even if 8 and 10 mm steel rebars provided acceptable bond strength. In this way, bond strength between SLWC and 8 and 10 mm steel rebars was developed. In addition, adequate bond behavior was achieved for 12 mm rebar but the beam in which 14 mm rebar used exceeded their bearing capacity by shear forces before yield stress. This result shows that SBHBT is more convenient for small sized steel rebars.

Keywords: bond strength; bending; structural lightweight concrete; ordinary concrete.

1. Introduction

Although many studies have been carried out, knowledge about properties of lightweight concrete (LWC) are still quite less than that of ordinary concrete (OC). In addition, current national and international codes, related to reinforced concrete, are usually prepared by evaluating the results of experimental and theoretical studies together on concrete with lower compressive strength than 50 MPa and higher unit weight than 20 kN/m^3. Therefore it isn't possible to say that equations and suggestions given in these codes are valid for LWC nowadays.

OC has better carrying capacity but its higher specific gravity is a problem in construction of high buildings for increasing the vertical carrying member dimensions. In addition, reducing the mass of the structures is of utmost importance, since the earthquake forces are proportional to the mass. One of the ways to reduce dead weight of the structures is the use of lightweight concrete. Lightweight concrete can be produced by replacing the normal weight aggregate (NWA) with lightweight aggregate (LWA), either partially or fully, depending upon the requirements and strength (Hüsem and Durmuş 1993, Hüsem 1995, Babu and Babu 2003, Juang and Hsu 2006, Shang *et al.* 2010, Dominguez *et al.* 2010).

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Chi *et al.* (2002) reported that properties of lightweight aggregates and the water/cement ratio are two significant factors affecting the compressive strength and elastic modulus of lightweight concrete. Kayali *et al.* (2002) investigated the effect of polypropylene and steel fibers on high strength lightweight aggregate concrete. They pointed out that addition of steel fibers considerably increased the ductility of lightweight aggregate concrete but did not significantly affect the value of compressive strength and using polypropylene fibers at 0.56% by volume of concrete resulted in a 90% increase in the value of the indirect tensile strength. Kılıç *et al.* (2003) showed that structural lightweight concrete (SLWC) could be produced by the use of scoria. In addition they expressed that it was mandatory to use mineral additives for producing of SLWHSC.

Complete knowledge of LWC properties is essential for evaluating the structural response (Campione and Mendola 2004). Bond strength is one of the most important properties of reinforced concrete. Even reinforced concrete owes its existence to this event, because bond strength allows redistribution of loads and moment. Many tests have been developed in order to determine distribution of shear stresses and parameters which influence development length, since beginning of the Twentieth Century. The simplest of those is pull-out test (Yeih *et al.* 2002, Ichinose *et al.* 2004). Although pull out is simple, it doesn't represent entirely bond strength behavior, because of the local compressive stresses at supports, thick concrete cover and absence of shear forces vertical to the rebar. For these reasons, pull out test isn't convenient in order to determine development length, but it can be used to compare bond behavior of rebars having different properties. Therefore, pull out tests have been improved to eliminate foregoing disadvantages. Eccentric pull out test is one of them and more reasonable than the other pull out tests, but still it doesn't represent the deflection of beams (Ersoy and Ozcebe 2001). Thus, beam tests have been developed to determine bond behavior of flexural elements more correctly. Standard Belgium Hinged Beam Test (SBHBT) is one of these and in this study, bond strength of SLWC and OC are investigated comparatively in bending by using this test (Hüsem and Durmuş 1995, Dahil 2001).

2. Experimental program

The aim of the research was to investigate bond-slip behavior of SLWC and OC comparatively in bending. For this purpose the experiments were carried out as three series on 12 beam specimens of OC and SLWC with 20ϕ development length and 12 beam specimens of SLWC with 25ϕ development length. For each series bond behavior of steel rebars with 8, 10, 12, 14 mm diameters were tested.

Table 1 Physical properties of lightweight aggregate and normal weight aggregate

Aggregate types	Aggregate size (mm)	Compressed unit weight (kN/m^3)	Loose unit weight (kN/m^3)	Specific gravity (kN/m^3)		Water absorption (%)
				Dry	Saturated	
LWA	Course >4 mm	11.70	10.10	17.95	19.85	10.6
	Fine ≤ 4 mm	12.35	10.45	17.10	19.46	13.8
NWA	Course >4 mm	15.84	14.30	26.16	26.40	0.9
	Fine ≤ 4 mm	16.27	14.60	25.71	26.00	1.1

Table 2 Mix proportions of the concretes

Concrete type	Quantities of aggregates (kg/m^3)					Saturation water (kg/m^3)	Mixing water (kg/m^3)	Cement (kg/m^3)
	Sieve size (mm)							
	0.5-1	1-2	2-4	4-8	8-16			
OC	277.6	277.6	277.6	462.7	555.3	7.40	175	350
SLWC	208.1	208.1	208.1	346.9	416.3	169.28	175	350

2.1 Materials and mixture proportions

SLWC and OC were produced by using LWA and NWA of Eastern Black Sea Region. Physical properties of aggregates are shown in Table 1. CEM I42.5 R was used as cement and dosage was kept constant at 350 kg/m^3 with 0.5 w/c ratio for both of the concretes. Mixture proportions of the concretes are given in Table 2.

2.2 Specimens, curing conditions and properties of concretes

As it was stated before, 36-beam specimens were produced to investigate bond-slip behavior of SLWC and OC. Before placing the concretes in the mold, steel rebars were covered with plastic cylinder to restrict the development length. Also 8 mm steel rebars were placed both sides of the rebars which will be tested. Purpose of using these rebars is to prevent bending and torsion of the rebars during the carrying of the beam specimens (Arslan 2007). Beam specimens used are shown in Fig. 1. In addition, three cylinder specimens were taken from all production of beams to determine and control mechanical properties of concretes. After one day, beam and cylinder concrete specimens were taken out of the casts and cured in water tank maintained at 23 ± 3°C 21 days and kept at 75 ± 5% relative humidity in the laboratory condition, till the age of testing. Specimens were tested at 28 days.

Physical and mechanical properties of SLWC and OC are shown in Table 3 and 4, respectively.

Fig. 1 Beam specimen

Table 3 Physical properties of structural lightweight concrete and ordinary concrete

Concrete type	W/C	Specific gravity (kg/m^3)			Water absorption (%)
		Oven dry	Air dry	Saturated	
SLWC	0.5	1700	1810	1995	17
OC		2340	2380	2441	4

Table 4 Mechanical properties of structural lightweight concrete and ordinary concrete

Concrete type	W/C	f_{cm} (MPa)	f_{ck} (MPa)	E_c (MPa)	Poisson ratio	$10^3 \times \varepsilon_{co}$
SLWC	0.50	19.2	18.5	11.650	0.11	2.2
OC	0.50	32.5	31.2	24.900	0.23	2.0

2.3 Test set-up

SBHBT is one of the bending tests which have some difficulties in test setup. Main purpose of choosing this test is that there isn't enough study for determining bond behavior of reinforced concrete flexural members. SBHBT enables to measure slips of the steel rebars by loading the beam at mid-point. Vertically applied loads and slips are measured by means of loadcell and LPDTs, respectively and they are recorded by acquisition system. LPDTs placed end points of the beam to measure slips of the steel rebars have 0.013 mm precision. Also a hinge is placed in the middle of the beam to ascertain the tensile forces more adequately (Arda 1968). Afterwards, yield, maximum and ultimate stresses are determined corresponding to the tensile forces at the steel rebars. Test set-up and implementing of the test are shown in Figs. 2 and 3, respectively (Arslan 2007).

Bond stress which has 0.25 mm slippage was accepted as reliable bond stress (Ferguson 1965, Ersoy and Ozcebe 2001, ACI 2005). Bond stress τ_b can be calculated as following

$$\tau_b = f_s \cdot \phi/4.1_b \qquad (1)$$

Here, tensile stress, development length and rebar diameter are shown with f_s, l_b and ϕ, respectively.

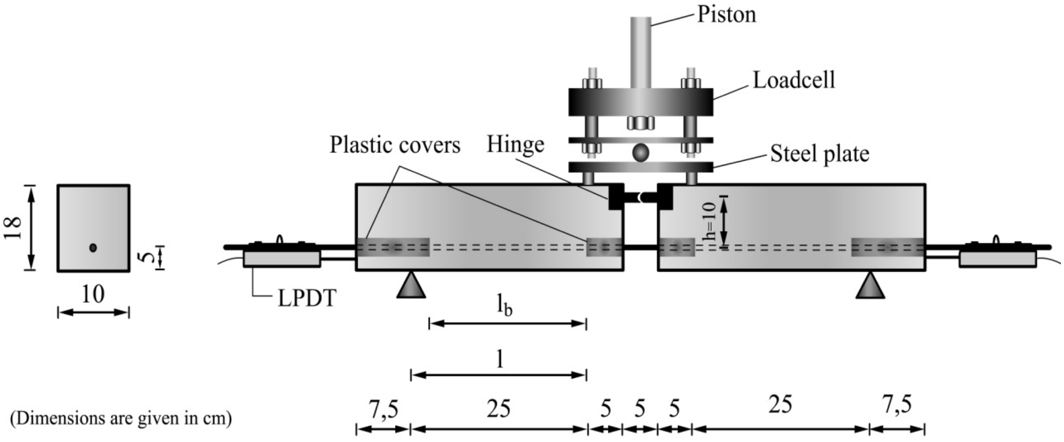

Fig. 2 Test set-up of standard belgium hinged beam test and dimensions of specimens

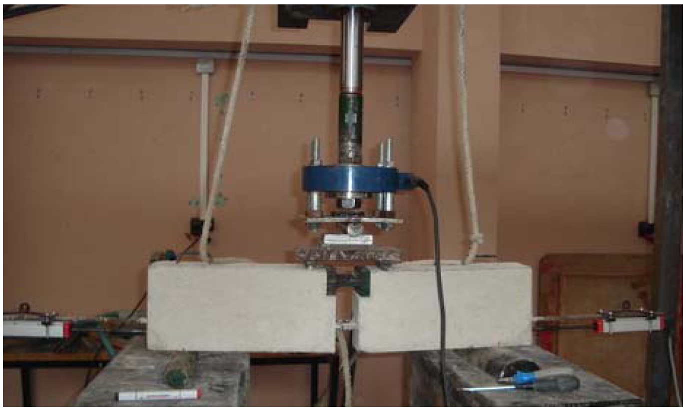

Fig. 3 A figure during standard Belgium hinged beam test

3. Results and discussion

The first series of tests were carried out on OC with 20ϕ development length for each rebars. Rebars with 8 mm diameters reached yield stress without any slippage to the OC and ruptured at the end. For 10 mm diameter rebars, there wasn't any slippage at yield stress and slip value was approximately 0.052 mm before rupture. Rebars with 12 mm didn't slip before yield stress. For this diameter, slippage increased at rupture and reached 0.142 mm. Before yield stress, 0.077 slip occurred at 14 mm rebars. When loading was carried on, beams exceeded their bearing capacity by shear forces. Amount of slip recorded for this diameter was 0.233 mm at maximum stress. This situation indicates effectiveness of the stirrups on fracture mechanism.

The second series of tests were carried out on SLWC with 20ϕ development length for each rebars. Rebars with 8 mm diameters reached yield stress without any slippage to the SLWC and at rupture 0.103 mm slip occurred. For 10 mm rebar, slippage started before yield stress and it was

Table 5 Results of bending tests

Concrete type	f_{ck} MPa	Rebar mm	l_b mm	f_{sf} MPa	f_{yk}/s_{yk} MPa/mm	f_{su}/s_{su} MPa/mm	f_{sr}/s_{sr} MPa/mm	τ_{bf} MPa/mm	τ_{bu} MPa	τ_{br} MPa
OC	31.2	8	160	-	510/0	570/0	490/0	-	7.12	6.12
		10	200	550.6	520/0	580/0.039	495/0.052	6.88	7.25	6.18
		12	240	509.4	480/0	560/0.116	465/0.142	6.36	7.00	5.81
		14	280	427.4	470/0.077	518/0.233	254/3.890	5.34	6.48	3.18
SLWC	18.5	8	160	514.2	510/0	570/0.103	490/0.103	6.42	7.12	6.12
		10	200	490.1	520/0.052	580/0.171	495/0.223	6.12	7.25	6.18
		12	240	397.3	480/0.262	560/0.405	465/0.496	5.64	7.00	5.81
		14	280	332.5	-	416/0.376	238/4.134	4.15	5.20	2.98
SLWC	18.5	8	200	-	510/0	570/0	490/0	-	7.12	6.12
		10	250	528.3	520/0	580/0.103	495/0.132	5.28	5.80	4.95
		12	300	471.8	480/0.013	560/0.182	465/0.234	4.71	5.60	4.65
		14	350	362.8	-	417/0.233	247/3.512	3.62	4.17	2.47

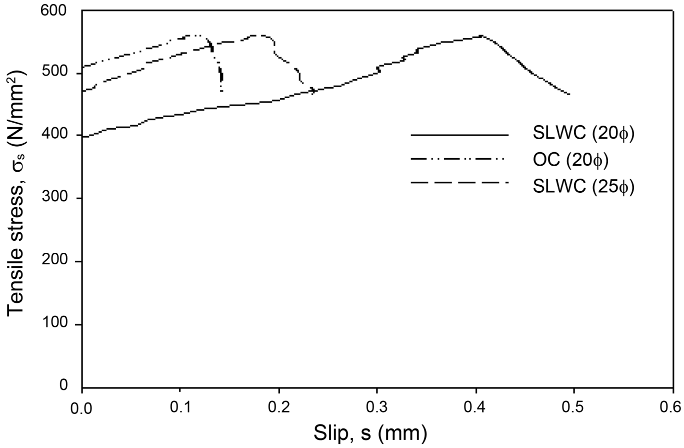

Fig. 4 Typical tensile stress-slip relationships of the experiments (Results of 12 mm diameter rebar)

approximately 0.052 mm. When the rebars ruptured, 0.223 mm slip was obtained for 10 mm rebar. Slips of 12 mm rebars exceeded 0.25 mm which is reliable bond stress by reaching 0.262 mm before yield stress. Slip was 0.496 mm at rupture for this rebar. The beams at which bond behavior of 14 mm rebars were investigated exceeded their bearing capacity by shear forces before yield stress and 4.134 mm slippage was recorded. This situation can be explained that shear strength of SLWC beams are lower than that of OC.

In the third series, 8 mm and 10 mm rebars reached yield stress without any slippage to the SLWC and ruptured at the end, like OC. Slip of 10 mm diameter rebar was approximately 0.132 mm when it ruptured. Small slips about 0.013 mm occurred before yield stress and slippage was 0.234 mm when 12 mm rebars ruptured. Nevertheless this length isn't enough for 14 mm rebars. Results of bending tests are given in Table 5 and in Fig. 4 representative typical tensile stress-slip relationships of the experiments for 12 mm diameter rebar is shown.

Here, tensile stress at the beginning of the slip, characteristic yield strength, slippage at yield stress, maximum tensile stress, slippage at maximum tensile stress, tensile stress at rupture, slippage at rupture, bond stress at the beginning of the slip, obtained maximum bond stress and bond stress at rupture are shown with f_{sf}, f_{yk}, s_{yk}, f_{su}, s_{su}, f_{sr}, s_{sr}, τ_{bf}, τ_{bu}, τ_{br}, respectively.

4. Conclusions

Based on the results of this investigation, the following conclusions can be made:

1. For OC, 20ϕ development length is sufficient to provide rebars and OC working together for each rebar.

2. Second series tests conducted on SLWC having 20ϕ development length show that this development length is sufficient for 8 and 10 mm rebars. But this length must be increased for 12 and 14 mm diameter rebars.

3. Bond strength of SLWC beam specimens which have 25ϕ development length increased in proportion to 20ϕ development length and provided stress distribution without exceeding their bearing capacity for 8, 10, 12 mm rebars. However, 14 mm rebars still exceeded their bearing

capacity by shear forces before yield stress, but maximum amount of slippage was 3.512 mm by decreasing.

4. All the tests show that small sized rebars have higher bond strength than bigger ones considerably.
5. Results of this investigation show that SBHBT is more convenient for small sized steel rebar (<16 mm for OC, <14 mm for SLWC), because beam specimens don't include stirrups and to reach yield stress higher tensile forces should be applied to rebar. In this way, specimens exceed their bearing capacity by shear forces before yield stress.

Consequently, mechanical properties of SLWC constituting this study can be improved by using admixtures and decreasing W/C ratio. In this way, it is clear that bond strength of SLWC is going to increase. However, that elastic modulus of SLWC is lower decreases the flexural rigidity, thus displacements of reinforced concrete members constructed with SLWC are more than OC at the same loading conditions. This situation refers that dimensions of structural members with SLWC must be increased. Therefore, mass of structures constructed with SLWC must be investigated in detail whether its mass is more or less than OC structures.

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