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The Bond Strength of Structural Lightweight Pumice Aggregate Concrete with/without Silica Fume

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ABSTRACT

In this study, the bond strength between concrete and steel reinforcement of structural concrete produced by lightweight pumice aggregate (SLWAC) is investigated by comparing with the normal-weight aggregate (NWAC) without additives. To achieve these objectives, 7 different types of concrete mixtures were produced. In producing of the SLWAC mixtures, a mineral additive, Silica Fume (SF), was used to replace the Portland cement in the ratios of 0 %, 5 % and 10 % by weight. The remaining three types of mixtures were obtained by adding Super Plasticizers (SP) to the above mixtures in the ratio of 2 % by weight.

In conclusion; the use of SF and SP together, increased the bonding between the concrete and the steel reinforcement in SLWAC. The bond strength of deformed bars in SLWAC was lower compared to those of NWAC. Normalized bond strength of L-5-2 and L-10-2 coded specimens were found to be 1.01 and 1.10 times (with respectively) higher compared to normal weight concrete without additives (R). Other all SLWAC specimens were less than R (ranges between 0.92 and 0.96 times). Besides, it was also observed that the slip at peak load for pullout failure of ribbed bar did not vary too much for both NWAC and SLWAC specimens (ranges between 1.0 and 2.3 mm).

INTRODUCTION

The bond feature between reinforcing bar and concrete is one of the most important properties in reinforced concrete structures. Steel-concrete bond is the combination of adhesion, friction, and support of the ribs in deformed steel. The adhesion mechanism is the first property activated by the load. Adhesion is partly microscopic interlock of paste into imperfections of the steel surface, and partly a possible chemical interaction between surfaces [1-2]. The two other mechanisms, friction and rib support, go into action when adhesion fails and some relative movement begins between concrete and steel. Then, this time significant slip may be observed, as well as the formation and growth of cracks.

There is a huge information with regard to bond behavior between reinforcing bar and normal weight aggregate concrete and some model equation developed by a number of researchers [2-10]. They clarified the effect of the bar diameter, embedded length in concrete, concrete strength, cover thickness and crack spacing on the bond strength [11].

Some studies were performed in terms of bond strength between reinforcing bars and concrete with artificial lightweight aggregate [12-16]. Because of the lower particle strength, Lightweight concrete have lower bond splitting capacities and a lower post-elastic strain capacity than normal concrete. Unless tensile splitting strengths are specified, ACI 318 [17] requires the development lengths for low-density concrete to be increased by a factor of 1.3 over the lengths required for normal-density concrete [18].

The interface between the lightweight aggregate/cement pastes is tight and [19, 20] characterized by a mechanical interlocking in combination with a chemical interaction in the form of pozzolanic reaction. Mehta [21] concluded that the nature and microstructure of the IZ vary depending on the aggregate type, the surface structure of aggregate, pore structure of the aggregate, the porosity of the cement paste, and the bleeding of water beneath the aggregate.

The silica fume is a pozzolanic material consisting of >90μm silicon dioxide. Silica fume used as an admixture in a concrete mix has significant effects on the properties of the resulting material. These effects pertain to the strength, modulus, ductility, abrasion resistance, and air void content, shrinkage, bonding strength with reinforcing steel, permeability, chemical attack resistance, alkali-silica reactivity reduction, and corrosion resistance of embedded steel reinforcement. In addition, silica fume addition degrades the workability of the mix [22].

An investigation was conducted by Hossain [23] to determine the bond characteristics of plain and deformed reinforcing bars in lightweight volcanic pumice concrete (VPC) and normal concrete (NC). According to the author, the most important result was in which the bond strength of deformed bars in lightweight VPC was lower compared to those of NC. Normalized bond strength of NC specimens was found to be about 1.12 (ranges between 1.08 and 1.14) times higher compared to VPC. This can be considered as normal for a lightweight concrete.

There is very little knowledge on the mechanical interaction (“bond”) between reinforcing bars and natural lightweight aggregate concrete as pumice etc. This paper is part of a large research project of evaluating the various properties (durability and high temperature effect on SLWC with pumice) of pumice aggregate structural lightweight concretes in order to determine the usability on reinforced concrete. The aim of this research was to study the effects of silica fume on the mechanical properties of pumice lightweight concrete and to compare these properties to ordinary concrete. The conventional Pullout test setup basically followed the specification ASTM C234, but the nominal diameter of rebar was 14 mm instead of no.6 (19mm) [24-25].

MATERIALS AND METHOD

Materials

The maximum size of limestone coarse aggregate was 16 mm. Grain size classified in the range of 0-4 mm and 4-16 mm of bulk specific gravity was 2.57 and 2.70 kg/dm^3, respectively. Besides, water absorption rate of them were 2.73 and 0.55, respectively. The chemical composition of the pumice aggregate is given in Table 1. The particle size ranged as 0-4 mm, 4-8 mm, and 8-16mm. Grain-size distribution curve of the pumice aggregate used was provided that complied with border curves to the requirements of ASTM C 330[26]. The specific gravity factors of pumice aggregate were obtained to determine concrete mixture proportion according to ACI 211 [27] as 2.09, 1.75, 1.50 kg/dm^3 respectively. The bulk density was around 0.650, 0.738, 0.893 kg/dm^3, respectively. Specific gravity of pumice was 2.47. The water absorption rate of pumice was 12%, 19%, 42% on the grain interval of 16-8 mm, 8-4 mm, and 4-0 mm, respectively. To obtain the required minimum strength (20 MPa for standard cylindrical strength) for both SLWAC and NWAC, different aggregate fraction was used in the concrete mixes.

An ordinary Portland cement (OPC) similar to ASTM Type I was used in this study. Its specific gravity and Blaine specific surface area were 3.15 and 3350cm^2/g, respectively. Initial and final setting times of the cement were 150 and 196 min. respectively. The 7-day and 28-day compressive strengths of OPC were 41.3 and 51.2 MPa, respectively. Chemical composition of OPC and other properties are given in Table 1.

Silica fume (SF) used in concrete production was obtained from Antalya Electro Ferro-Chrome Company in Turkey. Chemical composition of SF is shown in Table 1. The regular tap water was used in the whole tests.

Table 1 Chemical composition of OPC 42.5R, SF and Pumice aggregate

<table>
<tr><th colspan="2">Compounds (%)</th><th colspan="2">OPC</th><th>SF</th><th>Pumice</th></tr>
<tr><td colspan="2">CaO</td><td colspan="2">63.98</td><td>0.44</td><td>4.60</td></tr>
<tr><td colspan="2">SiO_2</td><td colspan="2">20.64</td><td>80.9</td><td>59.0</td></tr>
<tr><td colspan="2">Al_2O_3</td><td colspan="2">5.06</td><td>0.34</td><td>16.6</td></tr>
<tr><td colspan="2">Fe_2O_3</td><td colspan="2">3.14</td><td>0.55</td><td>4.80</td></tr>
<tr><td colspan="2">MgO</td><td colspan="2">1.20</td><td>5.23</td><td>1.80</td></tr>
<tr><td colspan="2">SO_3</td><td colspan="2">2.38</td><td>---</td><td>0.40</td></tr>
<tr><td colspan="2">K_2O</td><td colspan="2">0.8</td><td>4.50</td><td>5.40</td></tr>
<tr><td colspan="2">Na_2O</td><td colspan="2">0.31</td><td>0.35</td><td>5.20</td></tr>
<tr><td colspan="2">Cl</td><td colspan="2">0.035</td><td>0.13</td><td>---</td></tr>
<tr><td colspan="2">Loss on ignition (LOI)</td><td colspan="2">1.72</td><td>2.70</td><td>1.60</td></tr>
<tr><td colspan="2">Insoluble residue</td><td colspan="2">0.46</td><td>---</td><td>---</td></tr>
<tr><td colspan="2">Free CaO</td><td colspan="2">1.12</td><td></td><td></td></tr>
<tr><td colspan="4">Bogue composition (%)</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>C_3S</td><td>52.48</td><td>C_4AF</td><td>9.15</td></tr>
<tr><td>C_2S</td><td>19.63</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>C_3A</td><td>8.02</td></tr>
</table>

A high-range water reducing and early high strength providing agent (SP) conforming to ASTM C 494 [28]. In the concrete mixtures, Type F super plasticizer (SP), based on melamine sulfonate polymer, and with dark brown coloured solution, was used as 2% of cement weight. The dosages used during the specimen preparation were determined considering the range recommended by the manufacturer and the optimum dosage that had been found in a previous study. The density of SP was 1.21 kg/l, its pH value was 9, and the content of chloride ion was less than 0.2%.

The nominal diameter of ribbed reinforcing bar was 14 mm. For the mechanical characterization of six steel bar specimens tensile tests were carried out using a universal testing machine according to Turkish Standard (TS) 138 [29]. For the ribbed reinforcing bars average yielding stress *fy* and ultimate stress *ft* values, obtained from the testing of 6 specimens, were 104 and 679 MPa, respectively.

Specimen Preparation and Casting

Mixing was done in a stationary mixer (75 dm^3) and in accordance with ASTM C192 [30] procedure. For each batch, five pullout specimens were cast in 150x150x150 mm cubic steel molds with reinforcing bar positioned at the center. While casting the 150 mm cubic pullout and 100 mm cubic compression specimens, concrete was placed by rodding each layer 25 times in two layers of approximately equal thicknesses. After casting, the pullout and compressive specimens were covered with polyethylene sheets and left in the laboratory atmosphere. The specimens were demoulded after 24 h. After demoulding, the specimens were placed in lime-saturated water filled tanks until the age of 28 days. After the concrete samples were removed from lime-saturated water tanks, they were kept in the laboratory at ~20^oC and ~65% RH until testing day. Bond testing was done for all specimens at the age of 90 days.

Fresh concrete was tested for slump [31] and unit weight [32]. NWAC were designed to obtain a C20 strength class with a water-binder ratio (w/b) of 0.53. Mix proportioning of the SLWAC was made according to ACI 211 [27]. Slump was kept constant at 10±5cm in the mixes. In naming the concrete mixes, the type of the concrete (R for NWAC and L for SLWAC) was followed by the SF incorporation amount (5 for 5% and 10 for 10%) and finally by the SP content (0 for 0% and 2 for 2%). For example, L-10-2 denotes the SLWAC with 10% SF and 2% SP.

Testing Details

In this study, the used pullout specimens were modified ASTM C 234 [33] specimens. The reinforcing bars have a nominal diameter of 14 mm instead of no.6 (19mm) bars specified in ASTM C234. The load was applied at a loading rate of 0.075 kN /s. The critical bond strength is defined as the bond stress of a reinforcing bar corresponding to a slip distance of 2.5 mm [33]. Although, this method is not appropriate to determine bond strength or the development length of reinforcing bar for sufficient anchorage, the bond strength and the anchorage properties of two different types of concrete can be used to compare each other.

Experimental test setup is shown in Figure 1.

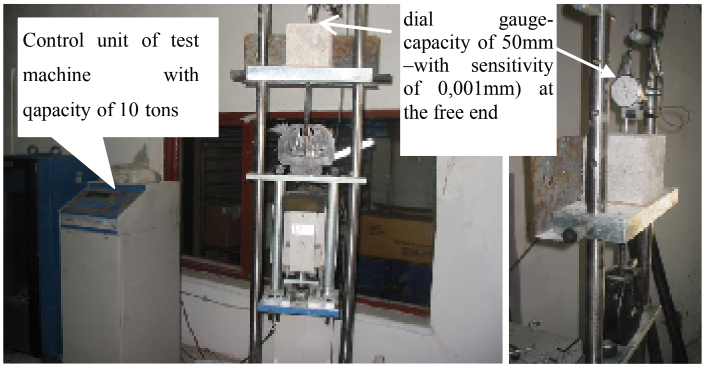

Figure 1 Pull-out test setup used to determine bond strength of R and SLWAC samples

The bond stress is calculated using the following expression Eq (1):

$$\tau_b = \frac{P_1}{\ell_b(\phi \cdot \pi)} \qquad (1)$$

Where τ_b; mean ultimate bond strength (MPa),
P_1; ultimate axial tensile load (kN),
Ø; The steel reinforcing bar diameter (mm),
ℓ_b; embedded length (150 mm for this study)

Experimental Findings and Discussion

Fresh concrete properties

Mix proportions and some fresh properties of the SLWAC and R are shown Table 2. As seen, water/binder ratio of the SLWAC was between 0.43 and 0.47. The mix designs are based upon an estimated active water demand. That portion absorbed by the aggregate is not considered for determining yield since it has no volumetric effect. The considered water amount is net weight of water which is the amount that is absorbed by the pumice subtracted from the total amount of water. The slump was tried to be kept constant at 7±2 cm. As seen from the table, water/binder ratio of the NWAC was 0.53.

Tables 2 shows that water requirement of both SLWAC increased when SF was used. In the study, different w/b ratio was used for both SLWAC and R due to obtain similar workability for the all concrete types.

Table 2 Mix Proportions (for 1/m^3) and Some Properties of the Concretes

Code	Cement (kg)	SF (kg)	Water (kg)	w/c	Aggregate (kg)			SP (kg)	Slump (cm)	Fresh Unit Weight (kg/m^3)	Dry Unit Weight (kg/m^3)	WAC *
					0-4 mm	4-8 mm	8-16 mm					
R	386	---	205	0.53	788	962		---	5.5	2297	2367	5.82
L-0-0	430	---	199	0.46	730	550	52	---	8.4	1678	1809	5.90
L-0-2	430	---	187	0.43	730	550	52	8.6	6.4	1722	1840	5.83
L-5-0	408.5	21.50	202	0.47	729	549	52	---	7.2	1665	1792	6.42
L-5-2	408.5	21.51	189	0.44	729	549	52	8.6	7.1	1711	1811	5.97
L-10-0	387	43	202	0.47	729	549	52	---	6.8	1656	1772	8.25
L-10-2	387	43	188	0.44	730	550	52	8.6	6.2	1696	1787	8.11
*	Water absorption capacity (%)											

Very fine spherical SF particles improve the grading of the binder by filling the gaps between the relatively coarser cement particles and increase the free water amount. Despite this beneficial effect, the high surface area of SF particles to be wetted causes high water requirement and lower durability without a super plasticizer admixture [34]. In these cases, use of SP enabled to reach the desired slump with much lower water contents, as seen from Table 3. Unit weights of SLWAC decreased slightly with the use of admixtures.

Properties of the Hardened Concrete

Physical properties

Some of the physical properties of the hardened concretes after 28 days are given in Table 2. The concretes containing SP resulted in higher unit weights when compared to those without SP. Similar to the results obtained for fresh states, use of SF slightly decreased the unit weights. Therefore, highest unit weights were obtained for the concretes containing 2% SP and no SF.

When absorption capacities are considered, it is seen that use of SP in SLWAC resulted in almost the same values when compared to the reference mix, except for L-10-2. The absorption capacity of SLWAC decreased by the use of SP, as SF content of concretes was kept constant. This can be attributed to the lower w/c when SP was used.

The comparison of the unit weights of SLWAC and R show that even the heaviest SLWAC (1722 kg/m^3) was 23% lighter than the lightest R (2297 kg/m^3). Similar reduction on the unit weight of lightweight concrete was reported by Hossain [35] and Yasar et al. [36].

Compressive strength

Average compressive (f_c) strength and standard deviation values for SLWACs and R, obtained from at least 5 specimens for each series, and are given in Table 3.

Table 3 Average and standard deviation values of concrete compressive strength in samples

Age(days)	7							28							90						
Mixes	R	L-0-0	L-0-2	L-5-0	L-5-2	L-10-0	L-10-2	R	L-0-0	L-0-2	L-5-0	L-5-2	L-10-0	L-10-2	R	L-0-0	L-0-2	L-5-0	L-5-2	L-10-0	L-10-2
N	4	5	5	5	5	5	5	4	5	5	5	5	5	5	4	5	5	5	5	5	5
f_c(MPa)	31.8	18.8	20.6	18.9	20.2	18.7	22.2	39.2	24.4	25.6	23.5	26.2	22.3	28.3	40.3	25.4	25.3	24.3	26.23	24.4	28.6
Std. dev. (MPa)	0.73	0.98	1.09	0.47	0.81	0.74	0.68	2.01	1.04	2.07	1.54	3.35	0.95	2.62	2.09	1.24	3.24	0.70	2.44	2.36	3.02

In SLWACs the highest CS value at 7th day were measured from sample L-10-2, in which the strength reached 91 % of 28-day L-0-0 strength. The lowest strength was observed in samples L-10-0 / L-0-0 / L-5-0.

In 28-day strength tests, L-10-2 gave highest value with the increase rate of 16% as compared to L-0-0. Between the samples, CS decreases while usage of SF alone increases without SP. In 90-day CS, similar to 7- and 28-day strength results, highest value belonged to L-10-2 (increase rate 17%). In other concrete series no significant change could be observed.

In SLWACs, highest strength in all ages was shown by L-10-2. To reduce the water demand of SF, SP addition is suggested. Because, the major factor affecting concrete strength is w/b ratio being inversely proportional with strength [37]. These results are in agreement with those of Malhotra et al.[38] and Neville [37] showing the increase of CS when SF used with SP addition.

As seen in Table 3, SF's alone addition and usage with SP are ineffective on 7 day strength, but in 28 and 90 day concretes SF's alone usage affected strength negatively at low rate, while in mixed usages of SF and SP no change (5 % SF) and increase at low rate (10 % SF) occurred[39]. After the 28th day, strength of concretes produced with SF addition decreases. 90 day strength values are slightly higher than 28 day values. Results are in agreement with that of Zhang and Gjørv [40].

Considering R and SLWACs, although cement dosage was 430 kg/m^3 in L-0-0 and 386 kg/m^3 in R (Table 2), a clear predominance of SLWACs coded with L-0-0 over NWACs coded with R in all series were seen. This was a result of lower CS caused by natural porosity of pumice aggregate (used for producing SLWACs) as compared with that of limestone aggregates. Cement dosage to certain level may increase CS of SLWACs, but as mortar phase fails, because of lower compressive strength of aggregate, the tension transferred to aggregate can not be carried [12, 41].

Bond strength

To be able to compare the bond strength behaviour of the various concrete mixes used in this research, the concept of normalised bond strength (τ_{nz}) has been introduced. It is obtained by dividing the stress value by the square root of the compressive strength of the batch tested $\left(\tau\sqrt{f_c}\right)$, which the criterion is found most often in the literature [4, 7-10, 23, 42-44]. The average and standard deviation values obtained from statistical analyses are given in Table 4.

Table 4 Axial pullout test results

Concrete	**Ultimate Axial Loads**		**Maximum Bond Strength**	τ_{nz}	Increase or decrease rate according to N-0-0	Mode of failure
	P_1 (kN)	**Std. Dev. (kN)**	**τ_b (Mpa) ***	**(Mpa)**		
R	63	1.14	9.55 (100)	1.53	1.00	3 Pull-out / 2 Splitting
L-0-0	48	2.55	7.28 (100)	1.47	0.96	Splitting
L-0-2	49	2.55	7.43 (102)	1.47	0.96	Splitting
L-5-0	46	2.17	6.97 (96)	1.44	0.94	Splitting
L-5-2	52	1.30	7.88 (108)	1.54	1.01	Splitting
L-10-0	44	2.24	6.67 (92)	1.41	0.92	Splitting
L-10-2	56	2.24	8.49 (117)	1.60	1.04	Splitting

As seen in Table 4, bond strength between concrete and steel reinforcement decreased with the use of SF alone. However, the bond strength of specimens with the use of both SF and SP increased. Because of the high specific area of SF particles, their tendency to absorb water will result in an increase in the water demand. Unless a water reducer is used, more water may have to be added to achieve a desired level of SF. Such water addition partially decreased the bond strength [37].

As the highest force in all concrete mixes was 63 kN at R specimens. While the lowest force in the structural SLWAC's was 44 kN at L-10-0 coded specimens, the highest force was reached at L-10-2 (56 kN). This can be considered as normal for a lightweight concrete because of individual lightweight aggregate weakness as required by natural characteristic behaviour of its structure [40].

Normalized bond strength of L-5-2 and L-10-2 coded specimens were found to be 1.01 and 1.04 times (with respectively) higher compared to R. Other all SLWAC specimens were not so less than R (ranges between 0.92 and 0.96 times).

When an evaluation was done between R and SLWAC specimens with bond strength values, similar case to the results obtained by compressive strength is observed that the using of SF and SP together in concrete mixes increases bond strength depending on SF usage rate (up to 10% by weight of cement).

The bond strength of SLWAC's was apparently lower than that of R. This has been possible due mainly to inherent weakness in the mechanical properties of the pumice aggregate because of its porous structure and large amount of void space, as was observed for compressive strength [12, 37]. Gjorv et al.[3], investigated the effect of SF on the bond strength by means of XRD analyses and reported that SF affected interfacial zone between reinforcing steel and cement paste. Small SF particles fill in some of the space between relatively large cement grains and densify the boundaries between cement paste, aggregate and reinforcing steel. SF greatly reduces the internal bleeding in fresh concrete, hence reducing the accumulation of free water under aggregate and reinforcing steel [34]. This is due to pore size reduction (the filler affect) and pozzolanic activity of the SF which enhance the strengths of the transition zone and the reinforcing steel.

The average ultimate bond strengths vs. SF and SP addition ratio are shown graphically in Figure 3. The trend from the figure results in reduction in the bond strength of SLWAC specimens when only SF was used (R square 0.99).

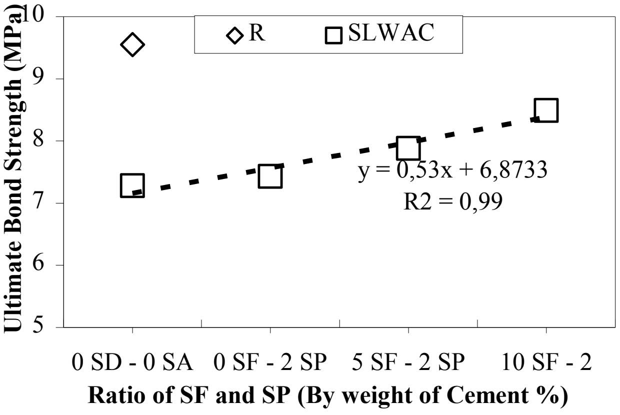

Figure 3 Relation between ultimate bond strength vs. admixture addition ratio

This tendency was also similar to the results of compressive strength test. The compressive strength of concrete is one of the most important factors affecting to the bond strength as is the case for other properties [45]. A small reduction was observed in the SLWAC when only SF was used, similar to the reduction that was observed in compressive strength for the same concrete. In this study, the highest bond strength between deformed steel bars and SLWAC specimens with 10%SF+2%SP was 8.49 MPa.

Load and slip relationship and failure pattern

In general, both R and SLWAC specimens exhibited similar behaviour between the slip values of 0.00-0.25 mm, which is a slow rise at load, while the slip increases rapidly. Similar load-slip response was reported by Mor [12] for high-strength lightweight concrete.

Typical load–slip curves associated with pullout failure at different concrete types for the deformed bars with an embedded length of 150 mm are shown in Figures 4, 5 and 6.

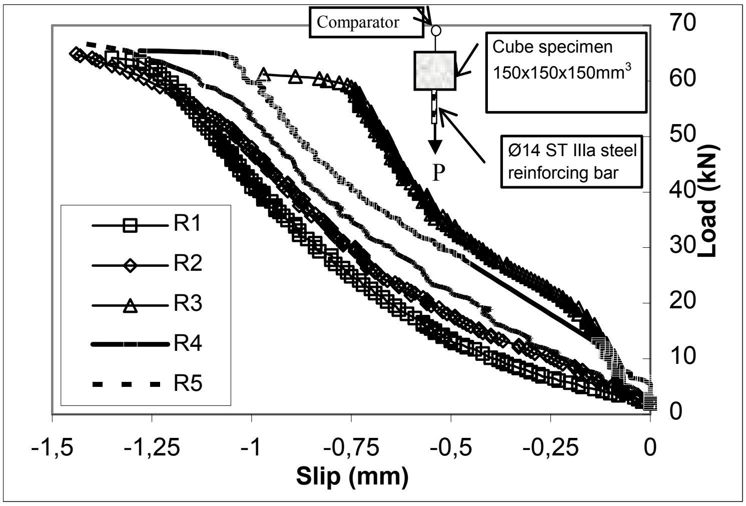

Figure 4 The slip-load relation on the specimens with coded R

A pullout type failure was characterized by a gradual increase of load-versus-slip up the maximum (peak) load followed by a gradual softening. The load–slip curve showed similar trend of variations for both R and SLWAC. However, for SLWAC specimens the peak load was lower and slip at peak load was almost same compared to R specimen (between Figures 4, 5 and 6).

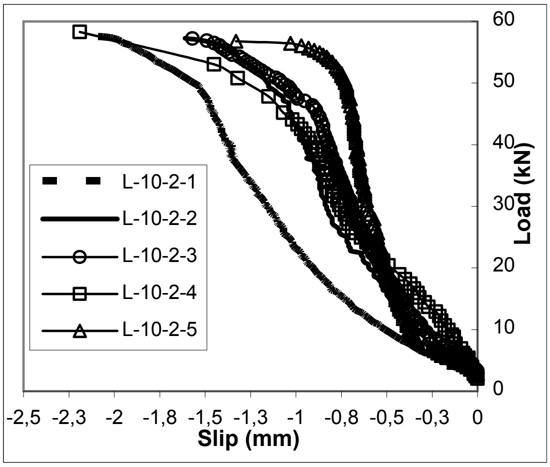

Figure 5 The slip-load relation on the specimens with coded L-0-0

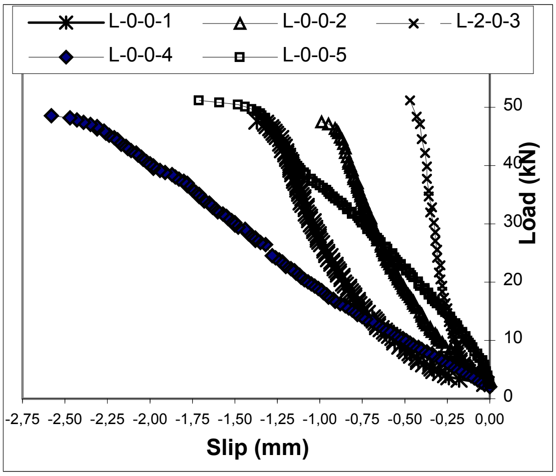

Figure 6 The slip-load relation on the specimens with coded L-10-2

The load–slip curves exhibited pullout failures where pullout load increases almost linearly up to the ultimate tensile strength of concrete no followed by an increase in load with large slip. In addition to this type of failure, some specimens failed due to splitting of concrete. The load–slip curves are similar to those of SLWACs with almost linear increase in load up to peak followed by a sudden failure.

It was also observed that the slip at peak load for pullout failure of ribbed bar did not vary too much for both R and SLWAC specimens (ranges between 0.7 and 2.5 mm).

As seen from Figures, a plateau exists after the loads reach the peak values. According to the basic rules for bond stress distribution, this plateau is followed by a linear line which decreases to the value of ultimate frictional bond resistance at a slip value which is assumed to be equal to the clear distance between the lugs of deformed bars [5-46]. Similar trends for the load-slip curves obtained by Campione et al. [47] for non fibrous lightweight concrete.

Pullout type failure was observed on three specimens of R series. Other two of R specimens exhibited the splitting type failure at the end of pullout tests (Figure 7).

Figure 7 The general view of the specimens coded with R after bond strength testing

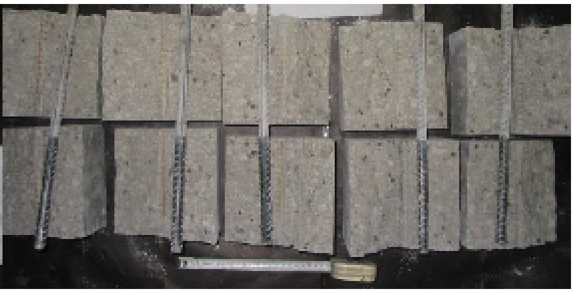

Figure 8 The typical behaviour of the specimens coded with L-10-2 after bond strength testing

But all SLWAC specimens, as seen from Figure 8, exhibited the splitting type failure for all bond specimens in the series.

CONCLUSIONS

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

In the structural SLWAC containing SF alone, there is a reduction tendency on bond strength by increasing the rate of SF. A small gain was observed in the structural SLWAC when SF and SP were used together in SLWAC. It was observed that the bond strength of non-additives SLWAC was 24 % lower than that of the non-additive NWAC coded with R. The SLWAC's bond strength was 89 percent of the bond strength of R when the SLWAC were produced with the addition of SF and SP.

Normalized bond strength of L-5-2 and L-10-2 coded specimens were found to be 1.01 and 1.10 times (with respectively) higher compared to Reference. Other all SLWAC specimens were less than R (ranges between 0.92 and 0.96 times).

The slip at peak load for pullout failure of ribbed bar did not vary too much for both R (ranges between 1.0 mm and 1.5 mm), and SLWAC specimens without additives (0.4 mm and 1.75 mm). But the positive effect of the usage of SP and SF was seen from the SLWAC specimens with 10%SF and 2%SP (ranges between 1.3 mm and 2.3 mm) when compared with normal weight concrete without additives.

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