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Full Length Research Paper

A comparative study on the bond performance between rebar and structural lightweight pumice concrete with/without admixture

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In this study, the bond strength between concrete and steel reinforcement of structural concrete produced by lightweight pumice aggregate (SLWAC) and normal-weight aggregate (NWAC) is investigated. To achieve this objective, 12 different types of concrete mixtures were produced. In producing the NWAC and 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 six types of mixtures were obtained by adding super plasticizers (SP) to the earlier mentioned mixtures in the ratio of 2% by weight. In conclusion, unit weight of SLWAC was 23% lower than that of NWAC. When compared with NWAC, compressive strength reductions in SLWAC were observed to change between 48 and 65%. Use of SF and SP together, increased the bonding between concrete and the steel reinforcement in both SLWAC and NWAC. The bond strength of deformed bars in SLWAC was lower when compared with 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 when compared with N-0-0. Other all SLWAC specimens were less than N-0-0 (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 0.7 and 2.5 mm).

Key words: Bond strength, pullout tests, structural lightweight concrete, pumice aggregate, silica fume, superplasticizer.

INTRODUCTION

Lightweight concrete has been widely used in buildings as masonry blocks, wall panels, roof decks and precast concrete units. Reduction in weight by the use of lightweight aggregate concrete is preferred, especially for structures built in seismic zones (Sari and Pasamehmetoglu, 2004). Lightweight concrete manufactured either from natural or from artificial aggregate is classified by the ACI 213 (1970) into three categories according to its strength and density. The first category is termed low strength, corresponding to low density and is mostly used for insulation purposes. The second category is moderate strength and is used for filling and block concrete. The third category is structural lightweight concrete and is used for reinforced concrete.

According to the classification given by RILEM (1978), LWC for structural purposes is defined as concrete with a density range of 1600 to 2000 kg/m^3 and strength grade not less than 15 MPa.

Satisfactory concrete that is lighter than normal concrete having good insulating characteristics with high absorption and shrinkage can be manufactured using volcanic pumice. Lightweight concrete has also been employed more recently to make structural elements, in particular in the field of precast concrete structures. Maintaining an adequate strength level, lightweight concrete, with respect to normal weight concrete, among other things permits a reduction in the horizontal inertia actions

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on structures in seismic regions, exerts a favourable effect on the foundations of buildings supported by soil having low bearing capacity and facilitates the carriage of precast concrete elements. For long-span bridges, the live load is a minor part of the total load and a reduction in density is translated into reductions in not only mass, but also in section size (Chandra and Berntsson, 2002; Neville, 2002; Topcu, 1997; Mor, 1992; Campione et al., 2005).

Bond strength and development length

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 (Cosenza and Zandonini, 1999; Lungren, 1999). 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 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 (Gjørv et al., 1990; Valcuende and Parra, 2009; Ožbolt et al., 2002; Lundgren, 1999; Kayali and Yeomans, 2000; Harajli et al., 2002; Banholzer et al., 2005). They clarified the effect of the bar diameter, embedded length in concrete, concrete strength, cover thickness and crack spacing on the bond strength (Elfgren and Noghabai, 2002).

Some studies were performed in terms of bond strength between reinforcing bars and concrete with artificial lightweight aggregate (Mor, 1992; Orangun 1967; Kayali and Yeomans, 2000; Hassan et al., 2010)

Field performance has demonstrated satisfactory performance light density concrete (LDC) with strength levels of 20 to 35 MPa with respect to bond and development length. Because of the lower particle strength, LDC have lower bond splitting capacities and a lower post-elastic strain capacity than NDC. Unless tensile splitting strengths are specified, ACI 318 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 (Holm and Bremner, 2000).

The interface between the lightweight aggregate/cement pastes is tight and (Zhang and Gjorv, 1990) characterized by a mechanical interlocking in combination with a chemical interaction in the form of pozzolanic reaction. Mehta (1986) 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. In addition to mentioned, when the condensed silica fume (CSF) is added to the concrete, the morphology and microstructure of the transition zone are affected (Gjørv et al., 1990), so that both porosity and thickness of the transition zone are reduced. The observed effect of CSF may be explained by several mechanisms: reduced accumulation of free water at the interface during casting of specimens; reduced preferential orientation of calcium hydroxide (CH) crystals at the transition zone and densification of the transition zone due to pozzolanic reaction between CH and CSF. When CSF is added to the concrete mix, the adhesion is greatly improved and LWA concrete utilizes the full adhesion, greatly improving its own bond strength (Mor, 1992).

The silica fume is a pozzolanic material consisting of >90 µm 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 (Xu and Chung, 2000).

An investigation was conducted by Hossain (2008) to determine the bond characteristics of plain and deformed reinforcing bars in lightweight volcanic pumice concrete (VPC) and normal concrete (NC). According to this author, the most important result was in which the bond strength of deformed bars in lightweight VPC was lower when compared with 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 with VPC. This can be considered as normal for a lightweight concrete.

Research significance

Because Turkey is subject to considerable and violently earthquake activities, investigations on the possible uses of pumice for lightweight concrete is getting common during the last decades. 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 on 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

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

Compounds (%)	OPC	SF	Pumice
CaO	63.98	0.44	4.60
SiO_2	20.64	80.9	59.0
Al_2O_3	5.06	0.34	16.6
Fe_2O_3	3.14	0.55	4.80
MgO	1.20	5.23	1.80
SO_3	2.38	---	0.40
K_2O	0.8	4.50	5.40
Na_2O	0.31	0.35	5.20
Cl	0.035	0.13	---
Loss on ignition (LOI)	1.72	2.70	1.60
Insoluble residue	0.46	---	---
Free CaO	1.12		

Bogue composition (%)			
C_3S	52.48	C_4AF	9.15
C_2S	19.63		
C_3A	8.02		

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 (19 mm) (Sancak, 2005; Sancak et al., 2008).

MATERIALS AND METHODS

The coarse aggregate having normal weight was 16 mm maximum size of limestone. Grain size classified in the range of 0 to 4 mm and 4 to 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. Pumice aggregates obtained from Isparta province, Türkiye, were utilized to prepare structural lightweight concrete specimens. The aggregates were used after washing and sieving. The chemical composition of the pumice aggregate is given in Table 1. The particle size ranged as 0 to 4, 4 to 8 and 8 to 16 mm. Grain-size distribution curve of the pumice aggregate used was provided that complied with border curves to the requirements of ASTM C 330 (2003). The specific gravity factors of pumice aggregate was obtained to determine concrete mixture proportion according to ACI 211 (1998) as 2.09, 1.75, 1.50 kg/dm^3 respectively. The bulk density was around 0.650, 0.738 and 0.893 kg/dm^3, respectively. Specific gravity of pumice was 2.47. The water absorption rate of pumice was 12, 19 and 42% on the grain interval of 16 to 8, 8 to 4 and 4 to 0 mm, respectively. The porosity of pumice was 29, 70 and 68%, respectively on the same grain interval. Both SLWAC and NWAC was used the different aggregate fractions, such as 0 to 4/4 to 16 mm for NWAC and 0 to 4/4 to 8/8 to 16 mm for the SLWAC to obtain the load-carrying concrete strength required (20 MPa of minimum standard cylindrical strength for TS 500).

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 3350 cm^2/g, respectively. Initial and final setting times of the cement were 150 and 196 min, respectively. The 7- 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.

A high-range water reducing and early high strength providing agent (SP) conforming to ASTM C 494 (1994) was used to provide desirable workability in the concrete mixtures. 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. 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 (Figure 1a, b). The details of rebar geometry are given in Table 2.

Specimen preparation and casting

Mixing was done in a stationary mixer and in accordance with ASTM C192 procedure. For each batch, five pullout specimens were cast in 150x150x150 mm cubic steel molds with reinforcing bar (having diameter of 14 mm) positioned at the center. The concrete was cast in vertical direction parallel to the loading.

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

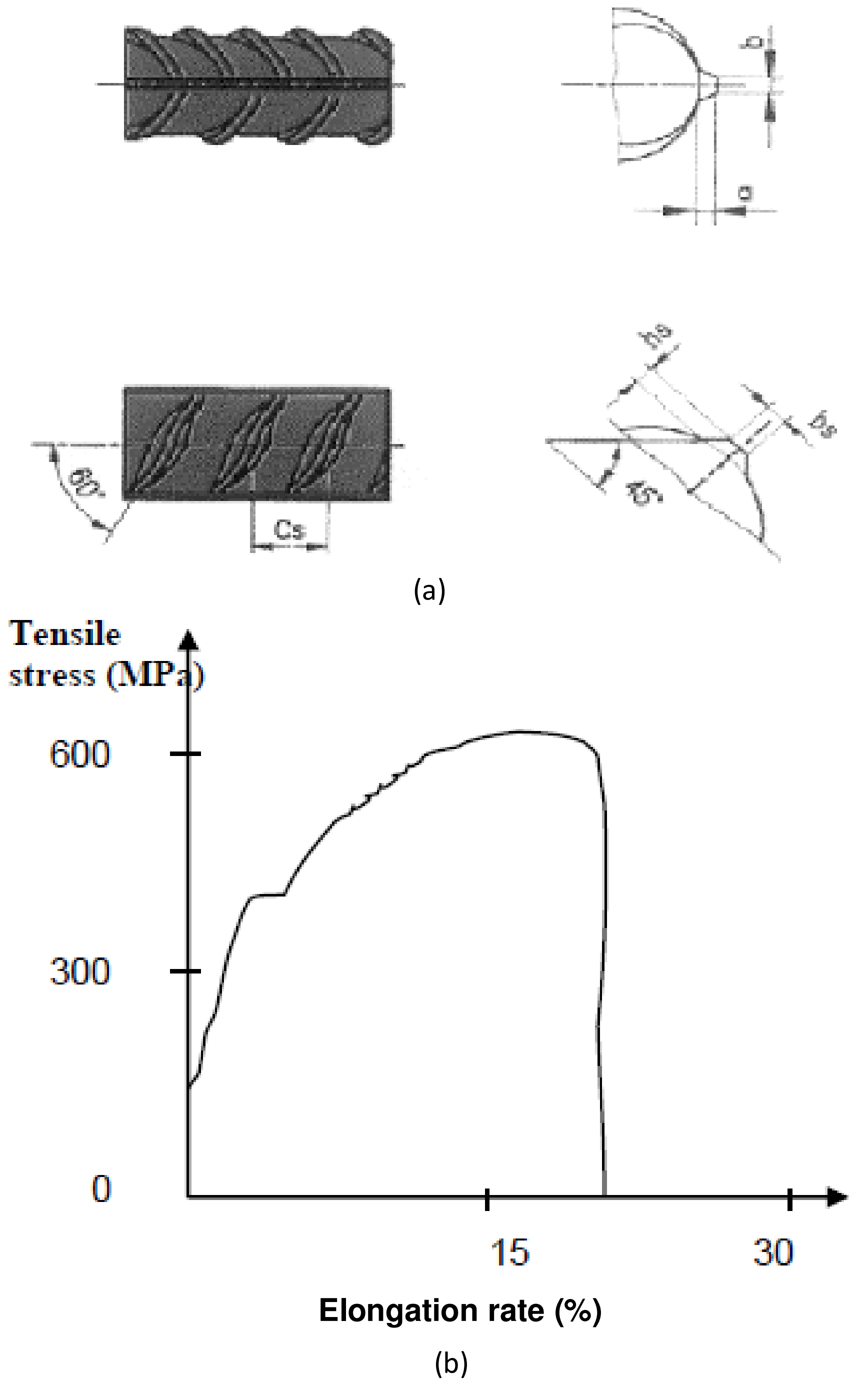

Figure 1. (a) Details of the reinforcing rebars; (b) a typical tensile stress versus elongation rate curve for reinforcing bars.

Table 2. The details of ribbed reinforcing bar geometry.

d_n, Nominal diameter (cm)	β (°)	Elongation rate at rupture (%)	Dimensions (mm)					Nominal cross section area (cm^2)	Weight
			hs	bs	cs	a	B		G (kg/m)
14	60	23.69	0.98	1.4	9.7	1.4	1.4	1.54	1.21

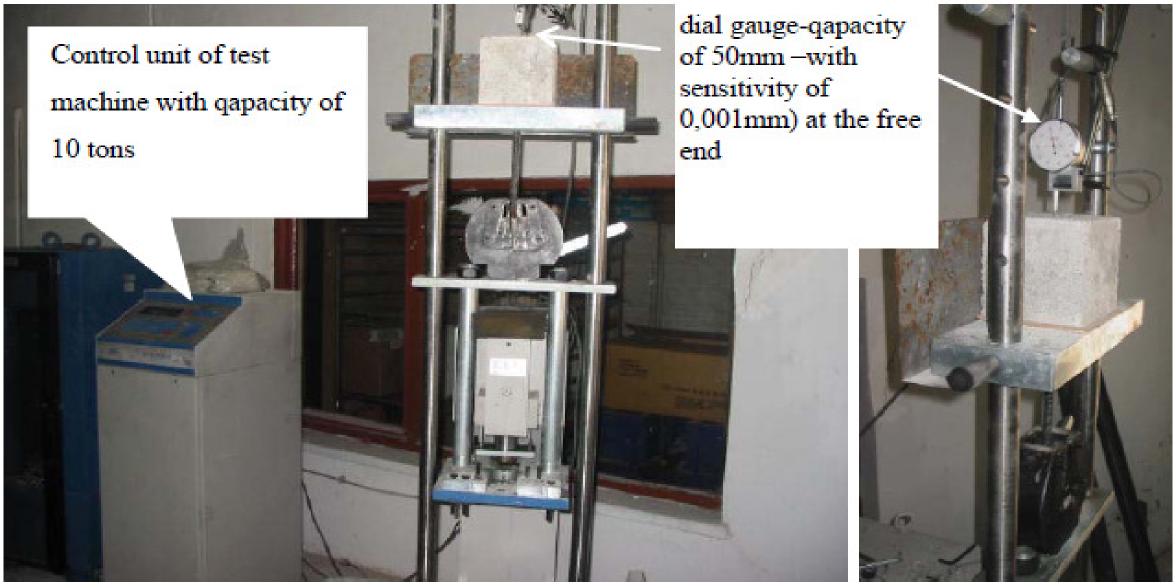

Figure 2. Pull-out test setup used to determine bond strength of NWAC and SLWAC samples.

specimens were demoulded carefully after 24 h. The bars projecting out of the bond specimens were painted with three layer anti-corrosive coating before placing them in lime-saturated water. 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°C and ~65% RH until testing day. Bond testing was done for all specimens at the age of 90 days.

These were also cured in lime-saturated water filled tanks for 28 days. Then, a part of specimens were tested and other specimens were kept at 20°C and 65% RH in laboratory atmosphere until the age of 90 days. Five specimens from each mix were tested at 7, 28 and 90 days.

Fresh concrete was tested for slump (ASTM C 143) (2000) and unit weight (ASTM C 138) (2001). Concretes were produced with a 75 dm^3 capacity mixer. 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. Slump was kept constant at 10±5 cm in the mixes. In naming the concrete mixes, the type of the concrete (N 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 (2000) specimens. The reinforcing bars have a nominal diameter of 14 mm instead of no.6 (19 mm) 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 (ASTM C234). 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.

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

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

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 test setup is shown in Figures 2 and 3. Besides, the pullout specimen dimensions are shown in Figure 4 and the specimens demoulded in Figure 5.

RESULTS AND DISCUSSION

Fresh concrete properties

Mix proportions and some fresh properties of the SLWAC are shown Table 3. 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. Due to the absorbed condition, this water is not available to affect the cement paste. Therefore, as noted in ASTM C 125 (concrete and concrete aggregates), absorbed water is not considered when calculating the water-cement ratio. 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. Mix proportions and some fresh properties of the NWAC are given in Table 4. The slump was tried to be kept constant at 7±2 cm. Since use of superplasticizer increased the slump by approximately 2 cm, water contents of the mixes were reduced accordingly. As seen from Table 4,

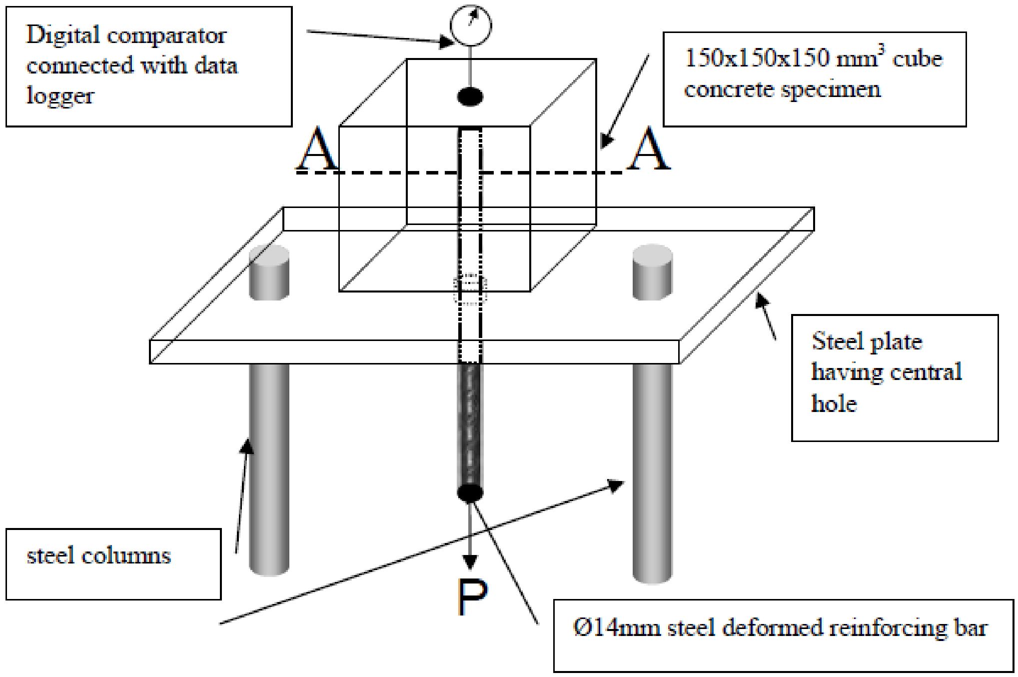

Figure 3. Experimental set-up.

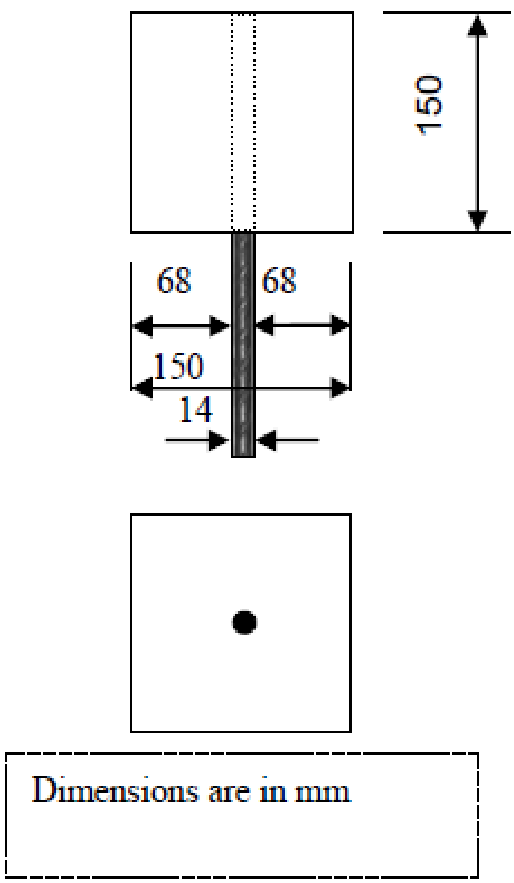

Figure 4. A-A cross-section of the bond specimen.

water/binder ratio of the NWAC was between 0.42 and 0.58.

Tables 3 and 4 show that water requirement of both SLWAC and NWAC increased when SF was used. In the study, different w/b ratio was used for both SLWAC and NWAC due to obtain similar workability for the all concrete types. As it can be estimated, the water demand for aggregates, especially for the lightweight aggregates, may vary from the minimum values and to the maximum. 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 (Khayat and Aitcin, 1992). In these cases, use of SP enabled to reach the desired slump with much lower water contents, as seen from both Tables 3 and 4. Unit weights of both SLWAC and NWAC 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 5. 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

Figure 5. Bond strength specimens after demolding.

Table 3. Mix proportions (for 1/m^3) and some fresh properties of the SLWAC.

Code	Additive: Admixture (by weight of cement %)	Cement (kg)	Water (kg)	w/c	Aggregate (kg) 0-4 mm	4-8 mm	8-16 mm	SP (kg)	SF (kg)	Slump (cm)	Fresh unit weight (kg/m^3)
L-0-0	None	430	199	0.46	730	550	52	---	---	8.4	1809
L-0-2	2%SP	430	187	0.43	730	550	52	8.6	---	6.4	1840
L-5-0	5%SF	408.5	202	0.47	729	549	52	---	21.50	7.2	1792
L-5-2	2%SP-5%SF	408.5	189	0.44	729	549	52	8.6	21.51	7.1	1811
L-10-0	10%SF	387	202	0.47	729	549	52	---	43	6.8	1772
L-10-2	2%SP-10%SF	387	188	0.44	730	550	52	8.6	43	6.2	1787

Table 4. Mix proportions (for 1/m^3) and some fresh properties of the NWAC.

Code	Additive: Admixture (by weight of cement %)	Cement (kg)	Water (kg)	w/c	Aggregate (kg) 0-4 mm	4-16 mm	SP (kg)	SF (kg)	Slump (cm)	Fresh Unit Weight (kg/m^3)
N-0-0	None	386	205	0.53	788	962	---	---	5.50	2367
N-0-2	2%SP	386	174	0.45	788	962	7.72	---	7.70	2385
N-5-0	5%SF	367	214	0.55	783	957	---	19.32	10.9	2347
N-5-2	2%SP-5%SF	367	164	0.42	788	962	7.72	19.30	9.80	2365
N-10-0	10%SF	347	224	0.58	782	957	---	38.67	10.2	2325
N-10-2	2%SP-10%SF	348	164	0.42	788	962	7.73	38.62	9.20	2342

Table 5. Some physical properties of the hardened concretes.

Concrete	Unit weight (kg/m^3)	Water absorption capacity (%)
L-0-0	1678	5.90
L-0-2	1722	5.83
L-5-0	1665	6.42
L-5-2	1711	5.97
L-10-0	1656	8.25
L-10-2	1696	8.11
N-0-0	2297	5.82
N-0-2	2325	5.13
N-5-0	2273	4.63
N-5-2	2302	4.27
N-10-0	2248	5.06
N-10-2	2277	2.84

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 NWAC resulted in lower values when compared with reference mix (N-0-0). On the other hand, for SLWAC mixes, the concretes containing SP and SF had generally higher absorption capacities when compared with control mix. The absorption capacity of both NWAC and 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 NWAC show that even the heaviest SLWAC (1722 kg/m^3) was 23% lighter than the lightest NWAC (2248 kg/m^3). This also means that the earthquake forces will be reduced by about 23% if a structure or building is made with SLWC (Yasar et al., 2003).

Compressive strength

Average compressive strength and standard deviation values for SLWACs and NWACs, obtained from at least 5 specimens for each series and are given in Table 6.

In SLWACs the highest CS value at 7th day was 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 measurement 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 strength measurements, 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. Although it can not be obviously seen, it can be said that the usage of SF alone lowers the CS. The reason is the demand for high mixing water during applications with SF. 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 (Neville, 2002). These results are in agreement with those of Malhotra (1987) and Neville (2002) showing the increase of CS when SF used with SP addition. Replacement of SF with cement at certain rates could be accepted to have slight positive effect on CS due to filling of space and pozzolanic activity (Khayat and Aitcin, 1992).

As seen in Table 6, 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. 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 (1991).

As given in Table 6, for the N-5-0 coded specimens, while a rising was around 5% when compared with reference concrete (N-0-0), the reduction rate was about 13% in the sample coded with N-10-0. In NWACs the highest 7 day strength was observed in N-0-2 type of concrete. There is a 16% increase compared with N-0-0. The lowest strength on the other hand, was seen in sample N-10-0 with a measured strength corresponding to 60% of 28-day strength of N-0-0.

Considering NWACs and SLWACs, although cement dosage was 430 kg/m^3 in L-0-0 (Table 4) and 386 kg/m^3 in N-0-0 (Table 3), a clear predominance of SLWACs coded with L-0-0 over NWACs coded with N-0-0 in all series were seen. This was a result of lower CS caused by natural porosity of pumice aggregate (used for producing SLWACs) when 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

Table 6. Average and standard deviation values of concrete compressive strength in samples.

Age (days)	SLWA concretes	N	$f_{c\bar{x}}$ (MPa)	‡)	Std. Dev. (MPa)	1)	NWA concretes	N	$f_{c\bar{x}}$ (MPa)	*)	Std. Dev. (MPa)	1)
7	L-0-0	5	18.80	77	0,98	100	N-0-0	4	31.79	81	0.73	100
	L-0-2	5	20.58	84	1,09	109	N-0-2	5	45.49	116	0.60	143
	L-5-0	5	18.93	77	0.47	101	N-5-0	5	29.23	75	0.60	92
	L-5-2	5	20.18	83	0.81	107	N-5-2	5	42.96	110	0.87	135
	L-10-0	5	18.69	77	0.74	99	N-10-0	5	23.66	60	0.53	74
	L-10-2	5	22.22	91	0.68	118	N-10-2	5	43.93	112	1.29	138
28	L-0-0	5	24.43	100	1.04	100	N-0-0	4	39.18	100	2.01	100
	L-0-2	5	25.60	105	2.07	105	N-0-2	5	47.08	120	1.80	120
	L-5-0	5	23.50	96	1.54	96	N-5-0	5	41.12	105	2.03	105
	L-5-2	5	26.21	107	3.35	107	N-5-2	5	55.01	140	3.52	140
	L-10-0	5	22.26	91	0.95	91	N-10-0	5	34.09	87	1.74	87
	L-10-2	5	28.26	116	2.62	116	N-10-2	5	58.62	150	2.14	150
90	L-0-0	5	25.40	104	1.24	100	N-0-0	4	40.34	103	2.09	100
	L-0-2	5	25.28	103	3.24	100	N-0-2	5	51.70	132	5.97	128
	L-5-0	5	24.31	100	0.70	96	N-5-0	5	45.74	117	5.54	113
	L-5-2	5	26.23	107	2.44	103	N-5-2	5	61.01	156	5.24	151
	L-10-0	5	24.42	100	2.36	96	N-10-0	5	36.78	94	7.92	91
	L-10-2	5	28.58	117	3.02	113	N-10-2	5	66.47	170	6.54	165

‡)These values are to percentages of CS values over SLWAC compressive strength without additive at the age of 28 days; *) these values are to percentages of CS values over NWAC compressive strength without additive at the age of 28 days; 1) CS change as percentage of samples N-0-0 and L-0-0 for each ages.

tension transferred to aggregate can not be carried (Mor, 1992; Topçu, 1997).

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 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 (Hossain, 2008; Valcuende and Parra, 2009; Al-Negheimish and Al-Zaid, 2004; Banholzer et al., 2005; Hassan et al. 2010; Harajli et al., 2002). The average and standard deviation values obtained from statistical analyses are given in Table 7.

As seen in Table 7, 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 (Neville, 2002).

As the lowest force in NWAC's was 58 kN at N-10-0 coded specimens, the highest force was obtained at N-10-2 coded specimens (94 kN). 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 (Zhang and Gjørv, 1991).

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 with N-0-0. Other all SLWAC specimens were less than N-0-0 (ranges between 0.92 and 0.96 times).

When an evaluation was done between NWAC 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). These increments are respectively 1.14 and 1.22 times with the series of N-5-2 and N-10-2 according to the N-0-0. Similar findings to

Table 7. 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)		
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
N-0-0	63	1.14	9.55 (100)	1.53	1.00	3 Pull-out /2 Splitting
N-0-2	76	1.48	11.52 (121)	1.68	1.10	1 Pull-out /4 Splitting
N-5-0	65	4.16	9.85 (103)	1.54	1.00	2 Pull-out /3 Splitting
N-5-2	85	3.65	12.88 (135)	1.74	1.14	1 Pull-out /4 Splitting
N-10-0	58	1.58	8.79 (92)	1.51	0.98	1 Pull-out /4 Splitting
N-10-2	94	2.70	14.25 (149)	1.86	1.22	1 Pull-out /4 Splitting

*) Values in parenthesis are bond strength change as percentage of samples N-0-0 and L-0-0.

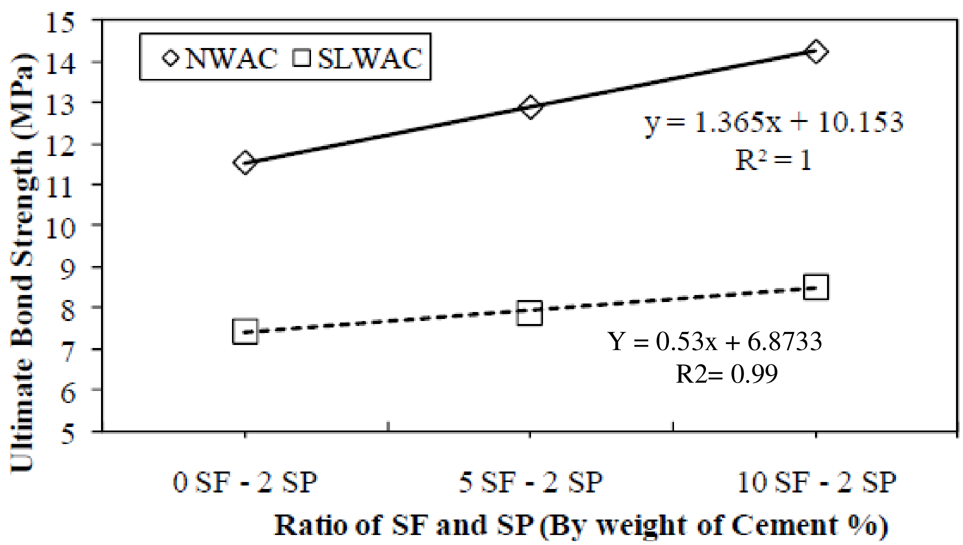

Figure 6. Relation between ultimate bond strength versus addition ratio.

these results reported by previous studies (Gjørv et al., 1990; Kayali and Yeomans, 2000).

In Figure 6, a plot of bond strength versus ratio of admixture is presented. It can be said that a rising tendency depends on the use of SF and SP together in the SLWAC's and NWAC's (R^2 is equal to 1 and 0.99, respectively).

The similar behavior had obtained for bond force in SLWAC's and NWAC's with admixture both SF and SP. The highest bond strength was obtained in the specimens of both types of concrete (L-10-2 and N-10-2).

On the other hand, the bond strength of SLWAC's was apparently lower than that of NWAC's. 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 (Mor, 1992; Neville, 2002). Gjorv et al. (1990) 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

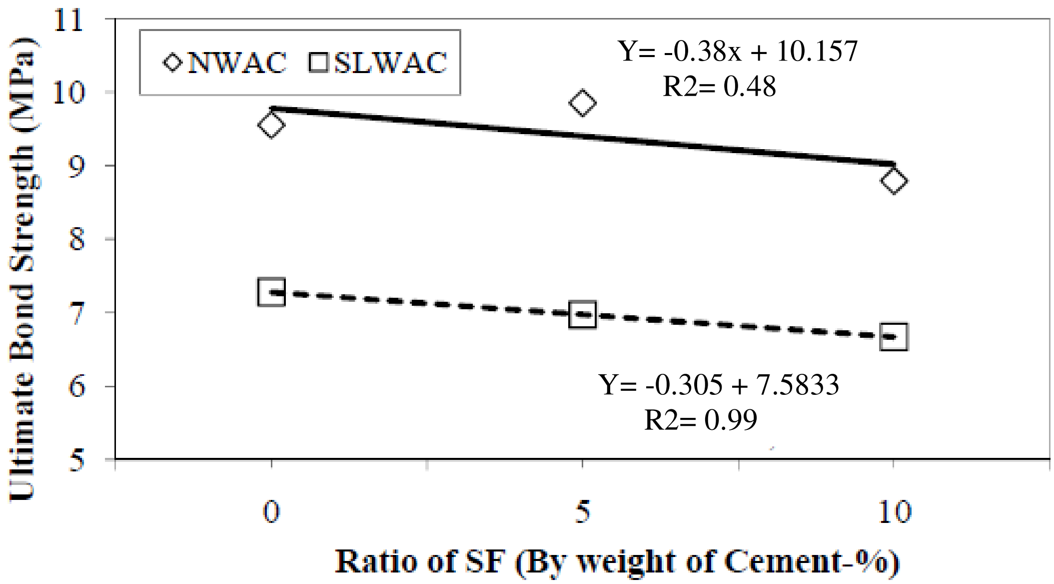

Figure 7. Relation between ultimate bond strength vs. SF addition ratio.

the internal bleeding in fresh concrete, hence reducing the accumulation of free water under aggregate and reinforcing steel (Khayat and Aitcin, 1992). 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 versus SF addition ratio are shown graphically in Figure 7. The trend from the figure results in reduction in the bond strength when only SF was used. This case did not obvious for NWAC (R square 0.48). In the SLWAC specimens, a reduction tendency was also similar to general case (R square 0.99).

This observation was also parallel 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 (Nilson and Winter, 1991). 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 10SF+2%SP was 8.49 MPa.

Load and slip relationship and failure modes

In general, both NWAC and SLWAC specimens exhibited similar behaviour between the slip values of 0.00 to 0.25 mm, which is a slow rise at load, while the slip increases rapidly. Similar load-slip response was reported by Mor (1992) 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 the figures between Figure 8 and 19. 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 NWAC and SLWAC (Figures 8 to 19). However, for SLWAC specimens the peak load was lower and slip at peak load was almost same when compared with NWAC specimens (between Figures 8 to 19)

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 NWAC and SLWAC specimens (ranges between 0.7 and 2.5 mm).

As seen from all graphs, 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 (Kwak and Filippou, 1990; Ožbolt et al., 2002). Similar trends for the load-slip curves were obtained by Campione et al. (2005) for non fibrous lightweight concrete. In fact, this line could not be observed herein since the automatic controlled testing machine was used to determine the bond strength.

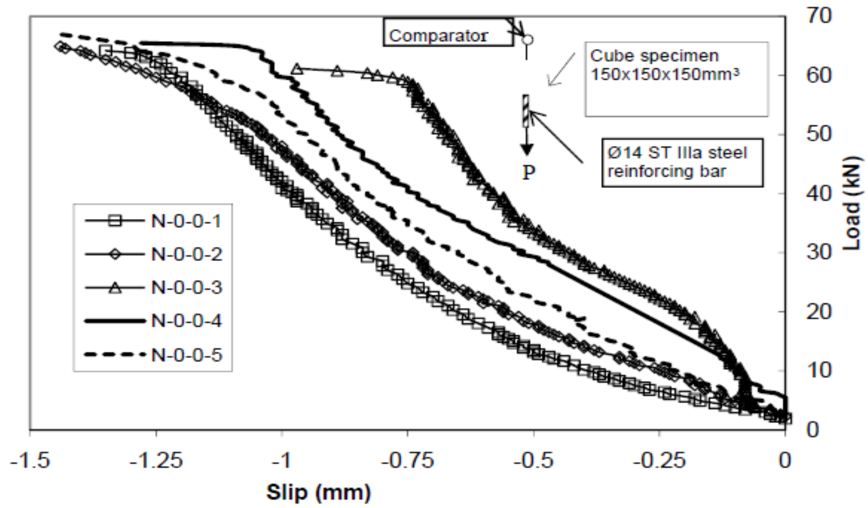

Figure 8. The slip-load relation on the specimens with coded N-0-0 (Reference).

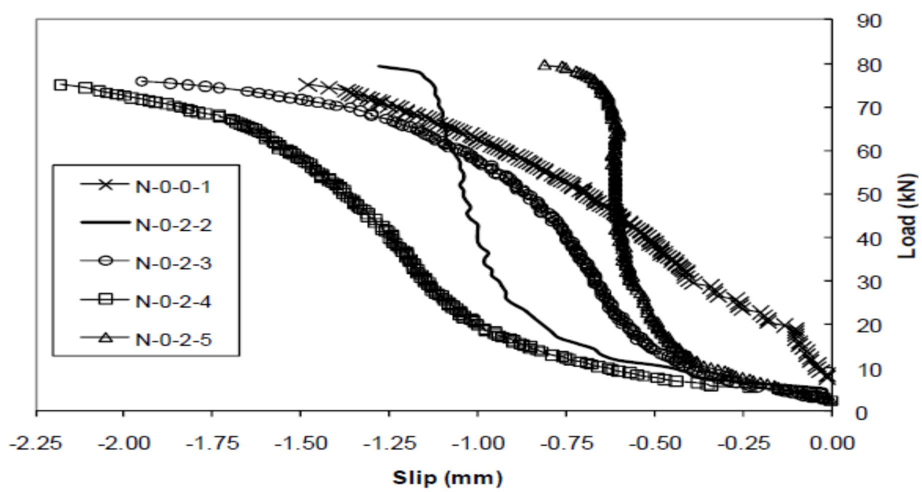

Figure 9. The slip-load relation on the specimens with coded N-0-2.

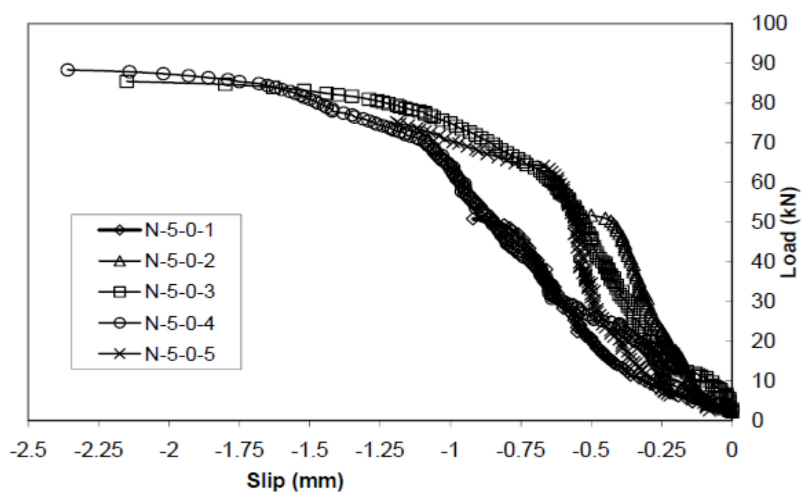

Figure 10. The slip-load relation on the specimens with coded N-5-0.

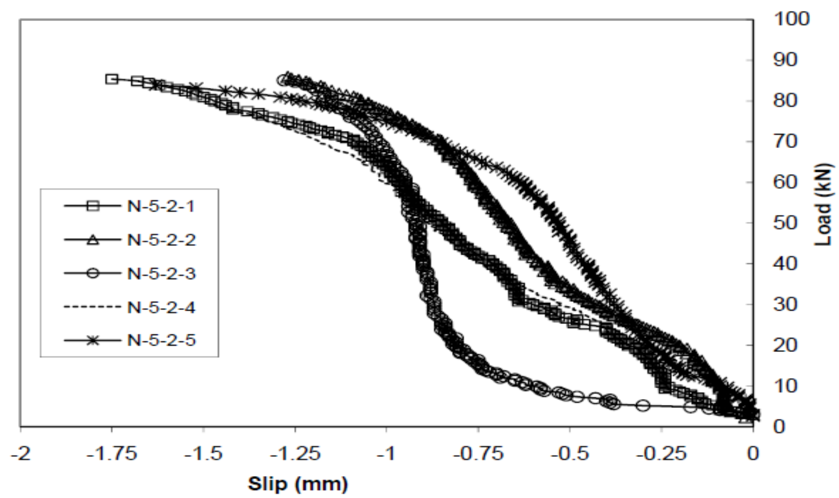

Figure 11. The slip-load relation on the specimens with coded N-5-2.

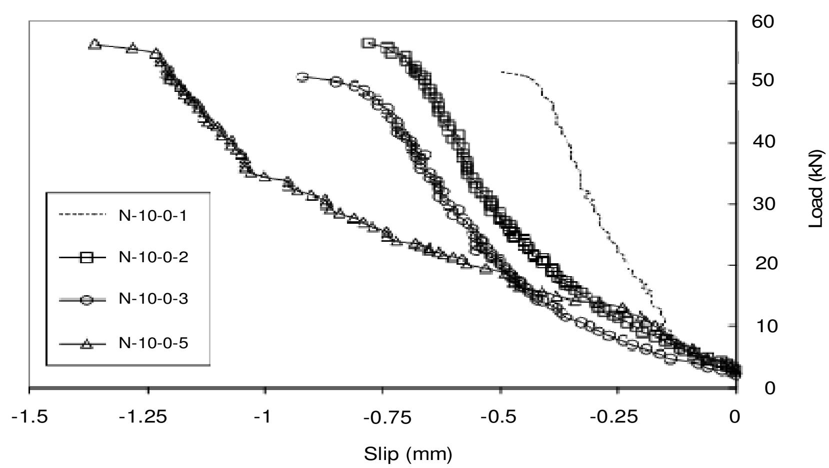

Figure 12. The slip-load relation on the specimens with coded N-10-0.

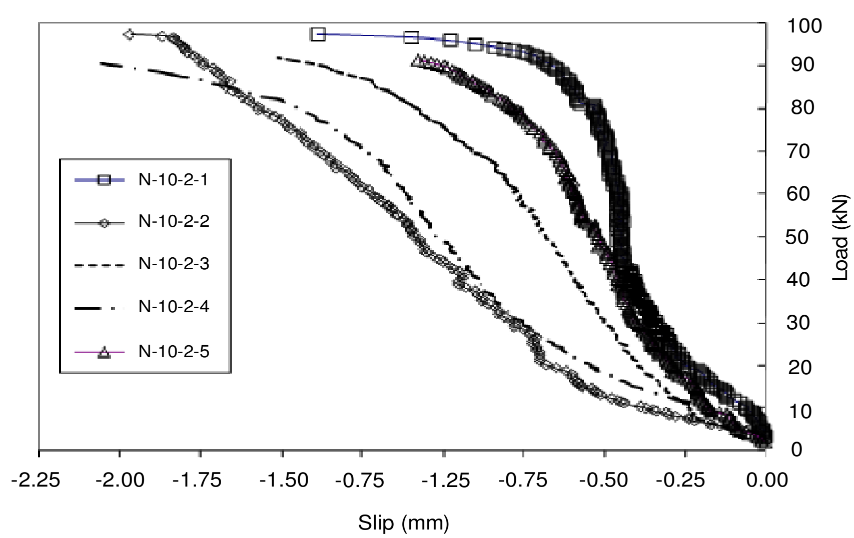

Figure 13. The slip-load relation on the specimens with coded N-10-2.

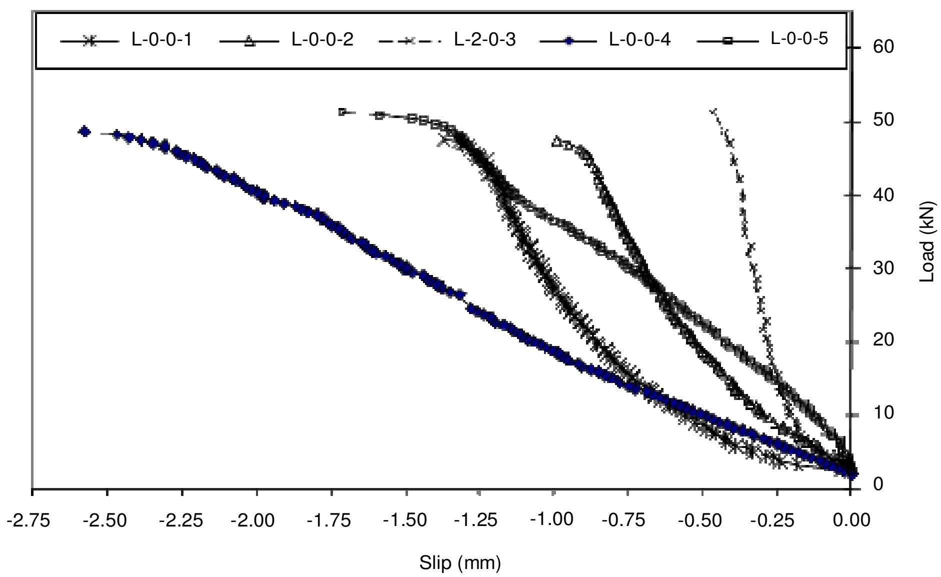

Figure 14. The slip-load relation on the specimens with coded L-0-0 (control).

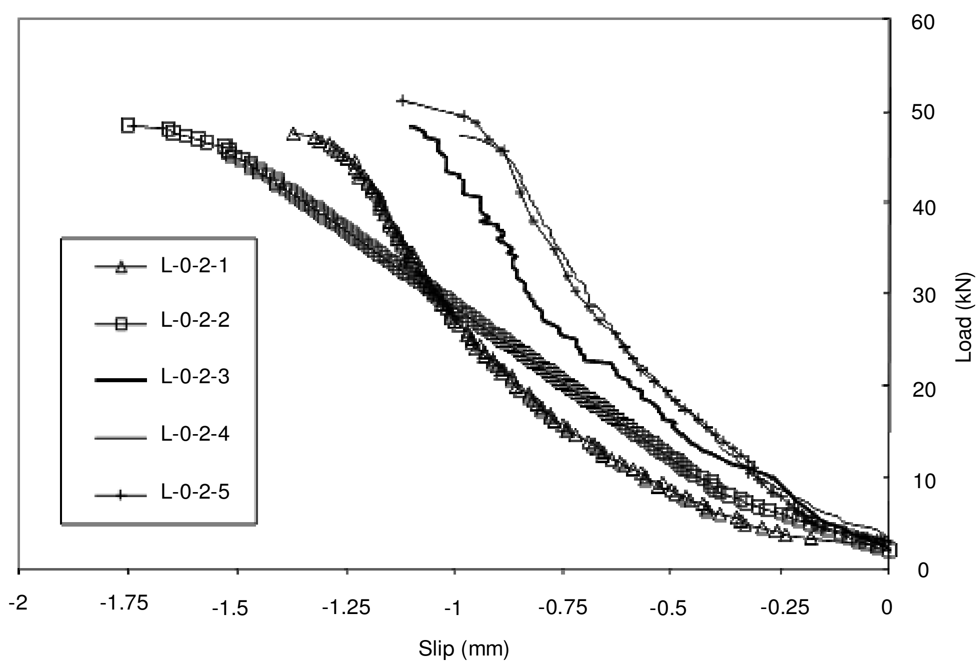

Figure 15. The slip-load relation on the specimens with coded L-0-2.

Pullout type failure was observed on three specimens of N-0-0 series. Other two of N-0-0 specimens exhibited the splitting type failure at the end of pullout tests (Figure 20). As for N-0-2, specimens showed that the four specimens of them were the splitting type failure and the other one was pullout type failure after the pullout test. This case was almost same for all NWAC specimens. But SLWAC specimens, as seen from Figure 21, exhibited the splitting type failure for all bond specimens in the series.

Conclusions

An experimental program was conducted to assess the effects of silica fume and super plasticizer on the bond behaviour of deformed bars on both structural lightweight aggregate and normal weight aggregate concretes. Based on the results of this investigation, the following conclusions can be made: (1) in the concrete samples having the same workability as NWACs, CS decreased

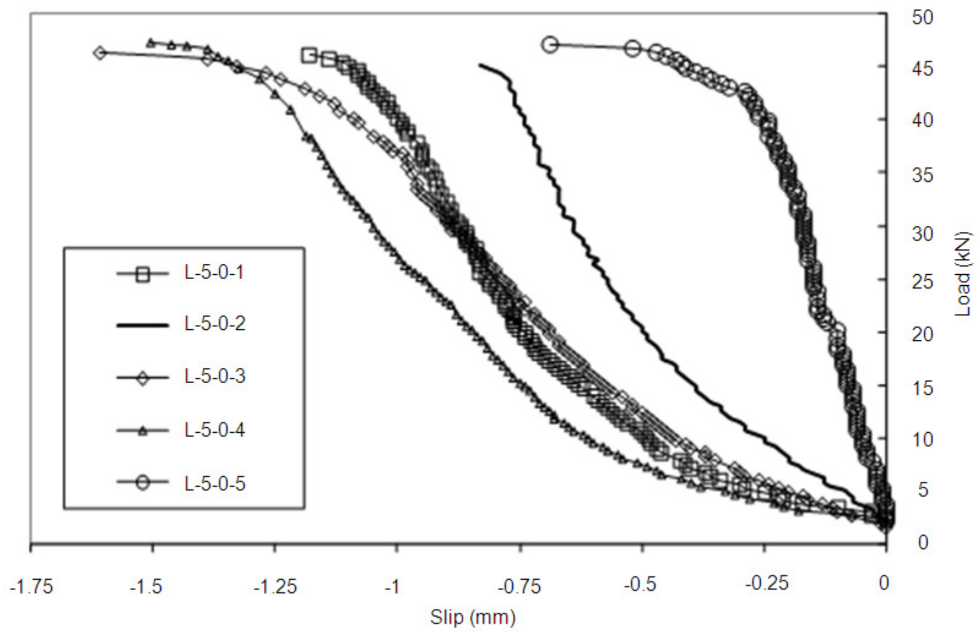

Figure 16. The slip-load relation on the specimens with coded L-5-0.

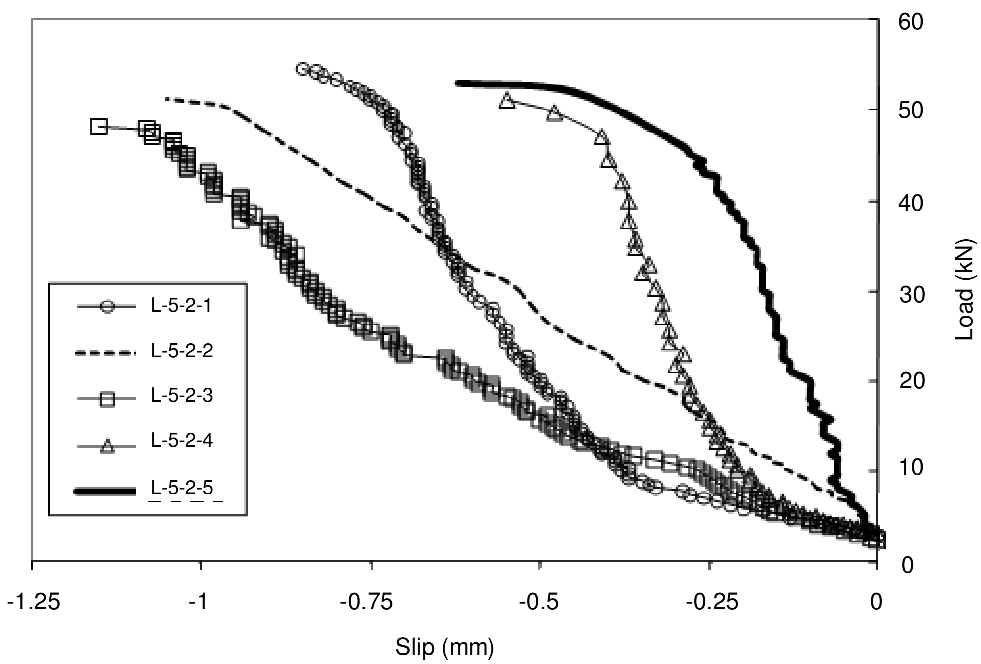

Figure 17. The slip-load relation on the specimens with coded L-5-2.

when the SF usage rate was 10%. In samples in which the SF and SP additions used together, in correlation with the rate of SF usage, CS increased up to 50%; (2) in reference SLWACs, 24 MPa CS values attained with 430kg/m^3 cement dosage by 28th day. If only SF was used additive, in correlation with the usage rate, increase in CS similar NWACs was recorded. Mixed usage resulted in relatively slightly increase in CS. When the compressive strength of NWAC and SLWAC were compared at 28th day, it was observed that compressive strength of SLWACs had 62% of NWACs' at specimens with non-additive. Among SLWAC and NWAC with SF

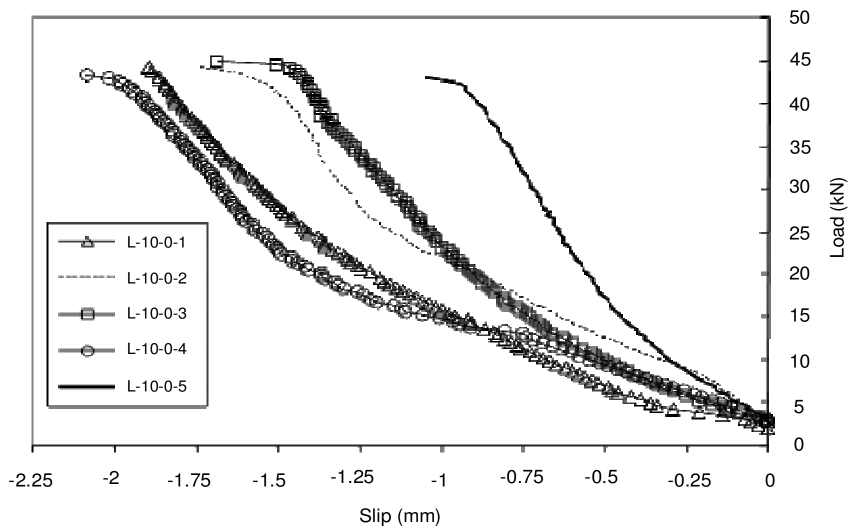

Figure 18. The slip-load relation on the specimens with coded L-10-0.

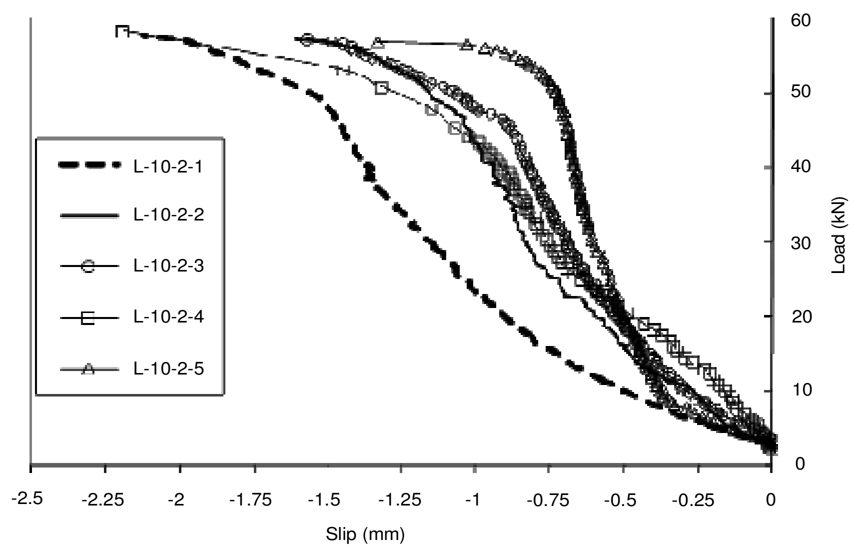

Figure 19. The slip-load relation on the specimens with coded L-10-2.

Figure 20. Typical failure of NWAC bond specimens after bond strength testing.

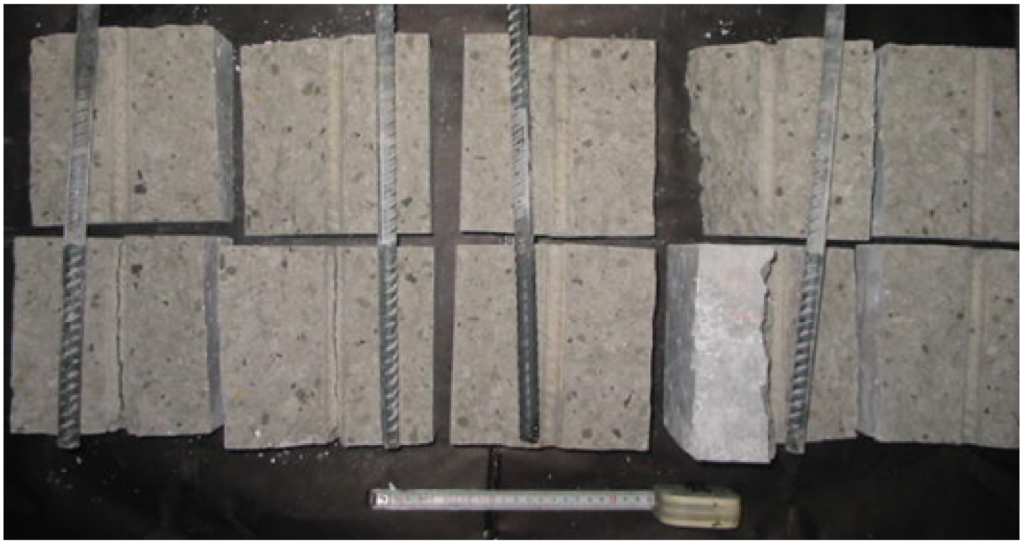

Figure 21. Typical failure of SLWAC bond specimens after bond strength testing.

(10%) + SP (2%) at specimens having the highest strength, strength of SLWAC was 48% of NWACs'; (3) the use of 10% SF alone reduced the bond strength between NWAC and reinforcing steel. In case of SF and SP used together, the bond strength increased as the rate of SF increased up to 10% replacement level. 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. The SLWAC's bond strength was 60% of the bond strength of NWAC when both the NWAC and SLWAC were produced with the addition of SF and SP; (4) the bond strength of deformed bars in SLWAC was lower when compared with 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 with N-0-0 (reference). Other all SLWAC specimens were less than N-0-0 (ranges between 0.92 and 0.96 times); (5) the slip at peak load for pullout failure of ribbed bar did not vary too much for both NWAC and SLWAC specimens (ranges between 0.7 and 2.5 mm).

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