Mechanical properties of lightweight concrete made with cold bonded fly ash pellets

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ABSTRACT

In this paper, compressive and splitting tensile strengths, modulus of elasticity and steel rebar-concrete bond strength of lightweight aggregate concretes (LWAC) produced at 0.40 w/c with sand and mixture of crushed stone and lightweight fly ash coarse aggregates are presented. Lightweight fly ash aggregates (LWA), plain (LC) and reinforced with 0.1% (L1P) and 0.5% (L5P) crumb rubber and0.1% (L1F) polypropylene fiber are utilized. Test results revealed that the compressive strength of all LWAC conformed to the limitation for structural use whereas a reduction in density up to 20% was achieved. Whereas the mechanical properties decreased with the use of lightweight aggregates, some increases were observed for the steel-concrete bond strength.

INTRODUCTION

The use of fly ash as cement replacement in concrete and the large scale utilization of fly ash for producing artificial lightweight aggregates remarkably reduces the emission of greenhouse gasses and rapid depletion of the natural aggregate resources. Besides, LWAC produced with LWA provides several advantages. Structural lightweight concrete is usually defined to have oven-dry density of 1680-1920 kg/m^3[1] and the type and properties of the lightweight aggregates determine the density, strength and durability characteristics of LWAC. Two methods namely sintering and cold bonding have been used practically to produce lightweight fly ash aggregate [2,3].Cold bonding as a method of lightweight aggregate production is considered to be more economical than sintering which is an energy intensive process. However, cold bonding depends on the pozzolanic reactivity of the fly ash and it usually results in lower strength aggregates. Gesoğlu [4] and Gesoğluet. al [5-7] produced cold-bonded lightweight fly ash aggregates with specific gravities in the range of 1.72 and 1.80. Water absorption of LWA was 27% by weight which was decreased to 3.0 and 18% by treating the surface of pellets with water glass and cement silica fume slurry, respectively. LWCs produced with water glass treated LWAs gave rise to higher compressive and splitting tensile strengths and modulus of elasticity. LWCs with untreated LWA had the lowest mechanical properties. Kockal [8] and Kockal and Ozturan [9-12] investigated the physical and mechanical properties of LWCs made with sintered lightweight fly ash aggregates containing glass powder(LWGC)and bentonite (LWBC) as well as cold-bonded lightweight fly ash aggregates (LWCC).Air content and density of fresh LWCC, LWBC, LWGC were 3.9, 4.3, 4.1% and 1991, 1960, 1975 kg/m^3, respectively. Compressive strength, splitting tensile strength and modulus of elasticity of LWCC, LWBC, LWGC were 42.3, 53.5, 55.8 MPa and 3.7, 4.8, 4.9 MPa and 19.6, 26.0, 25.7 GPa, respectively. Mor [13] observed perfect bond-slip behavior in high strength lightweight concretes due to better coherence between LWA and the cement paste.

EXPERIMENTAL STUDY

Materials

Two types of CEM I 42.5 R portland cement with the same specific gravity of 3.14 g/cm^3 and specific surface of 3910 and 3770 cm^2/g were used for the production of lightweight aggregates and concrete, respectively. An F type fly ash from Çatalağzı Thermal Power Plant, Zonguldak, Turkey with specific gravity of 2.06 g/cm^3 andspecific surface of 2880 cm^2/g was usedin the production of lightweight aggregate.Polypropylene fiber (PP) of 12 mm length and 32µ diameter having a tensile strength of 250 MPa and crumb rubberwith a maximum particle size of 4 mm were also used in the production of lightweight aggregates.Natural and crushed sand (0-4 mm)with specific gravities of 2.65 and 2.70 g/cm^3, respectively, and crushed stone No-1 (4-8 mm) and No-2 (8-16 mm) withspecific gravity of2.70 g/cm^{3}as well as cold bonded lightweight fly ash (4-16 mm) were used in concrete production. A naphthalin sulfonated formaldehyde superplasticizer (SP) was used to provide the required workability of fresh concrete.Deformed steel bars (S420) with a diameter of 12 mm were used to determine the bond strength through pull-out test.

Preparation of Lightweight Coarse Aggregates

Lightweight fly ash pellets were produced through the cold-bonding agglomeration process by a pelletization disc shown in Figure 1.The pelletizer disc has diameter of 40 cm and height of 15 cm. To produce plain and fiber reinforced lightweight pellets, dry fly ash-cement mixtures were fed into the disc with an inclination of 43˚ and rotated at 45 rpm according to the results of Baykal and Döven [2].In the next step, water was sprayed onto the powder mixtures during the first 10 minutes of the agglomeration process at an amount of 23-27 % of the total weight of material to get the spherical pellets. Extra 10 minutes was allocated to further compaction of the fresh pellets to increase their strengths. Lightweight aggregates were produced with a cement-to-fly ash ratio of 0.1 by weight. Polypropylene fibers (PP) and crumb rubber were added to the dry fly ash-cement mixture of plain/control lightweight aggregates (LC) at 0.1% (L1F) as well as 0.1% (L1P) and 0.5% (L5P), respectively, to produce fiber reinforced fly ash pellets. Fresh pellets were preserved in plastic bags and left for the final hardening inside a curing room at a temperature of 20 ˚C and 80 % RH for 28 days.

Tests and Measurements on Lightweight Fly Ash Aggregate Grains

After the curing period the fly ash pellets were sieved into 4-8mm and 8-16mm size fractionsto be used as replacement of coarse aggregates No-1 and No-2, respectively. After determining the specific gravity, unit weight and water absorption, the crushing strength of the lightweight aggregates were determined on individual pellets that were placed one by one between two parallel loading plates (Figure 2) by Eq.(1).

$$\sigma = \frac{2.8*P}{\pi*X^2} \quad (1)$$

where P is the failure load and X is the distance between loading points[9]. Forty randomlychosen pellets with an average diameter of 12 mm were tested in order to calculate the average crushing strength for each type of lightweight fly ash aggregates.

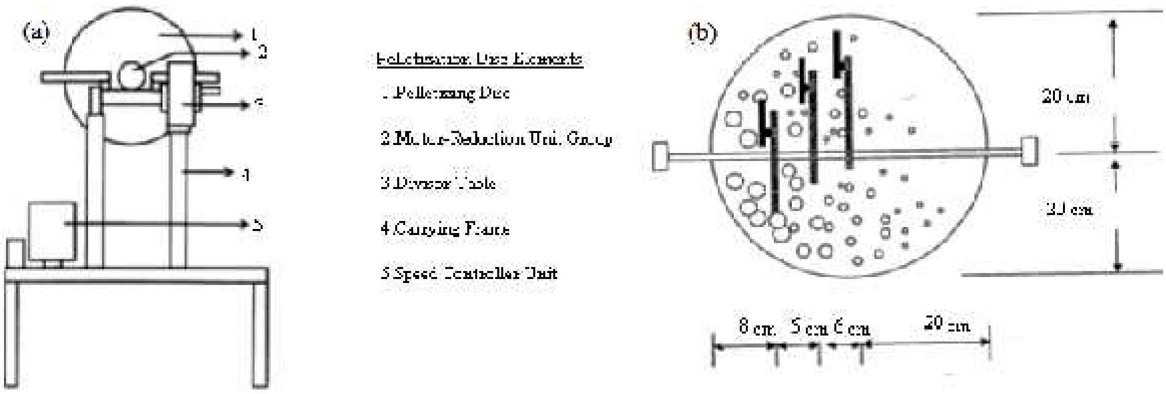

Figure 1. (a) Pelletizer and (b) A schematic view of the disc.

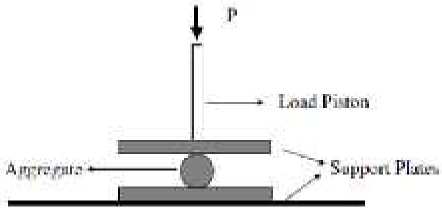

Figure 2.Aggregate crushing strength configuration.

Concrete Mix Design

Control concrete mixture was produced using 450 kg/m^3 portland cement, 228 kg/m^3 and 570 kg/m^3 natural and crushed sand, respectively, 490 kg/m^3 No I and No II crushed stone each and 180 kg/m^3 water as well as sufficient amount of superplasticizer. Lightweight concretes were produced by replacing the No I and No II crushed stone coarse aggregates by LC, L1P, L5P, and L1F lightweight fly ash coarse aggregates on volume basis as given in Table 1.

Casting and Curing of Concrete Specimens

A special procedure was applied for concrete casting to minimize the slump loss owing to the high water absorption of the lightweight aggregates. For this purpose, lightweight aggregates were first submerged in water for 24 hours to be saturated and then kept on large scale sieves for 1 hour to be surface dried before mixing. Slump, unit weight and air content of fresh concrete were measured. Three cylinder moulds of 100*200mm size were cast for testing the mechanical properties. After casting, the specimens were left in laboratory environment for 24 hours. After demouldingcylinder specimenswere stored in the curing room at a temperature of 20 ˚C and 85 % relative humidity for 56 days before testing for compressive, splitting tensile and steel-concrete bond strengths as well as modulus of elasticity.

TEST RESULTS AND EVALUATION

Properties of Lightweight Fly Ash Aggregates

Unit weight, specific gravity, water absorption and crushing strength of LWAs are presented in Table 2. Water absorption of LWAs in the size range of 8-16 mm are lower than that of LWAs in 4-8 mm size. When the size of the grain grows, the pellets become denser with less and mostly closed pores resulting in decreased absorption which was also observed by Koçkal and Özturan [10] for cold bonded fly ash aggregates with the same fly ash but different portland cement.Crumb rubber addition increased crushing strength of pellets from 3.78 MPa to 4.19 and 3.90 MPa, which decreased with increasing rubber content. Average crushing strength of L1F pellets, on the other hand, was slightly lower than that of LC.

Table 1. The mix proportions used in the experiments (kg/m^3)

Production Plan	Coarse Aggregates						SP	
	Crushed Stone		LC	L1P	L5P	L1F	(%)	(kg/m^3)
	No 1	No 2						
CCSt(4-16)	490	490	-	-	-	-	1.2	5.4
LC(4-8)CSt(8-16)	-	490	290.37	-	-	-	1	4.5
LC(8-16)CSt(4-8)	490	-	290.37	-	-	-	1	4.5
LC(4-8 and 8-16)	-	-	580.74	-	-	-	1	4.5
L1P(4-8)CSt(8-16)		490	-	292.19	-	-	1	4.5
L1P(8-16)CSt(4-8)	490	-	-	292.19	-	-	1	4.5
L1P(4-8 and 8-16)	-	-	-	584.38	-	-	1	4.5
L5P(4-8)CSt(8-16)	-	490	-	-	292.19	-	1	4.5
L5P(8-16)CSt(4-8)	490	-	-	-	292.19	-	1	4.5
L5P(4-8 and 8-16)	-	-	-	-	584.38		1	4.5
L1F(4-8)CSt(8-16)	-	490	-	-	-	290.37	1	4.5
L1F(8-16)CSt(4-8)	490	-	-	-	-	287.26	1	4.5
L1F(4-8 and 8-16)	-	-	-	-	-	577.63	1	4.5

Table 2.Properties of Lightweight Fly Ash Aggregates

Properties	LC		L1P		L5P		L1F	
	4-8	8-16	4-8	8-16	4-8	8-16	4-8	8-16
Unit Weight, (g/cm^3)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SSD Specific Gravity	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Water Absorption, %	28.2	24.4	27.9	24.1	27.6	24.9	25.4	24.5
Average Crushing Strength (MPa)	3.78		4.19		3.90		3.53	
Standard Deviation (MPa)	0.89		0.84		0.92		0.86	

Fresh Concrete Properties

Concrete mixes were cast by using a high range water reducing agent at required dosage for achieving a slump of 14±2 cm. Lightweight aggregate concretes were workable and cohesive and segregation was not observed. Fresh concrete properties are presented in Table 3. When LWAs replaced the normal weight aggregate at 50% volume fraction of coarse aggregate, unit weight decreased from 2425 kg/m^3 to 2170 kg/m^3 and air content increased from 1.10% to 2.10%. However, when natural coarse aggregate was fully replaced with lightweight fly ash aggregates, there was a significant reduction in the density of fresh concretes till the value of 1975 kg/m^3.

Compressive Strength and Modulus of Elasticity

Compressive strength and modulus of elasticity of concretes presented in Table 4 varied between 49.0 and 29.8 MPa and 25.7 and 19.7 GPa, respectively, when crushed stone was replaced with LWA. Similar results were obtained by Gesoglu et al. [7] as compressive strength and modulus of elasticity decreased from 40.1 to 29.1 MPa and 22.4 to 18.2 GPa, respectively when cold bonded lightweight fly ash aggregate content was increased in concrete with w/c of 0.35.

Table 4 Mechanical properties of hardened concretes.

Production Plan	Average Values			
	Comp. Strength (MPa)	E (Mpa)	Spltt. Ten. Strength (MPa)	Ultimate Bond Strength(Mpa)
CCSt(4-16)	49.0	25679.67	4.71	11.44
LC(4-8)CSt(8-16)	44.23	25183	4.42	12.15
LC(8-16)Cst(4-8)	45.42	23432.33	4.0	9.5
LC(4-8 and 8-16)	38.3	20750	2.86	8.52
L1P(4-8)CSt(8-16)	45.54	25185	3.86	8.62
L1P(8-16)Cst(4-8)	46.48	24642.33	3.26	12.8
L1P(4-8 and 8-16)	41.09	20251	2.82	10.3
L5P(4-8)CSt(8-16)	44.38	25268.33	3.88	10.59
L5P(8-16)Cst(4-8)	41.65	23580	4.35	14.74
L5P(4-8 and 8-16)	29.8	19688.67	2.87	9.51
L1F(4-8)CSt(8-16)	41.1	24141.33	3.90	16.11
L1F(8-16)Cst(4-8)	43.69	23856.67	4.24	14.33
L1F(4-8 and 8-16)	39.37	20228.67	2.83	10.52

Variation of compressive strength and modulus of elasticity with the type of lightweight fly ash coarse aggregate are shown in Figures 3 and 4, respectively. Among the lightweight concretes, higher compressive strength was obtained with the pellets containing 0.1% crumb rubber. Increase in crumb rubber content caused a decrease in strength. With the use of polypropylene fibers in the fly ash pellets, higher strength was obtained with coarser part of lightweight aggregates. When all coarse aggregate was replaced by all types of lightweight aggregate, the compressive strength and modulus of elasticity were the lowest. Modulus of elasticity was not affected much by the type of LWA where as the lowest values were obtained when all coarse aggregate was replaced by LWA.

Splitting Tensile Strength

Splitting tensile strength of concretes given in Table 4 changed between 4.71 and 2.82 MPa when crushed stone coarse aggregate was replaced with LWA. Figure 5 shows the variation of the splitting tensile strength by the type of coarse aggregate. Concrete mixtures consisted of both LWA and crushed stone coarse aggregate in equal volume fractions had lower splitting tensile strength compared to the concretes produced with normal weight coarse aggregate. The use of LWAs as a substitute of all crushed stone coarse aggregate gave rise to a considerable decrease in splitting tensile strength. Lightweight concretes with 0.5% crumb rubber and 0.1% polypropylene fibers showed higher tensile strength when LWA replaced 8-16mm fraction of the coarse aggregate.

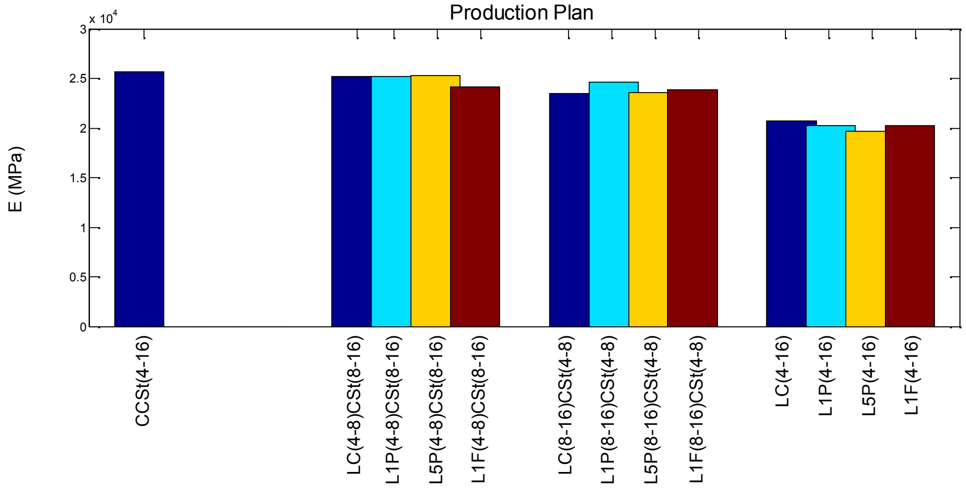

Figure 4.Variation of elastic modulus with the type of coarse aggregate.

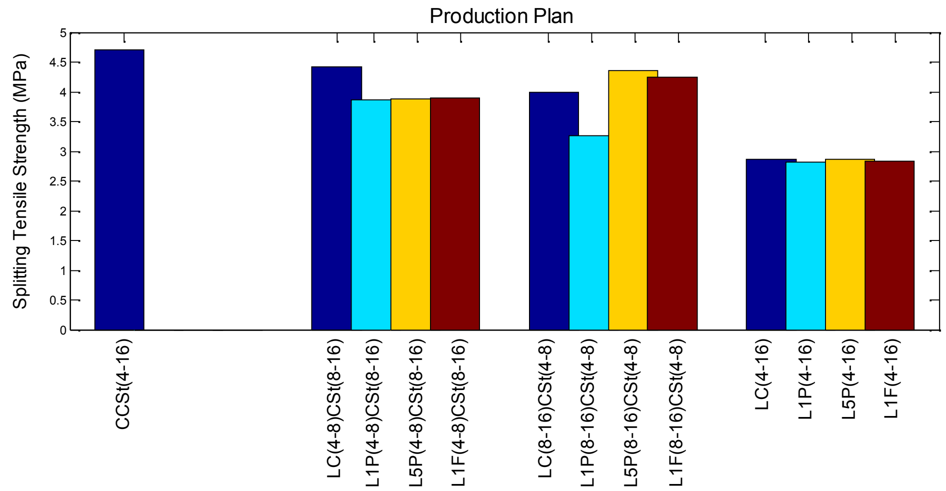

Figure 5.Variation of splitting tensile strength with the type of coarse aggregate.

Steel-Concrete Bond Strength

Pull-out tests were conducted at proper loading speed until the maximum load was reached where the specimens of all concretes split without yielding of steel bars. Steel bar-concrete bond strength of concretes given in Table 4 varied from 11.44 MPa to 8.52 MPa with the use of LWA as similarly reported by Gesoğlu [4] that a gradual decrease in ultimate bond strength was observed with the increase in volume percent of cold bonded lightweight fly ash aggregate. Figure 6 shows the variation of bond strength with the type of lightweight aggregate. When LWA and crushed stone were used together in equal parts, ultimate bond strength increased without any trend. Crumb rubber and polypropylene fiber containing lightweight aggregate replacing the 8-16mm fraction of coarse aggregate resulted in higher bond strength. The positive contribution of LWAs may be accounted for a better coherence and interlocking of the LWA with the surrounding concrete that minimizes the cracking and thus utilizes fully the adhesion between the concrete and rebar [4,13]. L1F(4-8) CSt(8-16) concrete had the highest (16.11 MPa) bond strength which may be attributed to the extra adherence between LWAs and matrix phase that prevents possible cracking by the help of the polypropylene fibers protruding from the surface of pellets.

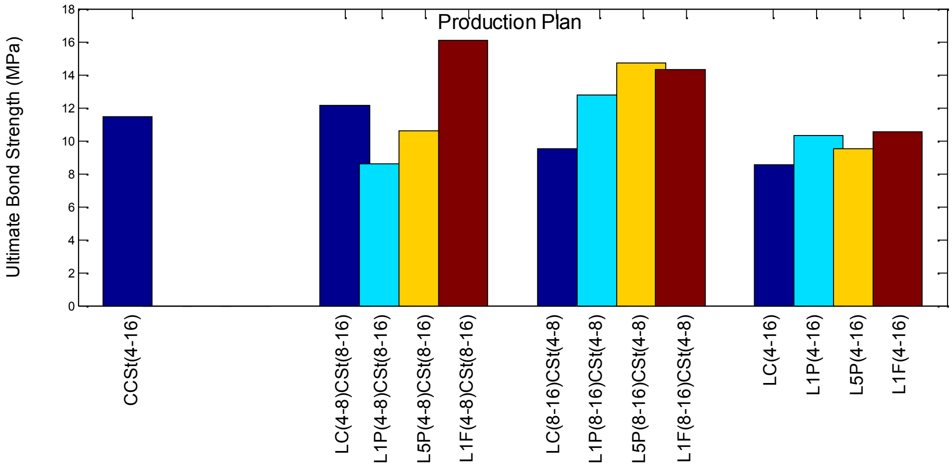

Figure 6.Variation of bond strength with the type of coarse aggregate.

CONCLUSION

Lightweight concretes produced with lightweight fly ash aggregates were cohesive and workable and didn't show segregation. Replacing the crushed stone coarse aggregate fully with lightweight fly ash aggregates significantly reduced the density of fresh concretes. The use of LWAs as partial or total substitute of crushed coarse aggregate resulted in slight to considerable decrease in compressive and splitting tensile strength and modulus of elasticity of concretes. The ranking of compressive strength of lightweight concretes from highest to lowest [L1P(4-8)CSt(8-16) > L5P(4-8)CSt(8-16) > LC(4-8)CSt(8-16) > L1F(4-8)CSt(8-16)] comply with the decreasing order of crushing strength of lightweight aggregates (L1P> L5P> LC> L1F).When LWAs were used to totally replace the crushed stone coarse aggregate bond strength slightly decreased. However, when LWA and crushed stone were used together in equal parts as coarse aggregate ultimate bond strength increased without any trend. Inclusion of crumb rubber and polypropylene fibers in the fly ash pellets replacing the coarse (8-16mm) part of crushed stone resulted in higher bond strength.

REFERENCES

[1] ACI Committee 213R-03, (2003)Guide for Structural Lightweight-Aggregate Concrete, *American Concrete Institute*, Farmington Hills, MI, USA.

[2] Baykal, G. and Doven, A.G. (2000) Utilization of Fly Ash by Pelletization Process; Theory, Application Areas and Research Results.*Resources Conservation and Recycling*, **30**(1), 59-77.

[3] Harikrishnan, K.I. and Ramamurthy, K. (2006) Influence of Pelletization Process on the Properties of Fly Ash Aggregates.*Waste Management*, **26**(8), 846-852.

[4] Gesoglu, M. (2004)Effects of Lightweight Aggregate Properties on Mechanical, Fracture and Physical Behaviour of Lightweight Concretes, *Ph.D. Thesis, Boğaziçi University*, Istanbul, Turkey.

[5] Gesoglu, M., Ozturan, T. and Guneyisi, E. (2007) Effects of Fly Ash Properties on Characteristics of Cold-Bonded Fly Ash Lightweight Aggregates.*Construction and Building Materials*, **21**(9), 1869-1878.

[6] Gesoglu, M., Ozturan, T. and Guneyisi, E. (2006) Effects of Cold-Bonded Fly Ash Aggregate Properties on the Shrinkage Cracking of Lightweight Concretes.*Cement & Concrete Composites*,**28**(7), 598-605.

[7] Gesoglu, M., Ozturan, T. and Guneyisi, E. (2004) Shrinkage Cracking of Lightweight Concrete Made with Cold-Bonded Fly Ash Aggregates.*Cement and Concrete Research*, **34**(7), 1121-1130.

[8] Kockal, N.U. (2008) Effects of Lightweight Fly Ash Aggregate Properties on the Performance of Lightweight Concretes,*Ph.D. Thesis, Boğaziçi University*, Istanbul, Turkey.

[9] Kockal, N.U. and Ozturan, T. (2011) Characteristics of Lightweight Fly Ash Aggregates Produced with Different Binders and Heat Treatments.*Cement & Concrete Composites*, **33**(1), 61-67.

[10] Kockal, N.U. and Ozturan, T. (2011) Durability of Lightweight Concretes with Lightweight Fly Ash Aggregates.*Construction and Building Materials*, **25**(3), 1430-1438.

[11] Kockal, N.U. and Özturan, T. (2010) Effects of Lightweight Fly Ash Aggregate Properties on the Behavior of Lightweight Concretes.*Journal of Hazardous Materials*, **179**(1-3), 954-965.

[12] Kockal, N.U. and Özturan, T. (2011) Strength and Elastic Properties of Structural Lightweight Concretes.*Materials and Design*, **32**(4), 2396-2403.

[13]Mor, A. (1992) Steel-Concrete Bond in High-Strength Lightweight Concrete.*ACI Materials Journal*, **89**(1), 76-82.