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Effects of expanded perlite aggregate and mineral admixtures on the compressive strength of low-density concretes

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Abstract

This article investigates the compressive strength of concretes made up of mixtures of expanded perlite (EPA) and pumice aggregates (PA). To determine the effects of silica fume (SF) and class C fly ash (FA) on the compressive strength of these lightweight aggregate concrete (LWAC), SF and FA were added as replacement for cement by decreasing the cement weights in the ratios of 10%, 20%, and 30% by weight. The binder dosage was kept constant at 200 kg/m^3 throughout this study. Superplasticizer was used 1.5% by weight of Portland cement (PC) to reduce w/c ratios. The obtained results showed that: Unit weights of all groups decreased from 1154 to 735 kg/m^3 with the increase of EPA in the mixtures. Both SF and FA decreased unit weight of samples. The compressive strengths increased by 52%, 85%, 55% for 7-day samples, and 80%, 84%, 108% for 28-day samples due to 20%, 40%, and 60% of EPA (used in place of PA) added into the mixtures, respectively. In general, FA decreased 7- and 28-day compressive strength of all groups for all percentage of FA replacement for PC. SF decreased 7-day compressive strength with increasing expanded perlite ratio in the mixtures. With the increasing curing period, the reductions in compressive strength due to SF and FA decreased drastically. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Silica fume; Fly ash; Lightweight concrete; Compressive strength

1. Introduction

There are a number of methods to produce lightweight concrete (LWC). In one method, the fine portion of the total concrete aggregate is omitted, which is called ‘no-fines’. Another way of producing LWC is to introduce stable air bubbles inside concrete by using chemical admixtures and mechanical foaming. This type of concrete is known as aerated, cellular or gas concrete. The most popular way of LWC production is by using lightweight aggregate. Such aggregates, natural or artificial, are available in many parts of the world and can be used in producing concrete in a wide range of unit weights and suitable strength values for different fields of applications [1].

LWC masonry units (LWC blocks) are defined as the ones having a minimum compressive strength of 3.5 MPa without exceeding an air-dry unit weight of 1680 kg/m^3. The main uses of LWC masonry units are internal and external walls, inner leaves of external cavity walls, in the fill panels, and isolation of roof decks and floors [2].

In view of the global sustainable development, it is imperative that supplementary cementing materials be used in replace of cement in the concrete industry. The most worldwide available supplementary cementing materials are silica fume (SF), a by-product of silicon metal, and fly ash (FA), a by-product of thermal power stations. It is estimated that approximately 600 million tons of FA are available worldwide now, but at present, the current worldwide utilization rate of FA in concrete is about 10% [3]. Due to the rapid economic development and the growth in the world population consumption of energy over the world, the FA has significantly increased. Thus, air and environment pollution has became a problem, thus, the idea of using waste material has gained popularity. FA and SF are two of the most common concrete ingredients due to their pozzolanic properties [3,4].

The concrete strength and other properties heavily depend on its microstructure. The microstructure of concrete depends upon a number of parameters such as type, amount, and structure of constituent materials, etc. [5–7]. Constituent materials for concrete include fine as well as coarse

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aggregates (traditional or lightweight aggregates), and hydrated cement paste as a binder resulting from hydration or pozzolanic reaction of cementitious materials with water. The structure of concrete is greatly influenced by the rate of hydration or reaction, type of hydration or reaction products formed, and their distribution in the hydrated cement paste. It is well established that the rate of hydration and reaction and the resulting hydration or reaction products can be substantially modified by use of chemical and mineral admixtures [5,6].

LWCs, made up of lightweight aggregates, have superior properties such as lightness, thermal isolation, freeze–thaw resistance, and fire protection but have the disadvantage of having low mechanical properties. There are a number of studies related to the effects of SF and FA on the properties of the traditional concretes and concretes made with mixes of traditional and lightweight aggregates [8,9]. However, there was not enough information about the properties of mixes of different lightweight aggregates and the effects of SF and FA on the compressive strength of these concretes in the technical literature. Most lightweight aggregates used today such as expanded clay, the expanded perlite aggregate (EPA), and FA have been manufactured at a fringe temperature of approximately 1200 °C or above [10–12]. Such a high fringe temperature may have an influence on the pozzolanic reactivity of the aggregate. Therefore, an experimental investigation related to the pozzolanic reactivity of EPA and effects of SF and FA on lightweight aggregate concrete (LWAC) made up of mixtures of pumice aggregate (PA) and EPA was carried out and the results reported.

2. Materials and methods

ASTM Type III, Portland cement (PC), from Bolu in Turkey was used in this study. SF, FA, PA, and EPA were obtained from Antalya Electro Metallurgy Enterprise, Afşin Thermal Power Plant, Kocapınar region in Van-Erciş, and Etibank Perlite Expansion Enterprise in İzmir in Turkey, respectively. The chemical composition and physical properties of the materials used in this study are summarized in Tables 1 and 2. Sulphonate naphthalene formaldehyde was used as a superplastisizer, compatible with ASTM C 494 F (high-range water reducer) at a dosage of 1.5 ml/kg of cement. The ASTM D 75, ASTM C 136, and ASTM C 29 were used for sampling, grading, unit weight, and fineness modulus of aggregates, respectively. The full details of these properties are given elsewhere [13].

Table 1
Chemical components of PC, SF, FA, and EPA (%)

Component	PC (%)	SF (%)	FA (%)	EPA (%)
SiO_2	19.80	85–95	30.6	71–75
Fe_2O_3	3.42	0.5–1.0	5.5	–
Al_2O_3	5.61	1.0–3.0	14.8	12–16
CaO	62.97	0.8–1.2	36.8	0.2–0.5
MgO	1.81	1.0–2.0	2.5	–
SO_3	2.36	–	4.9	–
C	–	0.5–1.0	–	–
K_2O	–	–	–	–
Na_2O	–	–	–	2.9–4
TiO_2	–	–	–	–
Sulphide (S^{-2})	0.17	0.1–0.3	–	–
Chlor (Cl^-)	0.04	–	–	–
(S)+(F)+(A)	–	–	50.9	–
Undetermined	0.30	–	–	–
Free CaO	0.71	–	11.5	–
LOI	0.36	0.5–1.0	2.4	–

Table 2
Physical and mechanical properties of PC

Specific gravity (g/cm^3)	3.15
Specific surface (cm^2/g)	3410
Remainder on 200-μm sieve (%)	0.1
Remainder on 90-μm sieve (%)	3.1
Setting time start (h)	2:10
Setting time end (h)	2:40
Volume expansion (Le Chatelier, mm)	3
Compressive strength (kg/cm^2)	
2 days	237
7 days	399
28 days	464

The binder (PC, or PC + SF, or FA) content was 200 kg/m^3 of concrete. Four main groups of mixes of PA and EPA were produced. They were specified as A (100% PA), B (80% PA + 20% EPA), C (60% PA + 40% EPA), D (40% PA + 60% EPA). For each group SF–PC, FA–PC mixtures were prepared adding 0%, 10%, 20%, and 30% SF or FA in replacement of PC separately. Hence, 28 different mixes were obtained and cast. The full details of these mixes are given in Table 3.

The concrete mixes were prepared in a laboratory countercurrent mixer for a total of 5 min. Hand compaction was used. Precautions were taken to ensure from homogeneity and full compaction. Slump was kept constant at 20 ± 5 mm. For each mix, three specimens 100 × 200 mm cylinders were prepared and cured in lime-saturated water at 20 ± 3 °C until the 6th and 27th days, and then, tested for compressive strength in accordance with ASTM C 192.

3. Results and discussion

The results obtained in the tests are shown in Table 4. They are also presented to some extent in graphical form in the figures, and evaluated and discussed below.

3.1. Workability

SF concrete was more cohesive than PC concrete. Due to the increase in cohesion and in the number of solid-to-solid contact points, SF rendered the mixtures more resistant to segregation and increased approximately 5–7 dm^3 of water demand of LWAC for each 10% SF replacement of PC to

Table 3
Mix proportions of all groups

LWAC groups	A: 100% PA							B: 80% PA + 20% EPA						
	Cont.	SF (%)			FA (%)			Cont.	SF (kg/m^3)			FA (%)		
	0	10	20	30	10	20	30	0	10	20	30	10	20	30
PA (kg/m^3)	839.5	833.9	826.7	822.1	842.9	847	849	651.4	646.5	640.1	635.5	651.8	653.8	657.1
EPA (kg/m^3)	–	–	–	–	–	–	–	38.11	37.79	37.42	37.16	38.10	38.22	38.42
Cement (kg/m^3)	201.3	180.5	162.2	141	180	160.5	141	200.8	179.5	160.7	140	181.5	160	140
SF (kg/m^3)	–	20	40.4	60.1	–	–	–	–	20.4	40	60	–	–	–
FA (kg/m^3)	–	–	–	–	20	40	60.2	–	–	–	–	19.6	40	60
Water (kg/m^3)	201.8	206	214	220.05	200	197	195.5	223.5	229.14	235.8	240.5	223.5	221.5	218
Superplasticizer (kg/m^3)	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057

LWAC groups	C: 60% PA + 40% EPA							D: 40% PA + 60 EPA						
	Cont.	SF (%)			FA (%)			Cont.	SF (%)			FA (%)		
	0	10	20	30	10	20	30	0	10	20	30	10	20	30
PA (kg/m^3)	474.7	468.9	466.2	463.7	474.7	475.2	477	311.9	301.5	298	294.6	308.8	309.1	311.1
EPA (kg/m^3)	74.07	73.10	72.69	71.98	74.03	74.09	74.4	108.3	105.76	104.6	103.7	108.3	108.4	109.1
Cement (kg/m^3)	199.8	181	160	119.5	179.5	160.5	120.8	203	180	160.6	119.5	181	160.9	120
SF (kg/m^3)	–	20.2	40	60.7	–	–	–	–	20	40.1	60	–	–	–
FA (kg/m^3)	–	–	–	–	20	41	60	–	–	–	–	20.5	40	20
Water (kg/m^3)	243.8	249.5	255	262.5	243.8	242	240	267.4	274.5	281.7	286.4	267.4	265	261
Superplasticizer (kg/m^3)	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057	3.057

0 is showing the control samples without SF and FA.

maintain a constant slump for 1 m^3 concrete. It is suggested that an additional 1 l/m^3 of water should be used for every 1 kg/m^3 of SF addition to maintain a constant fluidity, in the absence of a superplasticizer [14,15].

FA increased workability of mixture according to the mixture produced without FA. Furthermore, FA decreased approximately 3 dm^3 of the water demand of LWAC for each 10% FA replacement of PC to maintain a constant

Table 4
Unit weights and compressive strengths of all groups

LWAC groups	A: 100% PA							B: 80% PA + 20% EPA						
	Cont.	SF (%)			FA (%)			Cont.	SF (%)			FA (%)		
	0	10	20	30	10	20	30	0	10	20	30	10	20	30
7-day compressive strength (MPa)	4.35	5.21	5.54	3.10	3.65	3.86	3.02	6.62	6.4	5.89	5.12	5.8	5.05	49.5
Reduction (−) or increment (+) (%)	0	+ 20	+ 27	− 29	− 16	− 11	− 31	0	− 3	− 11	− 23	− 10	− 24	− 25
28-day compressive strength (MPa)	6.07	8.95	10.25	6.84	6.10	4.95	3.9	10.95	11.05	11.37	10.68	9.98	9.79	91.6
Reduction (−) or increment (+) (%)	0	+ 29	+ 69	+ 13	+ 0.4	− 19	− 36	0	+ 0.08	+ 4	− 2	− 9	− 11	− 16
Dry unit weight (kg/m^3)	1154	1139	1126	1114	1153	1130	1125	928	911	904	896	926	920	910

LWAC groups	C: 60% PA + 40% EPA							D: 40% PA + 60% EPA						
	Cont.	SF (%)			FA (%)			Cont.	SF (%)			FA (%)		
	0	10	20	30	10	20	30	0	10	20	30	10	20	30
7-day compressive strength (MPa)	8.04	7.16	5.44	3.37	7.16	6.04	5.05	6.74	5.58	2.91	2.51	6.10	4.28	41.3
Reduction (−) or increment (+) (%)	0	− 11	− 26	− 58	− 11	− 25	− 37	0	− 17	− 57	− 63	− 9	− 36	− 39
28-day compressive strength (MPa)	11.16	11.68	11.53	10.58	10.52	10.43	10.16	12.63	12.84	10.00	8.95	9.68	9.05	80.0
Reduction (−) or increment (+) (%)	0	+ 5	+ 3	− 5	− 6	− 7	− 9	0	− 2	− 21	− 37	− 23	− 28	− 37
Dry unit weight (kg/m^3)	858.8	854.5	850	845	855.4	853	853	755	743	738	735	753	750	748

0 shows the control samples without SF and FA.

slump for 1 m^3 concrete. The spherical shape of FA particles and their extreme fineness have beneficial effects on the workability. The shape reduces the friction at the aggregate–paste interface producing a ball-bearing effect at the point of contact and allowing the concrete to move more freely [16].

3.2. Dry unit weight

According to the obtained data, it was observed that unit weights of 28-day hardened LWAC decreased with increasing EPA in the mixtures, because the specific gravity of EPA is lower than that of PA. SF and FA used in replacement of PC also lowered the unit weight of samples a little. The highest unit weight was 1154 kg/m^3 at 100% PA + 100% PC samples. The values of unit weights decreased with increasing EPA ratio in the mixes. The lowest value was 735 kg/m^3 at 100% EPA and 70% PC + 30% SF. The other samples' unit weights changed between 1154 and 735 kg/m^3. Results are presented in Table 4.

3.3. Effects of EPA on the compressive strength

The results of the 7- and 28-day compressive strengths were given in Table 4. Using EPA replacement of PA 20%, 40%, 60% allows us to increase the 7-day compressive strength by up to 52%, 85%, 55% and the 28-day compressive strength to 80%, 84%, 108%, respectively. EPA increased the 28-day compressive strength up to 108% at 60% EPA replacement of PA while it increased the 7-day compressive strength by 85% at 40% EPA replacement of PA. The effect of EPA increased with increasing curing period, as can be seen in Table 4. Maximum strength value was 8.05 MPa at 60% PA + 40% EPA for samples without admixtures at 7-day compressive strengths and 12.6 MPa at 40% PA + 60% EPA at 28-day compressive strengths. This may be due to the filler effect of EPA on the LWAC, and to the lightweight aggregate manufactured at a firing temperature of approximately 1200 °C or above. Such a high temperature may have an influence on the pozzolanic reactivity of the aggregate–cement paste interface [17]. Moreover, it is believed that the interface is characterized by a mechanical interlocking in combination with a chemical interaction in the formation of pozzolanic reaction [12]. There is higher strength in the concretes with higher absorption capacity of aggregate [18] (the water absorption of EPA is more than twice of PA). This also might be caused by some additional delayed hydration made possible by suction of the water from the aggregate towards the hydrating paste [19]. The relationship between perlite ratio and compressive strengths is shown in Fig. 1.

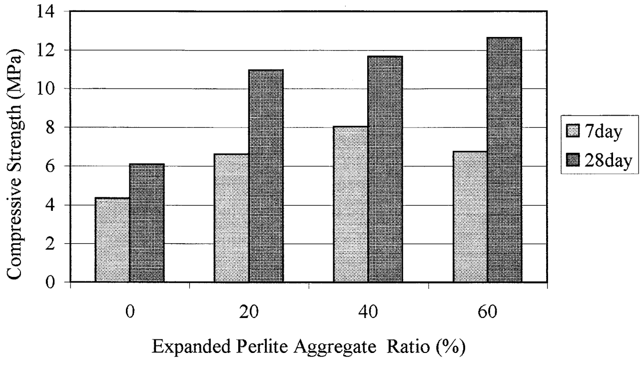

Fig. 1. Relationship between EPA ratio (%) and compressive strength (MPa).

3.4. Effects of SF on the compressive strength

Results of 7-day compressive strength are given in Table 4. 10% and 20% SF allow us to increase the compressive strengths of Group A by up to 20% and 27%, and 30% SF replacement of PC for the 7-day sample decreased the compressive strength by 29%. The 28-day compressive strength of Group A increased with increasing of the SF in the mixtures, the increment due to 10%, 20%, and 30% were 29%, 69%, and 13%, respectively. The increase in the strength is probably due to the high reactivity of SF and its famous micro filler effect [16,20]. When we compared the 7-day compressive strengths of Group A to the 28-day compressive strengths of the same group, we saw that there was a big discrimination in the increment ratio of its compressive strength results. This may be due to the curing time. The effect of SF increased with increasing curing time for Group A.

SF induced 7-day compressive strengths of Group B to reduce at all levels of SF replacement of PC. Reductions were 3%, 11%, and 23% for 10%, 20%, and 30% SF replacement of PC, respectively. The reduction value increased with increasing SF percentage in the mixtures. The 28-day compressive strength of Group B increased a little by increasing SF up to 20% in the mixtures. The increment due to 10% and 20% SF was 0.08% and 4%, respectively. However, the compressive strength decreased by 2% for 30% SF replacement of PC for Group B. When we compared the 7-day compressive strengths of Group B to the 28-day compressive strengths of the same group, we observed a little discrimination.

SF caused 7-day compressive strengths of Group C to reduce at all levels of SF replacement of PC. Reductions were 11%, 26%, and 58% for 10%, 20%, and 30% SF replacement of PC, respectively. When the reduction values of the compressive strength of Group C to Group B were compared, it was noticed that there were great differences, especially at the 30% SF replacement of PC. This may be due to the increase of the ratio of both EPA and SF in the mixture at the same time, and then the decrease of the heat of hydration of the mixtures. Thus, early age strength of the samples decreases dramatically due to low heat of hydration. When one of EPA and SF was used, the compressive strength increased significantly. The 28-day compressive strength of Group C increased a little with increasing SF up to 20% in the mixtures; the increment due to 10% and 20% SF was 5% and 3%, respectively. However, it decreased by 5% for 30% SF replacement of PC for Group C. When we compared the increment or reduction ratio of 7-day compressive strengths of Group C to that of Group C's 28-day compressive strengths, we found that there was a huge discrimination. The effect of SF increases with increasing curing time. If the heat of hydration and the 90-day compressive strength of these mixtures were studied, the result would be very clear.

SF induced a reduction of 7-day compressive strengths of Group D at all levels of SF replacement of PC. Reductions were 17%, 57%, and 63% for 10%, 20%, and 30% SF replacement of PC, respectively. The reduction value increased with increasing SF percentage in the mixtures. The increment due to 10% SF was 2% for Group D at the 28-day compressive strength. However, it decreased by 21% and 37% for 20% and 30% SF replacement of PC for Group D. The maximum reduction was at the 30% SF and it was 63% at the 7-day compressive strength. This group contains the maximum quantity of EPA and the maximum dosage of SF replacement of PC, and then the case may result in the lowest heat of hydration. Zhang and Gjorv [21] reported that the penetration of SF particles into the open pores of the aggregate is deeper inner than that of PC due to the lower viscosity of SF and the smaller particle size of SF. Thus, SF will penetrate into the aggregate and result in the low dosage of the cementations, when compared to the mixture's plain PC. For lightweight aggregate without a dense outer shell, this effect may be more significant, while for a dense outer shell, the effect may be small. Consequently, increase of reductions in compressive strength due to SF is also probably the result of increasing porous microstructure surface layer with increasing EPA in the mixture.

3.5. *Effects of FA on the compressive strength*

The 7-day compressive strength results are given in Table 4. Ten percent, 20%, and 30% FA replacement of PC induced reduction in 7-day compressive strengths of Group A by up to 16%, 11%, and 31%, respectively. The 28-day compressive strength of Group A also decreased with increasing FA in the mixtures, the reduction due to 20% and 30% FA was 19% and 36%, respectively, except for 10% FA which increased by 0.4%. The reduction due to FA at 28-day compressive strength was also high and around the 7-day compressive strength's reduction values for Group A. The compressive strength of SF was more effective than that of FA at both 7 days and 28 days. SF increased the 28-day compressive strength by 13% at 30% SF and by 69% at 20% SF for Group A, while the maximum reduction due to FA was 36% at 30% FA.

FA induced a reduction of 7- and 28-day compressive strengths in Group B at all levels of FA replacement of PC. Reductions of 7-day compressive strength were 10%, 24%, and 25% and for 28-day compressive strength were 9%, 11%, and 16% for 10%, 20%, and 30% FA replacement of PC, respectively. The reduction value increased with increasing FA percentage in the mixtures. The reductions due to FA decreased with increasing curing time (see Table 4). The reduction ratio decreased to 16% at 28 days for the same dosage of FA and Group B, while the maximum reduction was 25% at 7 days.

FA also caused a reduction of 7-day compressive strengths of Group C at all levels of FA replacement of PC. Reductions were 11%, 25%, and 37% for 10%, 20%, and 30% FA replacement of PC, respectively. When we compared the reduction values of Group C to those of Group B, it was seen that the reduction differences of Group C were greater than those of Group B. It was found that the reduction values of the 28-day compressive strength of Group C decreased when compared to the 7-day reduction values and they were 6%, 7%, and 9% for 10%, 20%, and 30% FA at 28 days. There was a huge discrimination when we compared the reductions of 7-day compressive strengths of Group C due to FA to those of SF. Thus, it can be said that FA becomes more effective than SF at 7 days, but SF becomes more effective than FA at 28 days. With increase of curing time, the effect of both SF and FA increases. The effect of FA increased with increasing EPA in the mixtures at 28 days, up to 40% EPA ratio. After 40% EPA ratio, the effect of FA decreased with increasing EPA in the mixtures at 28 days (see Table 4).

Group D's compressive strength also decreased with increasing FA in the mixtures. Reductions in 7-day compressive strengths were 9%, 36%, and 39% and in 28-day compressive strengths were 23%, 28%, and 37% for 10%, 20%, and 30% FA replacement of PC, respectively. The maximum reduction in 7-day compressive strength due to FA was 39% for 30% FA. The reduction values increased with increasing FA percentage in the mixtures. Reductions due to FA were less than those of SF at 7 days, up to 20% dosage of admixture. The reduction due to SF was less than that of FA at 28 days, but the reduction due to both was the same at 30% dosage of admixture. LWAC containing FA showed a steady reduction in 7-day strength as a function of replacement percentage, which can be directly related to the properties of FA that decreases the heat of hydration of concrete and needs a long curing period. Results of numerous studies have indicated that FA slows the rate of hardening and reduces the early compressive strength of concrete [16]. In this study, the reduction of 28-day compressive strength due to FA replacement of PC was very low. Results are provided in Table 4.

4. Conclusions

The results indicate the following:

(1) While FA increased the workability of mixtures, SF decreased.

(2) SF and FA decreased unit weight of samples. Unit weights also decreased with increasing EPA in the mixtures. The unit weights changed between 735 and 1154 kg/m^3.

(3) Using EPA replacement of PA at 20%, 40%, 60% allowed us to increase 7-day compressive strengths up to 52%, 85%, 55%, and 28-day compressive strengths up to 80%, 84%, 108%, respectively. EPA increased the 28-day compressive strength up to 108% at 60% EPA replacement of PA, while it increased the 7-day compressive strength up to 85% at 40% EPA replacement. The effect of EPA increased with increasing curing period.

(4) SF decreased the 7-day compressive strength of all groups except Group A, and up to 20% SF replacement of PC. With increasing EPA in the mixtures, the reduction value increased dramatically, and at the maximum EPA ratio, the reduction value was 63% at 7 days. SF increased 28-day compressive strengths of all groups for 10% SF a little, except in Group A. SF is more effective in Group A and increased the 28-day compressive strength at all levels of SF, especially at 20% SF. The maximum increment was 69% for Group A. With increasing EPA, the effect of SF decreased, and with increasing curing time, the effect of SF increased.

(5) FA induced a reduction of 7- and 28-day compressive strengths of all groups at all levels of FA replacement of PC except in Group A and 10% FA replacement of PC.

(6) Reductions due to FA at 7 days were less than those of SF for mixtures with EPA. Reductions due to FA also decreased with increasing EPA and curing time.

References

[1] A.M. Neville, Properties of Concrete, ELBS edition of third ed., Longman, Singapore, 1988.

[2] İ.B. Topçu, Semi-lightweight concretes produced by volcanic slags, Cem. Concr. Res. 27 (1) (1997) 15–21.

[3] A. Bilodeau, V.M. Malhotra, High-volume fly ash system: Concrete solution for sustainable development, ACI Mater. J. 97 (1) (2000) 41–49.

[4] A. Yeğinobalı, K.G. Sobolev, S.V. Soboleva, B. Kıyıcı, Thermal resistance of blast furnace slag high strength concrete cement, 1st International Symposium on Mineral Admixtures in Cement, Istanbul, Turkey, 1997, pp. 106–117.

[5] T.R. Naik, S. Singh, B. Ramme, Mechanical properties and durability of concrete made with blended fly ash, ACI Mater. J. 95 (4) (1998).

[6] M. Gillot, T.R. Naik, S.S. Singh, Microstructure of fly ash containing concrete, with emphasis on the aggregate–paste boundary, Proceedings, 51st Annual Meeting of the Microscopy Society of America, 1993, pp. 1148–1149.

[7] E.J. Garboczi, D.P. Bentz, Digital simulation of the aggregate–cement paste interfacial zone in concrete, J. Mater. Res. (1993) 196–201 (August).

[8] R. Demirboğa, R. Şahin, F. Bingöl, R. Gül, The usability of blast furnace slag in the production of high strength concrete, 5th International Symposium on Utilization of High Strength/High Performance Concrete, vol. 2, Sandefjord, Norway, 1999, pp. 1083–1091.

[9] M.A. Taşdemir, C. Taşdemir, E. Özbek, B. Altay, Fineness effect of GGBS on the properties and microstructure of concrete, 1st International Symposium on Mineral Admixtures in Cement, (1997) 198–215.

[10] FIB Manual of Lightweight Aggregate Concrete, second ed., Surrey Univ. Press, Glasgow, 1983.

[11] R.N. Swamy, G.H. Lambert, The microstructure of lytag aggregate, J. Cem. Compos. Lightweight Concr. 3 (4) (1981) 273–281.

[12] M.H. Zhang, O.E. Gjørv, Pozzolanic reactivity of lightweight concrete aggregates, Cem. Concr. Res. 20 (1990) 884–890.

[13] R. Demirboğa, Effects of silica fume and fly ash on the lightweight concrete made up of pumice and expanded perlite aggregates mixes (Silis Dumanı ve Uçucu Külün Perlit ve Pomza ile Üretilen Hafif Beton Özelikleri Üzerindeki Etkilerinin İncelenmesi). Atatürk Üni., Institute of Science and Technology, PhD Thesis, Erzurum, Turkey, 1999.

[14] P. Jahren, Use of silica fume in concrete, Am. Concr. Inst., SP-79 2 (1983) 625–642.

[15] K.H. Khayat, P.C. Aitcin, Silica fume in concrete—an overview, Proceedings, 1992 fourth Canment/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, vol. 2, Istanbul, Turkey, 1992, pp. 835–872.

[16] T.Y. Erdoğan, Admixtures for Concrete, Middle East Technical Univ. Press, Ankara, 1997.

[17] R. Wasserman, A. Bentur, Effect of lightweight fly ash aggregate microstructure on the strength of concrete, Cem. Concr. Res. 27 (4) (1997) 525–537.

[18] R. Wasserman, A. Bentur, Interfacial interactions in lightweight aggregate concretes and their influence on the concrete strength, Cem. Concr. Compos. 18 (1996) 67–76.

[19] A.M. Vaysburd, Durability of lightweight concrete bridges in sever environments, Concr. Int. 18 (7) (1996) 33–38.

[20] V.M. Malhotra, G.G. Carette, V. Sivasundaram, Role of silica fume in concrete: A review, Advances in Concrete Technology, CANMET-Energy, Mines and Resources, Ottowa, Canada, 1992, pp. 925–991.

[21] M.H. Zhang, O.E. Gjorv, Penetration of cement paste into lightweight aggregate, Cem. Concr. Res. 22 (1992) 47–55.