Thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures

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Abstract

This paper studies the influence of two admixtures on expanded perlite aggregate concrete. Both silica fume and fly ash 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 to reduce w/c ratios.

The obtained results showed that: the thermal conductivity decreased with the increase of silica fume and fly ash as replacement for portland cement up to 14 and 18%, respectively. Densities of all samples decreased from 522 to $483 \, kg/m^3$ with the increase of both admixtures. Silica fume and fly ash decreased the density of samples. The compressive strengths decreased 12, 19, 29 for 7 days, and increased 9, 13%, 4%, for 28 days due to 10, 20 and 30% silica fume, respectively. Fly ash induced to reductions in the compressive strength up to 36% at 7 days and 27% at 28 days.
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1. Introduction

Thermal behavior of concrete is relevant to any use of concrete, especially in relation to structures where it is desirable to have low thermal conductivity, dimensional stability, high specific heat, and little or no decrease of stiffness upon heating. Although much work has been done on the effect of admixture and the mechanical properties of concrete, relatively little work has been done on the thermal conductivity [1–4].

Thermal conductivity of concrete increases with increasing moisture content. Since water has a conductivity about 25 times that of air, it is clear that when the air in the pores has been partially displaced by water or moisture, the concrete must have greater conductivity [5–9]. Steiger and Hurd [10] reported that when unit weight of concrete increased 1% due to the water absorbsion, the thermal conductivity of these specimens increases 5%. Bouguerra et al. [11], reported that the thermal conductivity of lightweight concrete chages considerably with porosity.

Thermal conductivity of concrete increases with increasing cement content [2,12], and thermal conductivity of aggregate [7,8]. SF causes a decrease in the thermal conductivity and an increase in the specific heat of cement paste [1]. SF also causes an increase in the electrical resistivity [4]. However, the effect of SF and FA on the thermal conductivity of expanded perlite aggregate concrete (EPAC) has not been previously reported.

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, a by-product of silicon metal, and fly ash, a by-product of thermal power stations. It is estimated that approximately 600 million tons of fly ash is available worldwide now, but at present, the current worldwide utilization rate of fly ash in concrete is about 10% [13]. Due to the rapid economic development and the growth in the world population consumption of the energy over the world, the fly ash has significantly increased. Thus, air and environment pollution became a problem, then, 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 [13,14].

Lightweight concretes, made up of lightweight aggregates, have superior properties such as lightness, thermal isolation, freeze–thaw resistance, and fire protection but have

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disadvantage of low mechanical properties. There are a number of studies related to the effects of silica fume and fly ash on the properties of the traditional concretes and concretes made with mixes of traditional and lightweight aggregates [15,16]. However, there was no enough information about the effects of silica fume and fly ash on the compressive strength, thermal conductivity, unit weight etc., of the these concretes in the technical literature. Therefore, an experimental investigation related to effects of silca fume and fly ash on thermal conductivity of EPAC was caried out by us and the results of which have been reported.

2. Materials and methods

ASTM Type II, Portland cement (PC), from Bolu in Turkey was used in this study. Silica fume (SF), fly ash (FA), and expanded perlite aggregate (EPA) were obtained from Antalya Electro Metallurgy Enterprise, Afşin Thermal Power Plant, and Etibank Perlite Expansion Enterprise in İzmir in Turkey, respectively. The chemical composition and physical properties of the materials used in this study were summarized in Tables 1 and 2. Sulphonate naphthalene formaldehyde was used as a superplastisizer, compatible

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 (MPa)	
2 days	23.7
7 days	39.9
28 days	46.4

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 C 29 were used for sampling, grading, unit weight and fineness modulus of aggregates, respectively. The binder (PC, or PC + SF or FA) content was 200 kg per cubic meter of concrete. SF-PC, FA-PC mixtures were prepared adding 0, 10, 20, and 30% SF or FA in replacement of PC separately. Hence, seven 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 counter-current mixer for a total of 5 min. Precuations were taken to ensure from homogeneity and full compaction. For each mix, nine specimens 100 × 200 mm cylinders were prepared and cured in lime saturated water at 20 ± 3 °C until 6th, 14th and 27th day. For each mix three specimens 100 × 200 mm cylinders were tested at 7- and 28 days and then tested for compressive strength in accordance with ASTM C 39.

A quick thermal conductivity meter (QTM 500) based on ASTM C 1113-90 hot wire method was used to measure the aforemantioned as fallows: A constant electrical current is applied to a pure platinum wire placed between two bricks. The rate at which the wire heats is dependent upon how rapidly heat flows from the wire into the constant temperature mass of the refractory brick. The rate of temperature increase of the platinum wire is accurately determined by measuring its increase in resistance in the same way a platinum resistance thermometer is used. A fourier equation is used to calculate the k-value based on the rate of temperature increase of the hot wire and the power input [17]. QTM 500 device is a production of Kyoto Electronics Manufacturing Co., Ltd., Japan. Measurement range is 0.0116–6 W/mK. Measurement precision is ±5% of reading value per reference plate. Reproducibility is ±3% of reading value per reference plate. Measurement temperature is −100 to 1000 °C (external bath or electric furnace for temperature other than room). Sample size required is two pieces of 100 W × 80 L × 40 mm thick or more. Measuring time is standart 100–120 s.

This method has wide applications [18–20] in determining thermal conductivity of refractory materials where, instead of measuring heat flow, the temperature variation with time at certain locations is measured. Being transient in nature, this method takes only a few minutes in contrast to the earlier methods involving steady-state conditions.

3. Results and discussion

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

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

Table 3
Mix proportions of all groups

Mixtures	Content	Silica fume (%)			Fly ash (%)		
	0[a]	10	20	30	10	20	30
Expanded perlite aggregate (kg/m^3)	164.22	162.88	161.34	159.52	164.22	164.92	165.76
Cement (kg/m^3)	200	180	160	119.5	180	160	120
Silica fume (kg/m^3)	–	20	40	60	–	–	–
Fly ash (kg/m^3)	–	–	–	–	20	40	20
Water (kg/m^3)	317.33	322.5	328	334.5	317	315	312
Super plasticizer (kg/m^3)	3.057	3.057	3.057	3.057	3.057	3.057	3.057

[a] Note: 0 denotes the control samples without SF and FA.

Table 4
Thermal conductivity and density

EPAC groups	Content	Silica fume (%)			Fly ash (%)		
	0[a]	10	20	30	10	20	30
Thermal conductivity (W/mK) (± 0.05)	0.1797	0.1720	0.1552	0.1558	0.1676	0.1643	0.1472
Reduction ($-$) or increment ($+$) (%)	0	-4	-14	-13	-7	-9	-18
Density (kg/m3) (± 0.02)	522	509	493	485	511	498	483

[a] Note: 0 denotes the control samples without SF and FA.

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 maintain 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 superplasticizer [21,22].

FA increased workability of mixture according to the mixture produced without FA. Furthermore, FA decreased approximately 3 dm^3 the water demand of EPAC for each 10% FA replacement of PC to maintain constant slump for 1 m^3 concrete. The spherical shape of fly ash 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 [23].

3.2. Effects of SF and FA on the thermal conductivity

SF and FA reduced the thermal conductivity of group samples. The reductions in thermal conductivity induced by 10, 20 and 30% SF are 4, 14 and 13% compared to the corresponding control specimens, respectively. The reductions due to FA (10, 20 and 30% replacement of PC) are 7, 9 and 18%, respectively. This is because the density decreased with increasing SF and FA content (Table 3). The low density of LWAC by means of SF and FA is probably related to the higher air content [1], and partly to the amorphous structure of SF and FA, as indicated in [3,24]. As mentioned by Fu and Chung [1], the EPAC with SF is related to the high air void content. The effect of FA on the thermal conductivity is greater than that of SF at the 10 and 30% replacements. The differences between the FA replacements are very lit-

tle for 10 and 20% replacement, while it was doubled at the 30% FA replacement. Additionally, Gül et al. [2], Akman et al. and Blanco et al. [25,26] also reported that the thermal conductivity decreased due to the density decreasing of concrete. Lu-Shu et al. [27] experimentally formulated a correlation between the density and thermal conductivity, and reported that the thermal conductivity increased with increasing density (see Table 4).

Fu and Chung [4] reported that latex (20–30% by weight of cement), methyicellulose (0.4–0.8% by weight of cement), and silica fume (15% by weight of cement) decreased the thermal conductivity of cement paste up to 46%. However, as can be seen, they only used plain cement (that is, without aggregate). Thus, we can say that in our study the silica fume (SF) (30% by weight of cement) and fly ash decreased thermal conductivity up to 14 and 18% respectively, while in their study the silica fume (15% by weight of cement) decreased the thermal conductivity of cement paste up to 46% [1]. Demirboga and Gül [28] reported that 30% SF and 30% FA replacemen of PC, separately, redcud the thermal conductivity of lightweight aggregate concrete up to 18.3 and 18.6 percent, respectively. Demirboga [29,30] also reported that FA reduced thermal conductivity of cement paste and mortars for different replacement percent of PC.

In conclusion, the thermal conductivity decreased with increasing SF and FA content. The variation in the reductions may be due to the testing condition and moisture contents. Both SF and FA caused significant reductions in the thermal conductivities. The reduction due to the FA is greater than that of the SF. The reduction in thermal conductivity is primarily due to the low density of EPAC with SF and FA content (see Table 4), and may be partly due to the amorphous silica content of SF and FA [3,24].

Table 5
Seven and 28-days compressive strength

EPAC groups	Content	Silica fume (%)			Fly ash (%)		
	0[a]	10	20	30	10	20	30
7-Days compressive strength (MPa)	2.76	2.44	2.24	1.96	2.07	1.95	1.77
Reduction (−) or increment (+) (%)	0	−12	−19	−29	−25	−29	−36
28-Day compressive strength (MPa)	4.34	4.74	4.9	4.5	4.42	3.67	3.16
Reduction (−) or increment (+) (%)	0	+9	+13	+4	+2	−15	−27

[a] Note: 0 denotes the control samples without SF and FA.

3.3. Effects of SF and FA on the compressive strength

The compressive strengths decreased 12, 19, and 29% for 7 days, and increased 9, 13, and 4%, for 28 days due to 10, 20 and 30% silica fume, respectively. The increase in the strength is probably due to the high reactivity of silica fume and its famous micro filler effect [31,32]. When we compared the 7-day's compressive strengths of group A to 28 day's 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 of curing time.

FA decreased compressive strength of samples at all replacement percent and both 7- and 28-days compressive strength except 7-day compressive strength of 10% FA replacement. Thirty percent fly ash replacement for PC induced to reductions in the compressive strength up to 36% at 7 days and 27% at 28 days. Reductions due to SF and FA decreased with increasing curing time. EPAC containing FA showed a steady reduction in strength for 7 days 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 long curing period. Results of numerous studies have indicated that FA slows the rate of hardening and reduces the early compressive strength of concrete and mortar [26,28–30]. In this study, the reduction of compressive strength, due to fly ash replacement of PC, of 28 days was lower than that of 7 days. The effect of SF increases with the increasing of curing time. If the heat of hydration and 90 days compressive strength of these mixtures were studied, the result would be very clear. Results are provided in Table 5.

4. Conclusions

The results indicate that:

1. while FA increased the workability of mixtures, SF decreased.
2. Densities decreased from 522 to 483 kg/m^3 with the increase of admixtures. Both silica fume and fly ash decreased the density of samples;

3. the compressive strengths decreased 12, 19, 29 for 7 days, and increased 9, 13, 4, for 28 days due to 10, 20 and 30% silica fume, respectively. Fly ash induced to reductions in the compressive strength up to 36% at 7 days and 27% at 28 days. SF was more effective than FA in the increasing of 28-day's compressive strength. Both had a negative effect on the 7-day's compressive strength;
4. the thermal conductivity decreased with the increasing of silica fume and fly ash as replacement for portland cement up to 14 and 18% respectively. FA was more effective than SF in the decreasing of The thermal conductivity of EPAC.

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