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The effects of expanded perlite aggregate, silica fume and fly ash on the thermal conductivity of lightweight concrete

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Abstract

Thermal conductivity coefficients of concretes made up of mixtures of expanded perlite and pumice aggregates (PA) were measured. To determine the effect of silica fume (SF) and class C fly ash (FA) on the thermal conductivity of 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 highest thermal conductivity of 0.3178 W/mK was observed with the samples containing only PA and plain cement. It decreased with the increase of SF and FA as replacement for cement. The lowest value of thermal conductivity, which is 0.1472 W/mK, was obtained with the samples prepared with expanded perlite aggregate (EPA) replacement of PA and 70% cement + 30% FA replacement of cement. Both SF and FA had a decreasing effect on thermal conductivity. EPA (used in place of PA) also induced a decrease of 43.5% in thermal conductivity of concrete.

Keywords: Silica fume; Fly ash; Expanded perlite aggregate; Lightweight aggregate concrete; Thermal conductivity

1. Introduction

Differences in the apparent density and the effective thermal conductivity of concretes arise from differences in their porosity. In other words, voids filled with air contribute nothing to the weight of concrete, while the overall conductivity of a porous concrete is the resultant of the thermal conductivity of the silicate structure and that of the air contained in it. It is for this reason that the thermal conductivity of the concrete is related to the apparent density [1].

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 [2–5].

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 [1,6–9]. Steiger and Hurd [10] reported that, when unit weight of concrete increased 1% due to the water absorption, the thermal conductivity of these specimens increases 5%.

Thermal conductivity of concrete increases with increasing cement content [3,11] 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 [2]. SF also causes an increase in the electrical resistivity [5]. However, the effect of SF and FA on the thermal conductivity of lightweight aggregate concrete (LWAC) has not been previously reported.

Since the thermal conductivity of crystalline silica is about 15 times that of amorphous [4], it is natural for the concretes with amorphous silica to have lower conductivity [12,13]. The amorphous silica in the cement paste, which is the continuous phase in concrete taken as a composite, may also contribute to lower the thermal conductivity.

Admixtures, such as silica fume (SF) and fly ash (FA), are used in concrete for improving the mechanical properties, decreasing the rate of hydration, decreasing the alkali aggregate reactivity and decreasing the permeability of concrete. However, their effects on the thermal conductivity have received little attention [2,13].

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2. Materials and methods

ASTM Type III, Portland cement (PC), from Bolu in Turkey was used in this study. SF, FA, pumice aggregate (PA) and expanded perlite aggregate (EPA) were obtained from Antalya Electro Metallurgy Enterprise, Afsin Thermal Power Plant, Kocapinar region in Van-Ercis and Etibank Perlite Expansion Enterprise in Izmir in Turkey, respectively. The chemical composition and physical properties of the materials used in this study are summarized in Table 1. Sulphonate naphthalene formaldehyde was used as a superplasticizer, 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 C 29 were used for sampling, grading, unit weight and fineness modulus of aggregates, respectively. The full details of these properties are given elsewhere [14].

Table 1
Chemical analysis and physical properties of PC, SF, FA, PA and EPA (%)

Component	PC (%)	SF (%)	FA (%)	PA (%)	EPA (%)
SiO_2	19.80	93.7	30.6	71.35	72.54
Fe_2O_3	3.42	0.35	5.5	1.54	–
Al_2O_3	5.61	0.3	14.8	13.20	12–16
CaO	62.97	0.8	36.8	1.84	0.2–0.5
MgO	1.81	0.85	2.5	0.01	–
SO_3	2.36	0.34	4.9	0.04	–
C	–	0.52	–	–	–
K_2O	0.3	–	–	5.00	–
Na_2O	–	–	–	3.40	2.9–4
TiO_2	0.2	–	–	0.25	–
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	3.05	–
Physical and mechanical properties					
Specific gravity (g/cm^3)	3.15	2.18	2.4	1.12	0.28
Specific surface (cm^2/g)	3410	–	–	–	–
Remainder on 200-μm sieve (%)	0.1	–	–	–	–
Remainder on 90-μm sieve (%)	3.1	–	–	–	–
Setting time initial (min)	130	–	–	–	–
Setting time final (min)	160	–	–	–	–
Volume expansion (Le Chatelier, mm)	3	–	–	–	–
Compressive strength (MPa)					
2 days	23.7	–	–	–	–
7 days	39.9	–	–	–	–
28 days	46.4	–	–	–	–

The binder (PC, or PC + SF or FA) content was 200 kg/m^3 of concrete. Six 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), E (20% PA + 80% EPA) and F (100% EPA). For each group, separately, SF-PC and FA-PC mixtures were prepared adding 0%, 10%, 20% and 30% SF or FA in weight to PC. Hence, 42 different mixes were obtained and cast. The full details of these mixes are given elsewhere [14].

The concrete mixes were prepared in a laboratory counter-current mixer for a total of 5 min. Hand compaction was used. Precautions were taken to ensure homogeneity and full compaction. The maximum size of coarse aggregate was 16 mm. For each mixture, three samples of $110 \times 160 \times 40$ mm^3 prisms were prepared and moist-cured for 7 days, and then removed from the moist room and stored in lime saturated water at 20 ± 3 °C until the time of the testing. The specimens were dried at the age of 28 days in an oven at 110 ± 10 °C and weighed at 24-h intervals until the loss in weight did not exceed 1% in a 24-h (ASTM C 332). The specimens' surfaces were sandpapered before measuring their thermal conductivities.

A Quick Thermal Conductivity Meter (QTM 500) based on ASTM C 1113-90 Hot Wire Method was used [15].

QTM 500 device is a production of Kyoto Electronics Manufacturing, 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 standard 100–120 s.

This method has wide applications [16–18] 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. Test results and their evaluations

The results obtained in the tests are shown in Figs. 1–8. They are evaluated and discussed below.

3.1. Oven dry unit weights

It was observed that unit weights of the 28-day LWAC decreased with increasing EPA in the mixtures due to the lower specific gravity of EPA. SF and FA used as replacement for PC lowered the unit weights a little. The highest unit weight was 1154 kg/m^3 at samples 100% PA + 100% PC. The unit weights decreased with increasing EPA in the mixes. It was seen that the lowest unit weight value was 435 kg/m^3 at 100% EPA and 70% PC + 30% SF. Thus, the unit weights

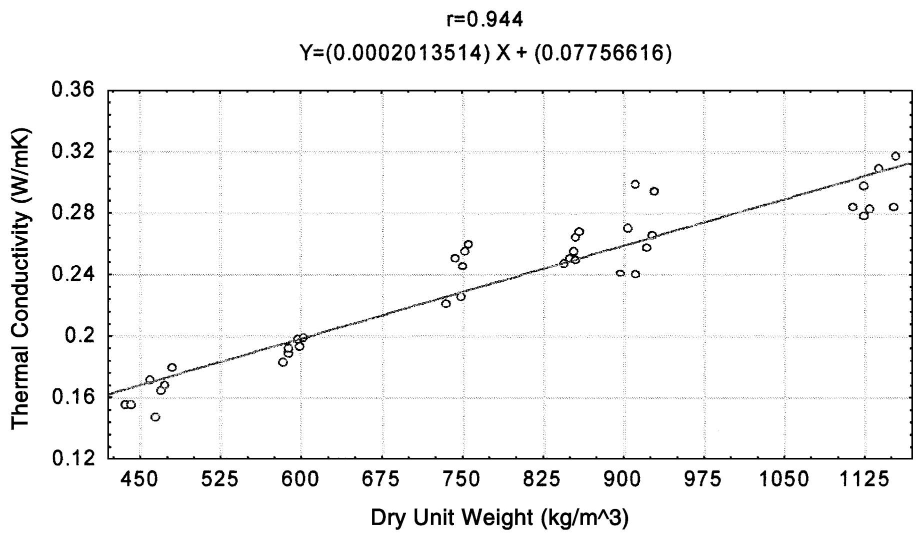

Fig. 1. Relationship between dry unit weights (±0.02) and thermal conductivity (±0.05).

varied between 1154 and 435 kg/m^3. Relationship between dry unit weight and thermal conductivity is shown in Fig. 1.

3.2. Thermal conductivity

Figs. 2–7 show the effects of SF and FA (10%, 20% and 30% replacement of PC) on thermal conductivity of the A, B, C, D, E and F groups of LWAC, respectively. The following results were observed. EPA (replacement of PA) decreased thermal conductivity of LWAC. For 20%, 40%, 60%, 80% and 100% replacement of PA, other ingredients and conditions were constant; the reductions were 7.3%, 15.4%, 17.9%, 37.5% and 43.5% compared to the corresponding control specimens, respectively (Fig. 8).

SF and FA reduced the thermal conductivity of Group A. The reductions in thermal conductivity induced by 10%, 20% and 30% SF for Group A are 2.5%, 6% and 10% compared to the corresponding control specimens, respectively (Fig. 2). The reductions due to FA (10%, 20% and 30% replacement of PC) for the same group are 10%, 11% and 12%, respectively. This is because the density decreased with increasing SF and FA content. The low density of LWAC by means of SF and FA is probably related to the higher air content [2], and partly to the amorphous structure

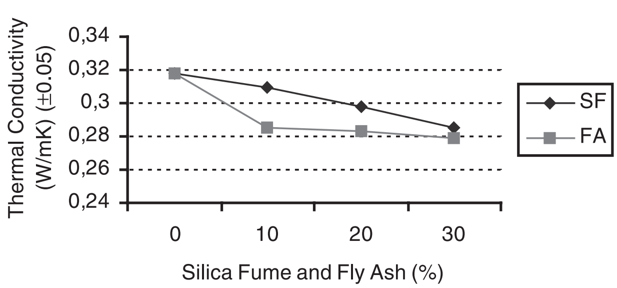

Fig. 2. Relationship between admixtures and thermal conductivity of A.

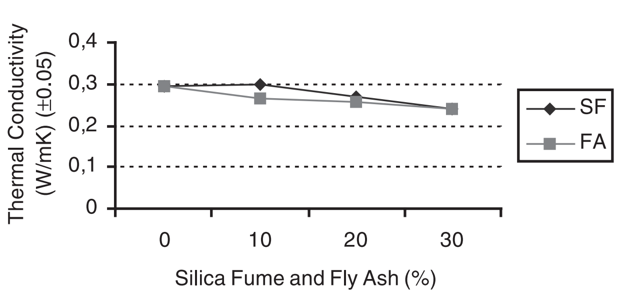

Fig. 3. Relationship between admixtures and thermal conductivity of B.

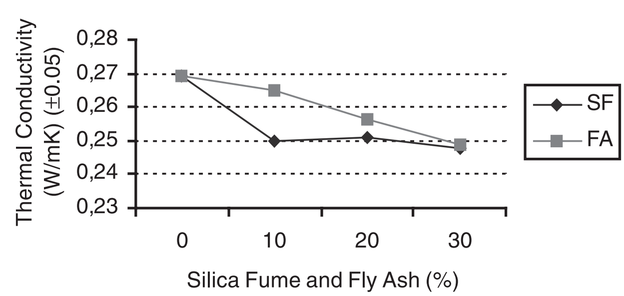

Fig. 4. Relationship between admixtures and thermal conductivity of C.

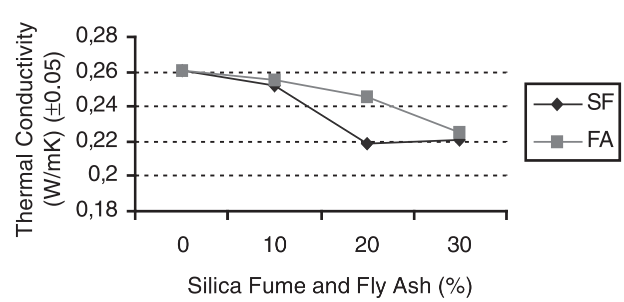

Fig. 5. Relationship between admixtures and thermal conductivity of D.

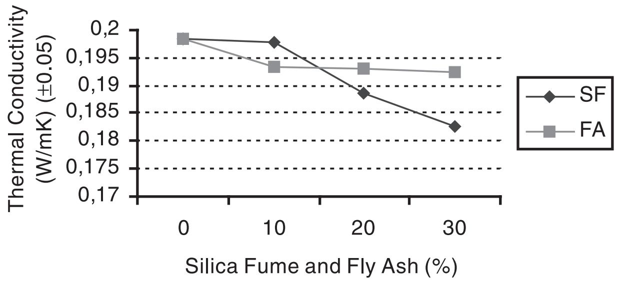

Fig. 6. Relationship between admixtures and thermal conductivity of E.

of SF and FA, as indicated in Refs. [4,19]. As mentioned by Fu and Chung [2], the LWAC with SF is related to the high air void content. The effect of FA on Group A is greater than that of SF for all replacements. The differences between the FA replacements are very little. Additionally, Gül et al. [3], Akman and Tasdemir [20] and Blanco et al. [21] also reported that the thermal conductivity decreased due to the density decreasing of concrete. Lu-shu et al. [22] experimentally formulated a correlation between the density and thermal conductivity, and reported that the thermal conductivity increased with increasing density (see Fig. 2).

For Group B, both SF and FA at the 30% replacement of PC reduced the thermal conductivity by 18.3% and 18.6%, respectively. The reductions due to FA (10%, 20% and 30%) for Group B were 9.5%, 12.2% and 18.6%, respectively. The effect of FA on Group B is greater than that of the SF at the 10% and 20% replacements. Hence, at the 30% replacement of PC, both SF and FA induce approximately equal reduction (Fig. 3).

Fig. 4 shows that, in Group C, the reductions in thermal conductivity for all SF percentages were around 7%, and increased from 1.5% to 7.4% at 30% FA content.

SF and FA caused decreases in the thermal conductivities of all samples of Group D. These reductions were 3.6%, 16% and 15.4% for SF, and 2%, 5.9% and 13.6% for FA, respectively (Fig. 5). Figs. 6 and 7 show the reduction in thermal conductivity values for Groups E and F. The maximum reduction of thermal conductivity was observed at 30% FA for Group F.

In our own study, it was determined that the higher reduction in thermal conductivity in all groups was at 30% SF and FA replacement of PC. When the groups are compared with each other, the effects of SF and FA at 30% replacement of PC on Group B were greater than the effects on the other groups. This is due to the fact that the effect of the 30% SF and FA replacement of PC on thermal conductivity lowers as the EPA ratio after 20% increases in these mixes. While the effect of the SF and FA (30%) without the EPA on thermal conductivity is around 10% and 12%, respectively, the effect of the SF and FA (30%) with the EPA of 20% on thermal conductivity is around 18.3% and 18.5%, respectively. The effect of the SF and FA (30%) with the EPA of 40%, 60% and 80% on thermal conductivity is around 7%, 7.4%, and 15.4%, 13.64%, and 8.7%, 3.2%, respectively.

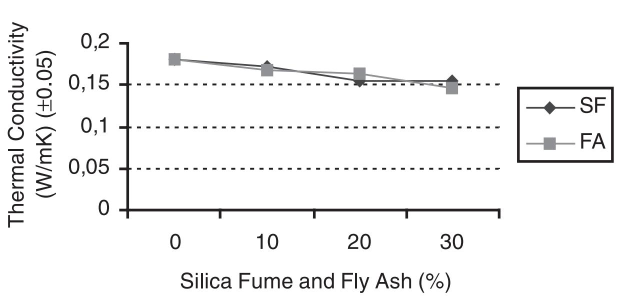

Fig. 7. Relationship between admixtures and thermal conductivity of F.

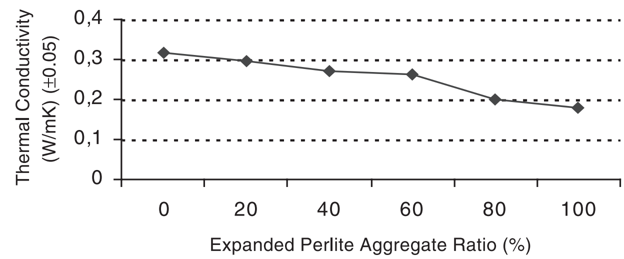

Fig. 8. Relationship between EPA ratio and thermal conductivity.

Chen and Chung [5] reported that latex (20–30% by weight of cement), methylcellulose (0.4–0.8% by weight of cement) and SF (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 SF (30% by weight of cement) plus PA and EPA decreased thermal conductivity up to 18.5%, while, in their study, the SF (15% by weight of cement) decreased the thermal conductivity of cement paste up to 46% [2]. Demirboga [23] reported that SF and FA decreased thermal conductivity of mortar up to 40% and 33% at 30% replacement of PC, respectively.

In conclusion, for all groups, 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 LWAC with SF and FA content, and may be partly due to the amorphous silica content of SF and FA [4,19]. EPA also reduced the thermal conductivity of samples up to 43.5%.

4. Conclusions

SF (10%, 20% and 30% replacement by weight of PC), FA (10%, 20% and 30% replacement by weight of PC) and EPA (20%, 40%, 60%, 80% and 100% replacement of PA) were effective for decreasing the thermal conductivity of LWAC up to 43.5%, mainly due to the relatively low conductivity of these admixtures and EPA and the consequent low density of the LWAC.

The thermal conductivity and dry unit weight of LWAC decreased with increasing SF and FA content. Both SF and FA showed the maximum reduction of thermal conductivity at 30% replacement of PC in all groups, and maximum reduction was observed at Group B.

FA was more effective than SF in decreasing the thermal conductivity. The maximum reduction was due to the FA (at 30% by weight of PC) and it was 18.6%. The EPA replacement of PA (20%, 40%, 60%, 80% and 100%, respectively) reduced the thermal conductivity, density and the dry unit weights of samples. The maximum reduction due to 100% EPA replacement of PA was 43.5%.

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