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USABILITY OF PCF-ASH AS LIGHTWEIGHT AGGREGATE IN FOAM CONCRETE

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Abstract

Foam concretes with low dry density can be produced with aggregate or without aggregate. However, if the aggregate-mineral admixture isn't used in the foam concrete, there may be a lot of problems such as precipitation in fresh condition, high- drying shrinkage in case of hardening, thermal shrinkage and high unit cost. In this study, the possibility of using PCF ash as lightweight aggregate in the production of foam concrete was investigated. Waste-PCF ash is emerging from the pulverized coal furnace about 10 tons/day in a textile factory located in the vicinity of Dinar (Afyonkarahisar). The chemical properties, particle size distribution and grain densities of PCF-ash were determined. Foam concrete with a dry density of 450 kg/m^3 at a cement dosage of 250 kg/m^3 and w/c:0.65 was produced after the aggregate analysis. The PCF-ash which is used in foam concrete mix is between 0 and 200 kg/m^3. 100 mm cube and 300x300x50 mm prism samples were prepared with this foam concrete. The compressive strengths of the cube samples and the thermal conductivity coefficient of the prism samples were tested at the 28th day. The average compressive strength of foam concrete samples with a density of 452 kg/m^3 was determined as 1.07 MPa and the thermal conductivity coefficient was determined as 0.097 W/mK. As a result, it has been determined that PCF- ash as lightweight aggregate can be successfully used in production of precast element and light floor-screed.

Keywords: Foam concrete, lightweight aggregate, PCF ash, compressive strength, thermal conductivity

1. Introduction

Foam concrete is a type of lightweight concrete. It is obtained by mixing the foam formed with the foam agent in the mortar composed of cement, water and aggregate. It contains 50% -80% of the volume of closed pores which aren't interconnected. Foam concrete is an environmentally friendly structure and insulation material which provides light, heat and impact sound insulation that can be used in place of the building elements used in the interior-exterior walls and floors of all buildings. Foam concrete has high flow ability in fresh condition, low density, function-dependent resistance and low thermal conductivity. The dry density of foam concrete is between 400 and 1600 kg/m^3. The compressive strength of foam concrete is between 1 and 15 MPa. Foam concrete can be easily pumped and placed. It does not require compression and vibration. It has excellent resistance to water and frost. Foam concrete mortar can be molded into blocks in enterprises, and if necessary, it can be prepared as mobile in the application area and can be easily carried with the help of a pump. Depending on its density, foam concrete can be used in the production of wall blocks, asmolene, panel, insulation leveling concrete, prefabricated building elements (Brady et al, 2001).

Foam concrete was first patented in 1923. However, it has become widespread in semi-reinforced and non-reinforced concrete construction applications in recent years (Ramamurthy et al. 2009). The first comprehensive review of cellular concrete was made by Valore in 1954. Detailed studies were made related to the composition, properties, usage and structure of foam concrete by Rudnai (1963) and Short and Kinniburgh (1963). In recent years, Jones and McCarthy (2005) investigated the history of foamed concrete, used materials, properties and construction practices in some projects carried out worldwide. These investigations include functional properties such as fire resistance, thermal conductivity and acoustic properties. But, the data of subjects such as the fresh concrete properties of foam concrete, durability and air gap system are limited

The success of foam concrete production depends on many factors such as choice of foam agent, material and admixture, foam preparation methods, mixing method etc. Ramamurthy et al. (2009) classified scientific studies such as foam concrete components, mixture design, production, fresh and hardened concrete properties. Based on this study, the results of these studies including the mix design, density and compressive strength of foamed concrete were presented in Table 1.

Table 1. The compositions, compressive strengths and densities of foam concretes investigated years (Ramamurthy et al. 2009)

Author(s) and Year	**Cement dosage (kg/m^3) or compositions**	**s/c**	**w/c**	**FA/c**	**Density range (kg/m^3)**	**Compressive Strength (MPa, 28d)**
McCormick (1967)	335-446	0.79-2.8	0.35-0.57		800-1800	1.8-17.6
Tam vd. (1987)	390	1.58-1.73	0.6-0.8		1300-1900	1.81-16.72
Regan ve Arasteh (1990)	LWA	0.6	0.45-0.6		800-1200	4-16
Van Deijk (1991)	Cement, sand/FA				280-1200	0.6-10 (91days)
ACI 523.1R-1992	Cement paste				240-640 (DD)	0.48-3.1
	Cement-sand				400-560 (DD)	0.9-1.72
Hunaiti (1997)		3			1667	12.11
Kearsly ve Booyens (1998)	Cement-FA (replacement)				1000-1500	2.8-19.9
Durack ve Weiqing (1998)	270-398	1.23-2.5	0.61-0.82		982-1185 (KY)	1-6
	137-380		0.48-0.7	1.48-2.5	541-1003 (DD)	3-15 (77days)
Aldridge (2000)	Cement-sand				400-1600	0.5-10
Kearsly ve Wainwright (2001)	Cement and FA				1000-1500	2-18
Tikalsky vd. (2004)	Cement, 149-420		0.4-0.45		490-660	0.71-2.07
	Cement, sand/FA 57-149		0.5-0.57		1320-1500	0.23-1.1
Jones ve McCarty (2005)	300	1.83-3.17	0.5		1000-1400	1-2
			1.11-1.56	1.22-2.11	1000-1400	3.9-7.3
Jones ve McCarty (2005)	500	1.5-2.3	0.3		1400-1800	10-26
			0.65-0.83	1.15-1.77	1400-1800	20-43
Nambiar ve Ramamurthy (2006)	Cement-sand mix (coarse)	With filler cement ratio varied from 1to3 and fly ash replacement for sand varied from 0% to 100%			800-1350 (DD)	1-7
	Cement-sand mix (fine)				800-1350 (DD)	2-11
	Cement-sand – Fly ash mix (coarse)				650-1200 (DD)	4-19

s/c : Sand-cement ratio s/c : water-cement ratio FA/c : Fly ash-cement ratio DD : Dry density (kg/m^3)

Many researchers have been carried out on the use of filler, pozzolanic material or lightweight aggregates in foam concrete. A significant proportion of these studies have focused on the use of fly ash in foam concrete. Nambiar and Ramamurthy (2006) investigated the effect of sand and fly ash on hardened foam concrete properties. Researchers have suggested that the reduction in sand particle size leads to an improvement in the strength of foam concrete. In addition, it has been determined that the replacement of sand and fly ash causes higher strength for given density (Kunhanandan and Ramamurthy 2006).

Jitchaiyaphuma et al. (2011) used fly ash in foam concrete mix at ratios 10%, 20%, 30% of cement weight. The w/c ratio in foam concrete with density of 800 kg/m^3 was kept constant. The compressive strengths of foam concrete samples were determined at 3, 7, 14, 28 and 60 days. The researchers concluded that as a result of the study, fly ash replaced by cement increased the compressive strength in the early period (Jitchaiyaphuma et al. 2011). Slabaugh et al. (2007) used foamed synthetic light aggregates (FSLA) as coarse aggregates in foamed concrete. As a result of the research, they obtained 20-25% lower density and more ductile foam concrete. Conversely, it has been stated that there is a reduction of 65-75% in the compressive strength of foam concrete (Slabaugh et al. 2007).

Kearsley and Wainwright (2001) have studied the properties of foamed concrete replaced by cement with both classified and unclassified fly ash (up to 75% by weight). It has been determined that there was little difference in the performance of classified and unclassified fly ashes (Kearsly and Wainwright 2001).

Expanded perlite, micronized pumice, vermiculite etc. lightweight aggregates can be used in foam concrete. However, the high unit costs of such lightweight aggregates limit their application areas and quantities. Materials such as micronized calcite, stone flour, very fine sieved natural sand, fly ash, etc., negatively changed thermal conductivity coefficient of foam concrete. Waste-PCF ash is emerging from the pulverized coal furnace about 10 tons/day in a textile factory located in the vicinity of Dinar (Afyonkarahisar; Fig. 1). This waste is stored in the around Acıgöl as wild and cause environmental pollution. In this study, the possibility of using PCF-ash as lightweight aggregate in the production of foamed concrete was investigated.

Fig 1. The satellite image of textile factory (upper left) and ash storage area (lower right)

2. Materials and Methods

Firstly, the chemical properties, particle size distribution and grain densities of Pulverized Coal Fly Ash (PCF- ash) were determined. Portland cement (CEM I 42.5 R) was used as binder for the production of foam concrete. The characteristics of the cement were given in Table 2.

Table 2. Cement properties

Chemical properties of clinker (%)			**Physical properties of cement**	
SiO_2		20.52	Volumetric expansion (mm)	≤ 1
Al_2O_3		4.00	Fineness (90μ, %)	0.10
Fe_2O_3		3.45	Fineness (200μ, %)	1.10
CaO		64.28	Specific surface area (cm^2/g)	3340
MgO		1.63	Initial setting time (min)	185
SO_3		2.53	Final setting time (min)	240
Na_20+K_2O		1.35	Specific gravity (g/cm^3)	3.12
Mechanical properties of cement (MPa)				
at 7 days	Flexure strength (MPa)	5.8	Compressive strength (MPa)	39.3
at 28 days	Flexure strength (MPa)	7.2	Compressive strength (MPa)	51.0

Chemical analysis of PCF ash was performed by Göltaş A.Ş. Quality and Control Laboratory. Particle size distribution, loose bulk density, grain densities and water absorption tests of PCF ash were performed in accordance with TS 3530 EN 933-1; TS EN 1097-3; TS EN 1097-6, respectively. The findings were interpreted according to TS EN 13055. Synthetic foam agent was used in foam concrete production. The foam agent was mixed with water at rate of 1/50 and foam was obtained from the foam generator at a density of 85 g/L. The w/c ratio of the mixture was chosen to be 0.65. The resulting foamed concrete mixture was poured into 100 mm cube molds and cured for 28 days in a climate cabinet at 95% relative humidity. In addition, the thermal conductivity samples were poured into 300x300x50 mm prism molds and then the samples were dried at 105 °C until reaching the constant mass, when the cure time was completed.

The compressive strengths at 28th day of the samples were carried out by the compressive strength test press according to TS 13565 standard and the thermal conductivity values were determined by HFM device according to TS EN 12664 standards. The properties of the fly ash as described in TS EN 450-1 standard were given in Table 3 and the PCF ash chemical constituents were given in Table 4. The proportions of total pozzolanic components ($SiO_2+Fe_2O_3+Al_2O_3$) were 81% in the PCF ash. The content of MgO and SO_3 which can react harmfully with the cement in the ash was less than 4% and 3% respectively. In addition, equivalent alkaline substance ($Na_2O+0.658*K_2O$) was than 5%, and the loss of ignition value was lower than 10%.

Table 3. Fly ash properties according to TS EN 450-1standard

Components	TS EN 450-1
$SiO_2+Al_2O_3+Fe_2O_3$ (%)	≥ 70
MgO (%)	≤ 4
SO_3 (%)	≤ 3
Amount of eq. alkaline subs. (%)	≤ 5
Total Chloride	≤ 0.1
Loss of ignition (LOI) (%)	≤ 10

Table 4. Chemical properties of PCF ash

Components	%
SiO_2	44.85
Al_2O_3	19.02
Fe_2O_3	17.11
CaO	9.05
Na_2O	0.33
K_2O	1.36
MgO	3.11
TiO_2	1.04
Cr_2O_3	0.09
SO_3	2.23
LOI	2.06

The physical analysis findings of the PCF gray were given in Table 5. The water absorption value at 24 hours by weight of the aggregate was 35%.

Table 5. Physical properties of PCF ash

Physical Properties of PCF ash	
Specific gravity (g/cm^3)	2.590
Bulk density (100%-dried) (kg/m^3)	570
Apparent grain density (g/cm^3)	2.19
Oven dried grain density (g/cm^3)	1.28
Saturated surface dry -grain density (g/cm^3)	1.70
Water absorption (by weight, %)	34

The oven dry-grain density of PCF ash was 1280 kg/m^3. This value was suitable the criteria described for light aggregates in TS EN 13055 (< 2000 kg/m^3). In addition, mineral based aggregates with an oven dry-grain density of < 2000 kg/m^3 and dry bulk density < 1200 kg/m^3 are defined as "lightweight aggregate" according to TS EN 206 standard.

The PCF ash has a fairly uniform grain size distribution (Table 6, Fig. 2). The maximum grain size was less than 2 mm, and the fineness module value was 0.54. This value indicates that the average grain size of the ash was around 0.5 mm. In addition, the amount of small particles in 90 microns was 12%. These particles may react with $Ca(OH)_2$ formed during the hydration of the cement to form additional C-S-H bonds.

Table 6. Particle size distribution of PCF ash

Particle Size Distribution		
Sieve (mm)	Retained (%)	Cumulative passing (%)
2.000	0.05	99.95
1.000	8.33	91.62
0.500	21.21	70.41
0.250	23.97	46.44
0.090	34.30	12.14
Pan	12.14	0.00

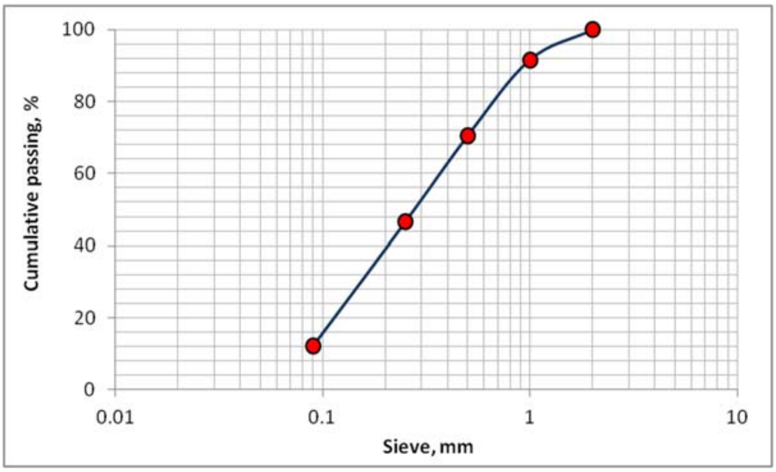

Fig 2. Particle size distribution curve of PCF ash

3. Results and Discussions

3.1 Mechanical and Thermal Properties of Foam Concrete

PCF ash was used at 0%, 11%, 22%, 33% and 44% by replacing with cement in the foam concrete. The components of the prepared foam concrete mixtures were given in Table 7.

Table 7. Mixture designs of foam concrete samples

Components	**FC Samples**				
	P0	**P50**	**P100**	**P150**	**P200**
Cement (kg/m^3)	450	400	350	300	250
PCF ash (kg/m^3)	0	50	100	50	200
Water (kg/m^3)	162	162	162	162	162.5
Foam (kg/m^3)	58.6	56.7	54.7	52.8	50.9
Water / solid	0.36	0.36	0.36	0.36	0.36

The densities (in fresh) of the P0, P50, P100, P150 and P200 samples were measured as 676, 674, 672, 670 and 667 kg/m^3, respectively. The cube samples were cured at 95% relative humidity for 28 days and then dried until reached constant volume. Subsequently, the masses of the samples were weighed and their dimensions were measured. The compressive strengths of 6 cube specimens from each sample group were tested. The density and compressive strengths of the samples were given in Table 8.

Table 8. Dry densities and compressive strengths of hardened foam concrete samples

S. No	P0		P50		P100		P150		P200	
	D	$f_{c\text{-}28d}$	D	$f_{c\text{-}28d}$	D	$f_{c\text{-}28d}$	D	$f_{c\text{-}28d}$	D	$f_{c\text{-}28d}$
1	452	1.95	465	1.80	454	1.59	451	1.45	452	1.12
2	450	1.89	452	1.73	455	1.59	464	1.30	448	1.13
3	452	1.94	458	1.81	451	1.73	455	1.37	457	1.03
4	453	1.93	448	1.82	453	1.69	463	1.48	443	1.10
5	457	1.87	454	1.77	448	1.62	457	1.28	453	1.06
6	458	1.93	458	1.77	455	1.60	460	1.35	457	0.98
Av.	454	1.92	456	1.78	453	1.64	458	1.37	452	1.07

D : *Dry density, kg/m^3* $f_{c\text{-}28d}$: *Compressive strength at 25d, MPa*

As the amount of PCF ash replacement by cement increased, the compressive strength of foam concrete samples decreased (Fig. 3). The compressive strength of P200 sample with 200 kg/m^3 ash decreased by 44% compared to the control sample.

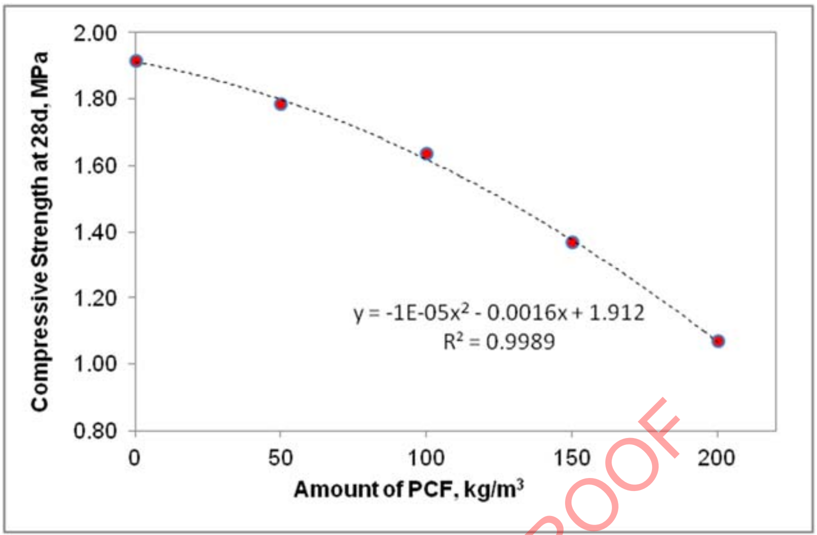

Fig 3. PCF ash content-compressive strength relationship in foam concrete samples with equivalent densities

The compressive strengths of foam concretes in dry-densities of 400-500 kg/m^3 were reported by Tikalsky et al. (2004), Aldridge (2000) and ACI-523 (1992) as 0.7, 0.5 and 0.9 MPa, respectively. The results obtained in this study were consistent with the literature.

The thermal conductivities of foam concrete samples were measured by the Lasercomp Fox 314 device. The density and thermal conductivity coefficient ($\lambda_{10\text{-dry}}$) test results of 3 samples from each group were given in Table 9.

Table 9. $\lambda_{10\text{-dry}}$ values of foam concrete samples

No	P0		P50		P100		P150		P200	
	D	$\lambda_{10\text{-dry}}$	D	$\lambda_{10\text{-dry}}$	D	$\lambda_{10\text{-dry}}$	D	$\lambda_{10\text{-dry}}$	D	$\lambda_{10\text{-dry}}$
1	452	0.1288	458	0.1139	448	0.1073	455	0.0995	445	0.0948
2	452	0.1285	454	0.1131	448	0.1073	457	0.0991	455	0.0967
3	454	0.1293	452	0.1136	454	0.1079	452	0.0989	462	0.0979
Av.	453	0.1289	455	0.1135	450	0.1075	455	0.0992	454	0.0965

$\lambda_{10\text{-dry}}$: *Thermal conductivity coefficient of samples in 100% dry condition at dT = 10℃ (W/mK)*

As the amount of ash displaced by cement increases, the thermal conductivity values of foam concrete samples also decrease. The thermal conductivity of the P200 sample was 25% better than the control sample (Fig. 4).

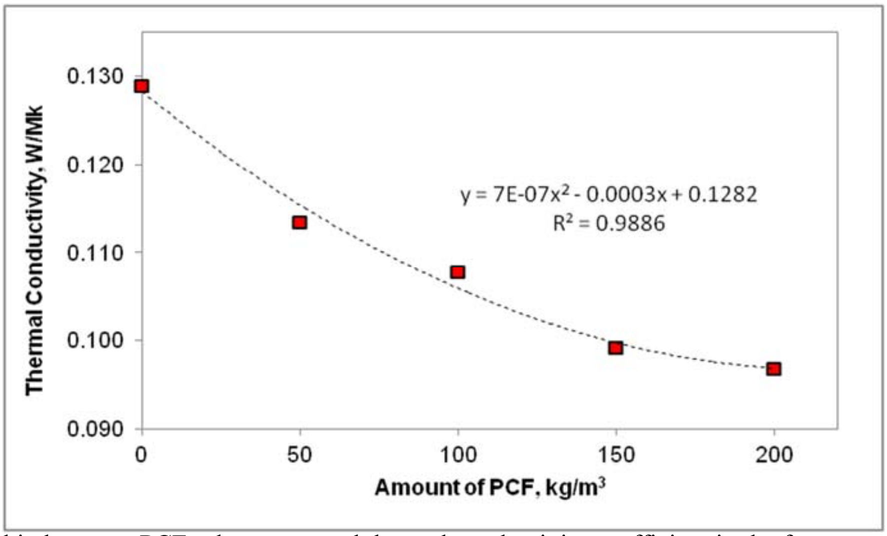

Fig 4. Relationship between PCF ash content and thermal conductivity coefficient in the foam concretes with equivalent densities

4. Conclusion

PCF ash was classified as a lightweight aggregate when it was evaluated in terms of the physical properties (bulk density and oven particle density). The content of pozzolanic substance in PCF ash was very high (81%) and other chemical properties were suitable for use in concrete. Moreover, PCF ash provided the required criteria for F-class fly ashes. In the foam concrete, the aggregate should be the largest grain size less than 2 mm and the average grain size <0.6 mm. The largest grain size of PCF ash is less than 2 mm and the fineness module is 0.5 mm.

In this study, PCF ash was used as replacement of cement at 4 different rates in foam concrete with a density of 450 kg/m^3. Compared with the control mixture, the 28d-compressive strength of the mixture (P200) which is used the maximum PCF was reduced by 44%. In addition, the P200 sample is 40% cheaper than the control mixture in terms of unit production costs for March 2018. Furthermore, according to the equivalent density values, the thermal conductivity of the P200 sample (0.097 W/mK) was 25% lower than the P0 sample (0.13 W/mK). This difference makes the P200 sample more advantageous in the production of precast wall and filler elements.

Considering the pozzolanic substance content of PCF ash, it is possible to say that the increase in strength after 28 days according to the control mixture will accelerate under suitable cure conditions. In particular, if steam cure is applied, it can be expected that the resistance difference in the early ages will decrease significantly. As a result, the findings of this study revealed that PCF ash that causes environmental pollution, can be used as an industrial raw material.

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