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Research Article

Thermal and mechanical analysis of thermal power plant ashes, cement and resin composites

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ABSTRACT

This study used thermal power plant fly ash (FA) and bottom ash (BA) as fill materials and investigated the thermal properties of composites made of cement and pine tree resin binders. For each ash group, 36 samples were prepared by adding 50% cement and 1% to 2% resin as binders. i) FA samples had 23.18%, 22.99%, and 77.01% lower density, thermal conductivity, and compressive strength than BA samples, respectively. FA samples had 9.42% higher porosity than BA samples. ii) FA (0.177 W/mK) and BA (0.221 W/mK) samples with resin and cement had the lowest heat transfer coefficients. iii) FA (14.46 MPa) and BA (36.96 MPa) samples (resin + cement binder) had the highest compressive strength values.

Introduction

Fly ash (FA) results from burning low-calorie lignite coals in thermal power plants (TPPs). Fly ash is entrained by flue gases and kept in electrostatic filters. Bottom ash (BA) is coarser-grained ash falling on the bottom of a boiler. These ashes are not utilized adequately because they are dumped on vacant lands around power plants. Disposing of FA and BA in this way wastes resources and causes environmental pollution. These wastes are a significant problem for TPPs. If we make use of FA and BA, we will have significant environmental, technical, and economic benefits and solve the waste problem of TPPs.

Land and energy costs rise, resulting in vertical growth and increased demand for low-density and insulated building materials. Porous and lightweight aggregates should be used as fillers to produce low-density building materials concrete, brick, briquette, plaster, etc). Lightweight aggrega, volcanic slag, etc.) and artificial aggregates (perlite, tes are divided into two: natural aggregates (pumice FA, BA, expanded clay, expanded polystyrene, etc.). This study focused on two artificial aggregates: FA and BA.

There is a large body of research on FA. We can group those studies into two: The first group consists of studies that add FA to cement in different proportions. The goal of these studies is to produce affordable and high-quality binders [1-4].

The second group consists of studies on lightweight concrete production. Those researchers replace conventional aggregate with FA. These studies aim to produce building materials with insulating properties by using binder materials (porous ash particles, cement, gypsum, polymers, etc.). Babu et al [5], Karasin and Dogruyol [6], Yu et al [7] investigated the change of mechanical properties in fly ash-cement mixtures with fly ash ratio. Rafieizonooz et al [8] examined the physical properties of concrete that is prepared by using bottom ash instead of sand 0, 20, 50 and 100% and fly ash instead of cement 20%. Siddique [9], Dan [10] researched the effect of using fly ash instead of partially sand on fresh concrete characteristics. Thirumal and Harish [11] got a high performance concrete that will flow under its own weight without a mechanical vibration. Bicer investigated the influence of grain diameter and resin usage on thermal and mechanical properties of fly ash as aggregate in concrete [12]. Biçer [13] investigated the effect of production temperature on thermal and mechanical properties of polystyrene - fly ash composites. Rivera et al [14] have obtained pressure strengths more than 30 MPa by using fly ash. Aydın and Arel [15] analyzed the application of high volume fly ash-cement composites for the locations with low mechanical properties in the buildings. Li et al [16] analyzed the content of unburned carbon in hardened cement-fly ash paste. In addition, some researchers have used resin to produce building materials with insulating properties.

These studies aim to create artificial pores with porous aggregate and resin and to produce low-density building materials by increasing total porosity. Bicer and Celik [17] used pumice aggregate and pine resin to manufacture concretes with thermal conductivity of 0.231 W/mK. Devecioglu and Bicer [18], Kaya and Kar [19, 20] identified thermal and mechanical features of expanded polystyrene-resin-cement composites and the utility of them as construction materials.

Unlike earlier studies, this study used two TPP ashes (FA and BA) for two objectives. The first objective was to reduce the amount of cement in concrete. The second was to create artificial pores by using the ashes as aggregates and thus produce a pine tree resin (PTR) added to an insulating concrete with adhesive properties.

Materials and Methods

Materials

Ashes:

The TPP ashes (FA and BA) were supplied from the Afsin-Elbistan TPP in the east of Turkiye.

Fly ash is formed during the combustion of low-calorie coals in TPPs between 1100 °C and 1600 °C. It is collected in the cyclone and electro filters of TPPs. It is darker than cement and consists of tiny grains (particle diameter $(20\text{-}80)\times10^{-6}$ m). The fly ash used in the present study had a density of 1.69 g/cm^3.

Bottom ash is collected at the bottom of the combustion chamber. It has a particle diameter of $(500\text{-}7000)\times10^{-6}$ m and a density of 2.20 g/cm^3. It is dark gray and soft. Its color depends on charcoal and its flammability [8]. It consists of silica, aluminum, and iron oxides.

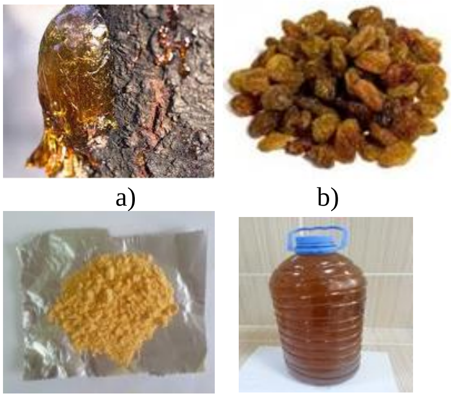
Table 1 shows the chemical composition of the components.

Table 1 Chemical composition of the components (%)

Chemical characteristics	Fly ash	Bottom ash	Cement
SiO_2	33.9	32.1	18.65
Al_2O_3	12.5	15.3	6.15
Fe_2O_3	5.9	15.2	3.25
CaO	35.5	11.6	57.71
MgO	1.9	2.8	2.34
SO_3	7.2	19.9	2.91
K_2O	0.7	0.5	0.7
TiO_2	0.7	1.2	--
LiO_2	-	1.1	--
Na_2O	0.3	0.4	--
Loss on ignition	1.4	1.1	2.84
Not available	-	-	6.08
Total	100	100	100.03

Pine tree resin:

Pine tree resin is a viscous and sticky material that seeps from the bark of pine trees. It becomes solid when it comes into contact with oxygen. It sticks to the place where it flows after a while (Fig. 1-a). The resin was ground and mixed with cement in extract form for two reasons (Fig. 1-b, c and d). First, when immersed in water, resin absorbs some water and expands. It removes the water during drying and results in micro structured artificial pores in the sample structure. This improves the insulating properties of the new material. Second, when resin dries, it hardens and thus increases the binding properties of the cement.



a) b)

c) d)

Fig. 1 View of pine resin a) natural resin on tree, b) dried, c) powder resin, d) extract resin

Cement:

CEM IV/B(P)32.5 R cement and resin-water mixture were used to bind the ashes. The cement had a density of 3.1 g/cm^3 and a thermal conductivity of 0.751 W/mK.

For experiments, cement mortars were prepared with FA and BA aggregates at 0%, 10%, 20%, 30%, 40%, and 50% by volume (Table 2). Some mortars were poured into 20x60x150 mm molds and left to dry for 28 days for thermal tests, while some others were poured into 100x100x100 mm molds and left to dry for 28 days for mechanical tests.

Testing methods

The following tests and calculations were applied to each sample:

The thermal conductivity coefficient was measured using a device (Shoterm QTM) that performs measurements under the transient regime and works with the hot wire method (Fig. 2). The device performs measurements according to DIN 51046 norm. Thermal conductivity coefficients were measured from three points on each sample and then, the arithmetic averages of those measurements.

Fig. 2 Thermal conductivity meter unit

Compressive strength tests were carried out according to TS 699 [21, 22]. The tests were performed using a device (Ele International) that can apply force on one axis.

The density method is used to determine the porosity of the samples. Porosity (φ) is defined by Equation (1), [18].

$$\Phi = 1 - \frac{\rho_{porous}}{\rho_{solid}} \qquad (1)$$

Equation (1) applied to this study can be written as equation (2).

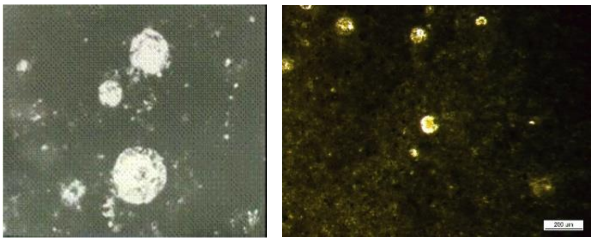
$$\Phi = 1 - \frac{\rho_{ash} \cdot Z + \rho_{binder} \cdot (1\text{-}Z)}{\rho_{ash\ matrix} \cdot Z + \rho_{binder\ matrix} \cdot (1\text{-}Z)} \qquad (2)$$

where ρ_{ash} is the density of the porous material, while the $\rho_{ash\ matrixs}$ is the density of solid material (the density of the sample after milling and so causing no porosity). ρ_{binder} is the density of the resin mixture of cement, and $\rho_{binder\ matrix}$ is the density of the resin mixture with a 0% porosity ratio. Z is the ash ratio (%), and (1-Z) is the binder ratio (%). The porosity of the samples was calculated using the density values (FA:1.69 g/cm^3, FA$_{matrix}$:3.403 g/cm^3, BA:2.20 g/cm^3, BAmatrixs: 3.44 g/cm^3 and R:1.8 g/cm^3). The results are shown collectively in Table 3.

Results and Discussions

Density and Porosity:

Fly ash had a 23.18% lower density and 9.42% higher porosity than BA. Similarly, the samples with FA had a 23.18 % - 14.46 % lower density and 9.4 %-6.38 % higher porosity than the samples with BA. The submicroscopic views of the 50% cement+ash mixed FA and BA aggregates in Fig 3 as well as in Fig 4-a and Fig 4-b seem to confirm this.



a) b)

Fig. 3 View of ashes + cement block under a microscope a) FA, b) BA

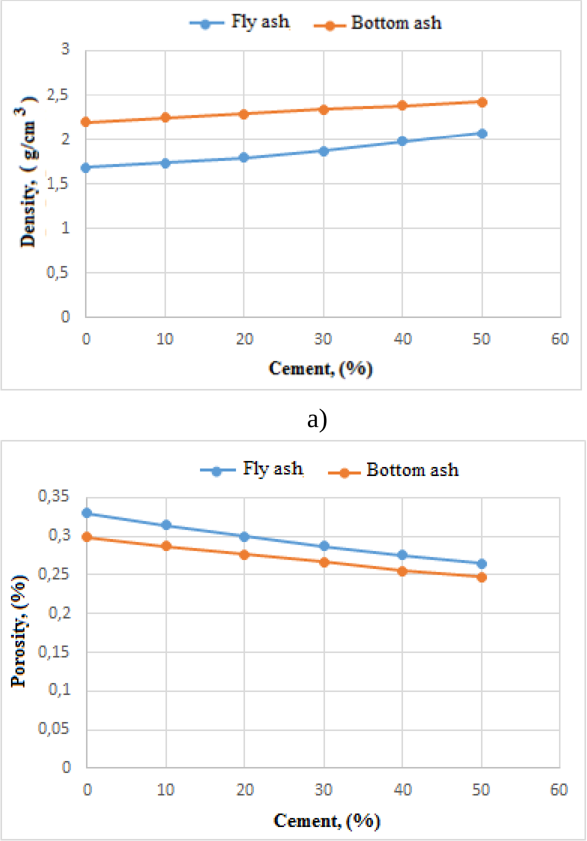
Table 2 Details of the cement—ash—resin

Volumetric ratio (%)		**Weight (gram)**					
Fly-bottom ash	**Cement**	**Fly or bottom ash**	**Cement**	**Total weight (gram)**	**Resin (gram)**	**Resin (liter)**	**(W+R)/(C+A)**
Resin (0 %)							
0	100	0	500	500	-	-	0.6
10	90	50	500	550	-	-	
20	80	100	500	600	-	-	
30	70	150	500	650	-	-	
40	60	200	500	700	-	-	
50	50	250	500	750	-	-	
Resin (1 %)							
0	100	0	500	500	5.00	0.30	0.6
10	90	50	500	550	5.50	0.35	
20	80	100	500	600	6.00	0.40	
30	70	150	500	650	6.50	0.45	
40	60	200	500	700	7.00	0.50	
50	50	250	500	750	7.50	0.55	
Resin (2 %)							
0	100	0	500	500	10	0.60	0.6
10	90	50	500	550	11	0.70	
20	80	100	500	600	12	0.80	
30	70	150	500	650	13	0.90	
40	60	200	500	700	14	1.00	
50	50	250	500	750	15	1.10	

W:Water, R:Resin, C:Cement, Resin= Total weight (g) x Resin ratio (%)

Table 3 Measurement results

Cement (%)	**Fly ash**				**Bottom ash**			
	Density (g/cm^3)	**Porosity (%)**	**Thermal conduc. (W/mK)**	**Comprres. strength (MPa)**	**Density (g/cm^3)**	**Porosity (%)**	**Thermal conduc. (W/mK)**	**Compres. strength (MPa)**
Resin 0 %								
0	1.69	0.3300	0.278	3.43	2.20	0.2989	0.361	14.92
10	1.74	0.3145	0.293	5.11	2.25	0.2876	0.375	17.55
20	1.80	0.3004	0.305	6.6	2.29	0.2764	0.386	20.24
30	1.87	0.2875	0.315	8.22	2.34	0.2665	0.406	23.27
40	1.98	0.2757	0.324	9.76	2.38	0.2555	0.425	26.59
50	2.07	0.2648	0.331	11.45	2.42	0.2479	0.452	30.23
Resin 1 %								
0	1.44	0.3470	0.158	4.81	2,05	0.3266	0.204	19.28
10	1.5	0.3255	0.170	6.7	2,11	0.3096	0.215	21.95
20	1.58	0.3184	0.179	8.83	2,15	0.2943	0.223	25.12
30	1.66	0.2965	0.187	10.95	2.21	0.2805	0.230	28.96
40	1.77	0.2847	0.193	13.12	2.25	0.2679	0.234	33.21
50	1.86	0.2758	0.197	15.74	2.30	0.2564	0.237	37.55
Resin 2 %								
0	1.23	0.3600	0.142	4.57	1.92	0.3465	0.189	18.52
10	1.31	0.3445	0.153	6.43	1.98	0.3296	0.199	21.24
20	1.42	0.3304	0.162	8.22	2.05	0.3086	0.208	24.56
30	1.53	0.3175	0.169	10.33	2.12	0.2944	0.214	28.17
40	1.62	0.3017	0.174	12.34	2.18	0.2799	0.218	32.34
50	1.74	0.2938	0.177	14.46	2.25	0.2644	0.221	36.96

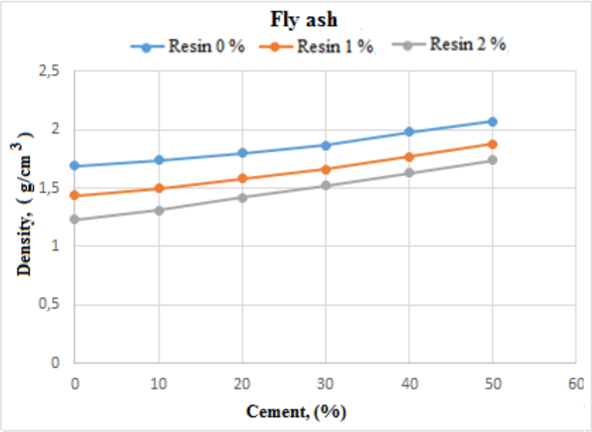


a)

b)

Fig. 4 Variation of a) density, b) porosity of TPP ash samples according to cement ratio

The addition of resin resulted in a reduction in density in cementless FA and BA by 2.72% (with 2% of the resin) and 1.27% respectively (Fig 5). It also increased porosity in the samples with FA and BA by 8.33% and 13.73%, respectively (Fig 6). This is because resin absorbs water and swells. During drying, it loses water, which results in artificial pores, increasing total porosity. The higher the cement ratios, the higher the density (cement has a higher density than ashes.) and lower the porosity of the samples with FA and BA.



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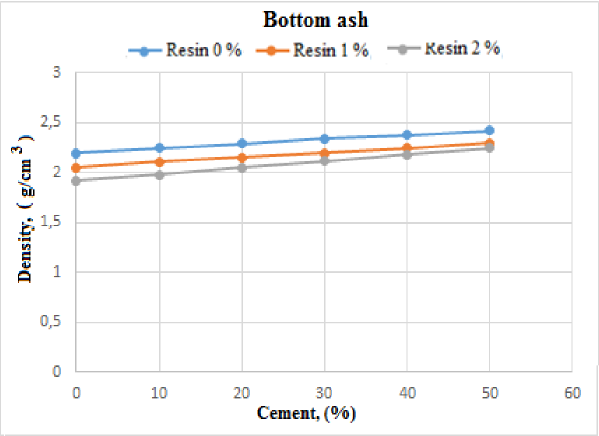
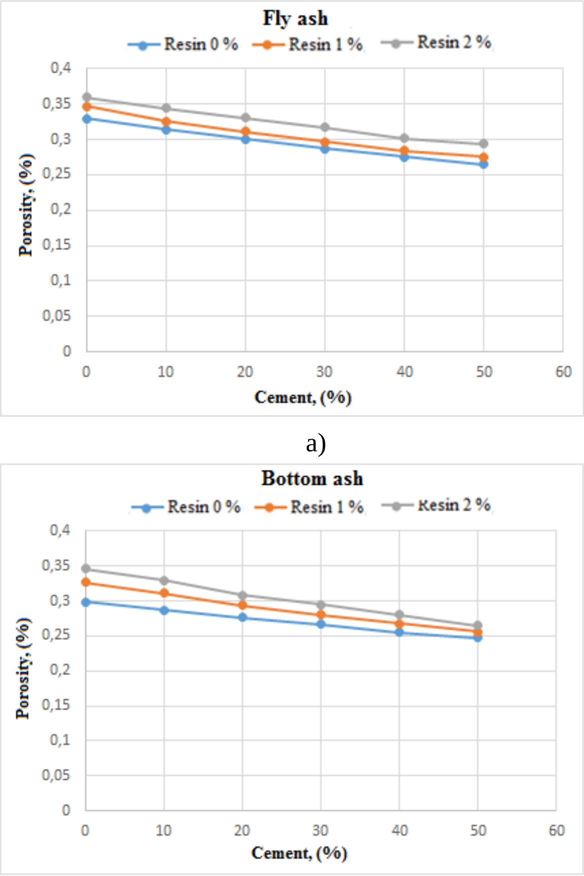


b)

Fig. 5 Effect of resin on density a) FA, b) BA aggregate samples.



a)

b)

Fig. 6 The effect of resin on parity a) FA, b) BA aggregate samples

Thermal Conductivity Coefficient:

Fly ash had a 22.99% smaller thermal conductivity than BA (Table 3 and Fig. 7). Similarly, cemented samples with FA had 22.99%-21.56% lower thermal conductivity (cement increases by 0%-50%) than samples with BA. This is mainly due to the porous structure of FA.The cementless sample with FA (0.278 W/mK) and BA (0.361 W/mK) had the lowest thermal conductivity coefficient. The addition of 2% resin resulted in a reduction in the thermal conductivity of cementless samples with FA (48.92 %) and BA (47.64%) (The dry resin had a thermal conductivity coefficient of 0.150 W/mK). The cementless FA (0.142W/mK) and BA (0.189 W/mK) samples with 2% resin by weight had the lowest thermal conductivity coefficient. The resin-free FA (0.331 W/mK) and BA (0.412 W/mK) aggregate sample with 50% cement by weight had the highest thermal conductivity coefficient. Thermal conductivity decreases due to a reduction in the amount of ash with an increase in the amount of cement. Fig. 8 shows the change in thermal conductivity coefficient depending on the amount of resin and cement in FA and BA aggregate samples. The higher the amount of resin, the smaller the heat transfer coefficient of the FA and BA samples. Fig. 9 shows the variation of thermal conductivity coefficients according to density values.

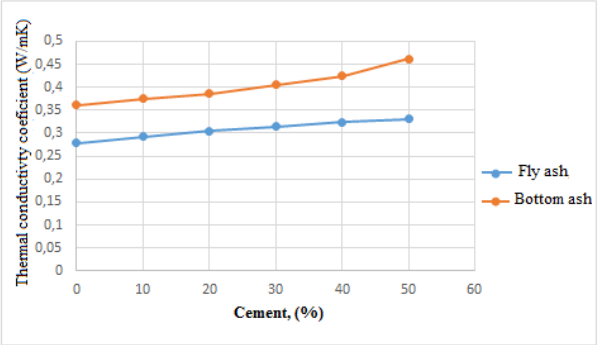
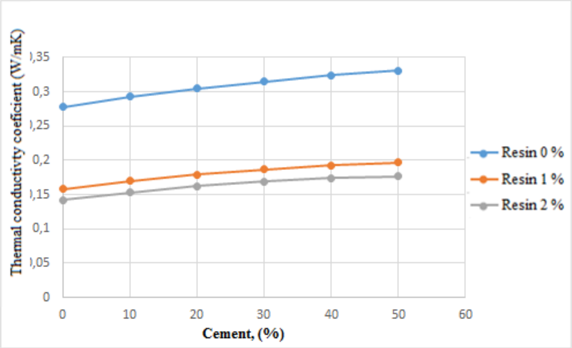


Fig. 7 Variation of thermal conductivity coefficients by cement ratio



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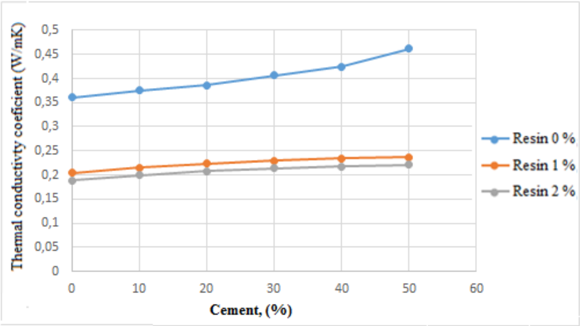
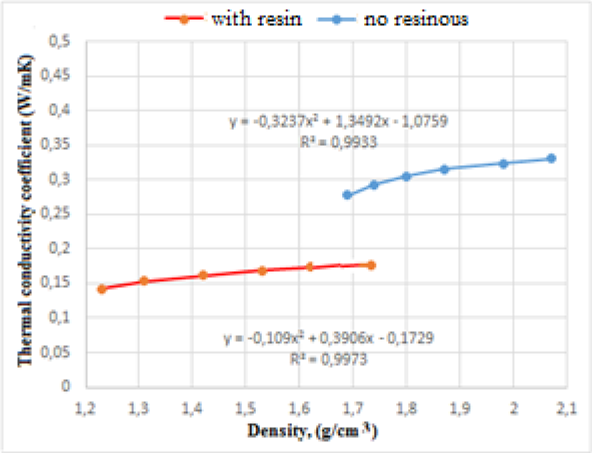


b)

Fig. 8 Variation in thermal conductivity coefficient of ash cement mixtures according to cement mixture ratio a) FA, b) BA aggregate samples



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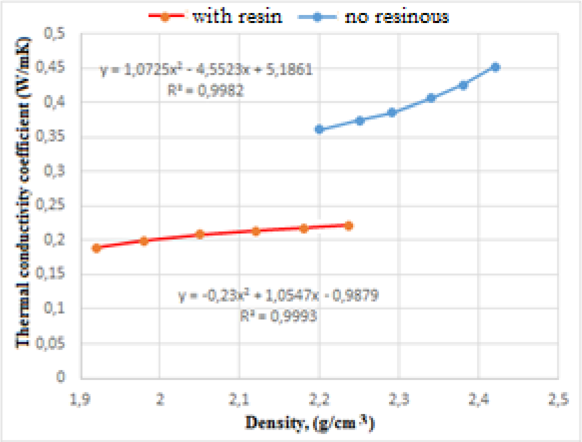


b)

Fig. 9 Change in density thermal conductivity coefficient of density a) FA, b) BA

Table 4 shows the thermal conductivity values of some materials. Ash-cement mixed samples had lower thermal conductivity than many building materials due to the porous structure caused by ash and resin.

Table 4. Thermal conductivities of some materials [17]

	Measured Values		Literature	
Materials	Density (g/cm^3)	Thermal conducti. (W/mK)	Density (g/cm^3)	Thermal conducti. (W/mK)
Concrete	2.500	1.420	2.272	1.512
Ytong wall	0.617	0.180	0.800	0.383
Brick wall	2.093	1.148	1.8-2.0	0.972
Outer plaster	1.856	1.173	1.600	0.930
Inner plaster	1.763	1.163	1.800	1.163
Cement block (Perlite)	0.427	0.292	0.1046	0.300

Compressive Strength:

Resin-free samples with FA aggregates had compressive strength values of 3.43 to 11.45 MPa, while those with BA aggregates had compressive strength values of 14.92 to 30.23 MPa. The compressive strength values increased by 62.12 %-77% depending on the amount of cement in the FA and BA samples (Fig 10). Samples with BA aggregates had higher compressive strength values than those with FA aggregates. This was because samples with BA had lower porosity.

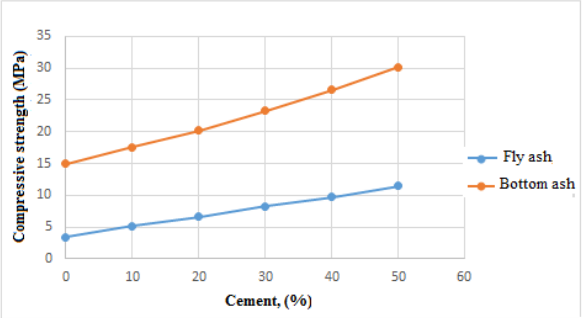
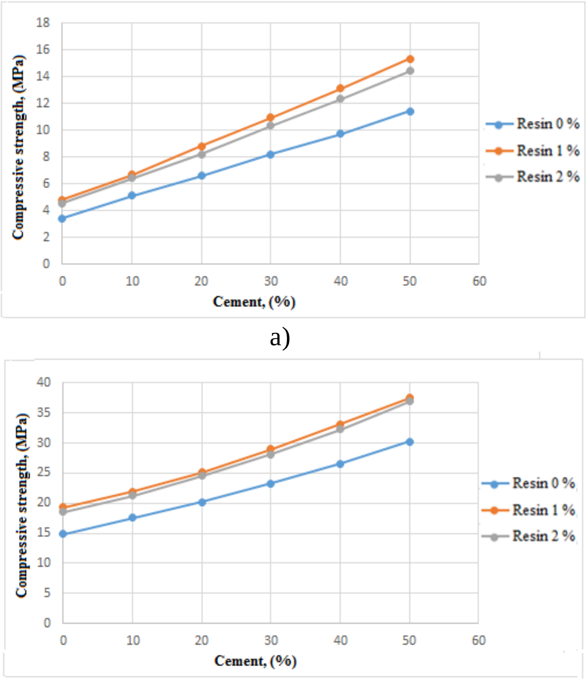


Fig. 10 Change in cement compressive strength in ash aggregate concrete

Fig. 11 compares the compressive strength values of samples with and without resin depending on the amount of cement. The samples with 1% resin had slightly higher compressive strength values than the resin-free samples. This is because the adhesive property of the resin increases the binding property of the cement (TPP ashes are pozzolanic materials, which, when mixed with water, gain binding properties with the released CaO). However, when the amount of resin was increased to 2%, compressive strength showed a partial decrease. Therefore, the resin ratio should be determined according to what the ash-cement-resin composites will be used for (where a composite material is used, it should be considered that thermal conductivity or compressive strength is important).



a)

b)

Fig. 11 Change in cement compressive strength in ash aggregate concrete a) FA, b) BA

Usability Tests:

Various tests were performed on samples with FA and BA. The results showed that the samples could be sawed, screwed, ducted for plumbing, drilled, and painted (Fig 12).

a) b) c)

Fig. 12 Tests on samples: a) drilling, b) oil paint, c) plastic paint

Conclusions

This study was conducted to assess Afşin-Elbistan TPP fly ash and bottom ash as a new construction material in resin and cement binder combinations. The following are the results:

1. Waste ash material in TPPs causes economic and environmental problems. These ashes have low thermal conductivity. Therefore, if we can reuse them, we both save energy and prevent environmental pollution.

2. Fly ash has 22.99% lower thermal conductivity than bottom ash. If 50% cement is added, FA has 21.56% lower thermal conductivity than BA.

3. The addition of 2% resin results in a 48.92% and 47.64% reduction in the thermal conductivity of uncemented and 50% cemented FA samples, respectively. The addition of 2% resin results in a 46.52% and 51.1% reduction in the thermal conductivity of uncemented and 50% cemented BA samples, respectively. The lowest heat transfer coefficient in cemented FA and BA samples with resin is 0.177 W/mK and 0.221 W/mK, respectively.

4. In resin-cement binder samples, If the amount of resin is up to 1%, the compressive strength increases, but when the amount of resin is increased up to 2%, it shows a partial reduction. The highest compressive strength (with 2% resin and 50% cement) is 14.46 MPa in the sample with FA and 36.96 MPa in the sample with BA.

5. The samples with FA and BA can be sawed, screwed, ducted for installation, drilled, and painted.

6. Due to their pozzolanic property, FA and BA can be used as intermediate filling material or roof insulation plaster in sandwich walls without binders. When the resin is added to them as a binder, the thermal conductivity value decreases, and the strength increases.

In conclusion, TPP ashes + cement + resin composites can be used as building materials to produce low-density and insulating concrete, briquettes, bricks, and plaster.

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