



## LIGHTWEIGHT BUILDING BLOCKS INCORPORATING BOTTOM ASH AGGREGATE UNDER DIFFERENT CURING CONDITIONS

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**Received:** 20 February 2015; **Accepted:** 6 May 2015

### ABSTRACT

In this study, the utilization of bottom ash as an aggregate in the production of lightweight building blocks was investigated. Pumice aggregate which was used in lightweight control mixture replaced by the bottom ash aggregate and on the other hand, cement replaced by high volume fly ash. Physical and mechanical properties of mixtures were determined after different curing regimes (standard water, in air, in oven, steam and autoclave curing) and in addition, water resistance of the mixtures was also determined. After that, microstructure of the specimens was investigated by using the scanning electron microscopy. Then, the thermal conductivity of the mixtures containing pumice and bottom ash was compared. Finally, in order to produce construction elements, prototypes of lightweight building blocks were manufactured. After these very procedures, it concludes that bottom ash is a good alternative for pumice aggregate in producing lightweight building blocks.

**Keywords:** Bottom ash; pumice; waste management; curing; building blocks.

### 1. INTRODUCTION

Significant increases in coal-fired generation capacity are taking place in many of the developing nations and large capacity increases are planned. Since coal resources are far more abundant than the other fossil fuel resources and also due to the fact that the power plants have a long working life, coal will remain as an important source of energy for many years [1].

However, coal burning electric power plants cause several problems, such as air and environmental pollution [2]. During coal-fired electric power generation, three types of coal combustion by-products (CCBs) are obtained. These by-products; fly ash, bottom ash and

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boiler slag are the largest sources of industrial waste in Turkey. Utilizing all the power plant wastes in large quantities in the construction industry seems to be a reasonable solution for these environmental and economic problems. One of the main functions of power plant wastes is in building materials. The development of composite binders and the prefabricated building elements composed of chemical gypsum and pozzolanic materials were studied [3, 4]. However, due to high carbon content and large particle size in most of the cases, bottom ash is not also suitable in producing construction materials. A few studies have been conducted on potential use of bottom ash [5-10]. Bottom ash is predominantly used in structural fill, road base and sub-base, backfill, drainage media, aggregate for concrete, asphalt and masonry, abrasives/traction, and manufactured soil product applications In USA [11]. Bajare et al. [12] reported that the usage of grinded coal combustion bottom ash can decrease the cost of concrete (C30/37) by 10% and reduce the amount of CO<sub>2</sub> emission by 22.9%.

Additionally, some researchers have dealt with the utilization of bottom ash as an aggregate in concrete and mortar [13-27]. Furthermore, Siddique [28] has investigated the utilization of coal bottom ash in self-compacting concrete.

Previous study showed that flue gas desulfurization sludge, fly ash and, bottom ash containing construction materials have sufficient mechanical properties to produce building blocks [29]. In this experimental research, utilization of bottom ash of Dalan Chemical Company and fly ash of Soma B power plant (placed in Turkey), as a construction material, were investigated. Test results showed that, high volume bottom ash and fly ash can be used in the production of lightweight building blocks as light weight aggregate and binder, respectively.

## 2. EXPERIMENTAL

Materials used in this study are ordinary Portland cement (CEM I 42.5 N), fly ash (FA) of Soma B plant and bottom ash of Turkey's Dalan Chemical Company. According to ASTM C 618, FA can be classified as class C. The physical, chemical and mechanical properties of Portland cement and FA are given in Table 1. Bottom ash and pumice were used as aggregate (0-5 mm). The chemical composition and the physical properties of bottom ash and pumice are presented in Table 1 and 2, respectively.

Table 1: Chemical composition of cement, fly ash, pumice and bottom ash

Chemical Composition (%)					Other properties of cement and FA	
	Cement	Fly ash	Pumice	Bottom Ash		
SiO <sub>2</sub>	19.10	47.15	75.51	37.07	Specific gravity	3.13
Al <sub>2</sub> O <sub>3</sub>	4.40	20.42	9.94	18.96	Initial setting time (min)	110
Fe <sub>2</sub> O <sub>3</sub>	396	4.15	1.10	4.96	Final setting time (min)	166
CaO	61.85	20.47	0.25	12.52	Volume expansion (mm)	1.00
MgO	2.05	1.51	0.04	1.74	<b>Specific Surface (M<sup>2</sup>/KG)</b>	<b>368</b>
Na <sub>2</sub> O	0.27	0.59	2.04	0.39	Mechanical properties of cement (MPa)	
K <sub>2</sub> O	0.70	1.36	5.12	0.79		
SO <sub>3</sub>	3.72	2.08	---	0.02		
					2 days	27.1
					7 days	43.3

Cl <sup>-</sup>	0.0004	0.0149	---	0.043	28 days	56.0
					Specific gravity of FA	2.15
					Blaine of FA (m <sup>2</sup> /kg)	292
					Pozzolanic activity (28-day of FA)	% 92.9

Table 2: Physical properties of pumice and bottom ash aggregates

Physical properties	Pumice	Bottom ash
Loose bulk density (kg/m <sup>3</sup> )	1188	996
Compacted bulk density (kg/m <sup>3</sup> )	1249	1202
Water absorption capacity (%)	9.96	22.0
Water absorption capacity in 30 min. (%)	2.2	10.2
Moisture as handled (%)	10.0	40.0
Saturated surface dry specific gravity (g/cm <sup>3</sup> )	2.30	1.94
Dry specific gravity (g/cm <sup>3</sup> )	2.09	1.59

In the first stage, the effect of bottom ash aggregate replacement on mechanical properties was investigated in three different curing conditions (28-day water curing, steam curing, and autoclave curing). The mixture proportions and some properties of these mixtures are given in Table 3. It can be seen from Table 3 that only five different mixtures were prepared. These mixtures are BA0, BA25, BA50, BA75 and BA100, which indicates bottom ash replacement level by weight. The solid proportions of the mixtures were also given in Table 3. In the second stage, selected bottom ash mixture (BA) and control pumice mixture (P) were prepared (Table 4). Mechanical and physical properties of these mixtures were investigated in detail.

Table 3: Mix proportions according to the BA content

Mixture	Cement (%)	FA (%)	P (%)	BA (%)	Water (%)	W/Binder	P/Aggregate (%)	BA/Aggregate (%)	Aggregate/Binder	Flow Tab. (mm)
BA0	12.5	12.5	75	0	13	0.525	100	0	3	110
BA25	12.5	12.5	56	19	13	0.525	75	25	3	110
BA50	12.5	12.5	37.5	37.5	13	0.525	50	50	3	109
BA75	12.5	12.5	19	56	13	0.525	25	75	3	108
BA100	12.5	12.5	0	75	13	0.525	0	100	3	125

Table 4: Mix proportions for selected mixtures

Mixture	Cement (%)	FA (%)	P (%)	BA (%)	Water (%)	W/Binder	P/Aggregate (%)	BA/Aggregate (%)	Aggregate/Binder	Flow table (mm)
BA	12.5	12.5	37.5	37.5	16	0.64	50	50	3	125
P	12.5	12.5	75	0	16	0.64	100	0	3	125

The mixtures were prepared in a Hobart mixer. Test specimens were cast from the same batch into steel molds. Physical and mechanical properties were determined after different curing regimes. These different curing regimes are standard water curing at  $20\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ , air curing in laboratory atmosphere ( $20 \pm 2\text{ }^{\circ}\text{C}$  relative humidity of  $60 \pm 10\%$ ), curing in oven ( $50\text{ }^{\circ}\text{C}$  for 12 hours), steam curing ( $50\text{ }^{\circ}\text{C}$  for 12 hours) and autoclave curing ( $0.5\text{ MPa}$  pressure,  $150\text{ }^{\circ}\text{C}$  for 5 hours).

After pre-heating period (5 hours) specimens were exposed to steam curing at  $50\text{ }^{\circ}\text{C}$  for 12 hours. To avoid the thermal shock heating, the rate of steam curing treatment was kept by  $9\text{ }^{\circ}\text{C/h}$ . Therefore, low steam curing temperature was chosen to prevent crack formation relatively. Furthermore, oven or autoclave cured specimens kept in molds by  $20\text{ }^{\circ}\text{C}$  temperatures during 1-day before curing. Afterwards these heat treatments were applied. The autoclave temperature was raised gradually and reached to the peak temperature in 3.0 hours. After the completion of their oven, steam or autoclave curing periods, specimens were kept in laboratory atmosphere for cooling.

After the curing period, three cube specimens ( $50\text{ mm} \times 50\text{ mm} \times 50\text{ mm}$ ) from each mixture were subjected to compressive strength test. Furthermore, physical properties of specimens were also determined. Prismatic specimens ( $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$ ) were used in thermal conductivity and capillary suction tests. Bottom surface of the prismatic specimens up to a height of 3–4 mm is in contact with water inside a steel tray. Specimens were removed from the steel tray at the intervals of 4, 8, 12, 16, 20, and 24 min and weighed carefully. Furthermore, in order to determine the volume stability of mixtures, prismatic (width: 25 mm, height: 25 mm, length: 285 mm) specimens were used. Building blocks and hollow blocks were prepared by using the selected mixtures.

### 3. RESULTS AND DISCUSSION

#### *3.1 Mechanical properties of the mixtures*

Mechanical performance of the mixtures according to the bottom ash replacement level was presented in Fig. 1. Pumice aggregate was replaced by bottom ash aggregate. It can be seen from the Fig. 1 that compressive strength of the mixtures reduced by increasing the amount of bottom ash replacement after different curing regimes. This situation is distinctive in autoclaved ones. Furthermore, the dimensional stability problem was observed especially over 50% bottom ash replacement ratios (Fig. 2) in standard water curing. This preliminary test results showed that bottom ash replacement level must be limited for good mechanical performance as well as dimensional stability. Therefore, the replacement level was stabled at 50% replacement level for further tests. BA (50% bottom ash and 50% Pumice by weight) and control mixture (P mixture, 100% pumice) were chosen to produce lightweight building elements. For this purpose, the mixture designs were slightly changed deliberately to obtain more functional mixtures. Selected mixture designs were given in Table 4. The mechanical, physical and dimensional stability properties of these mixtures were investigated under five curing regimes. Mechanical test results were discussed below.

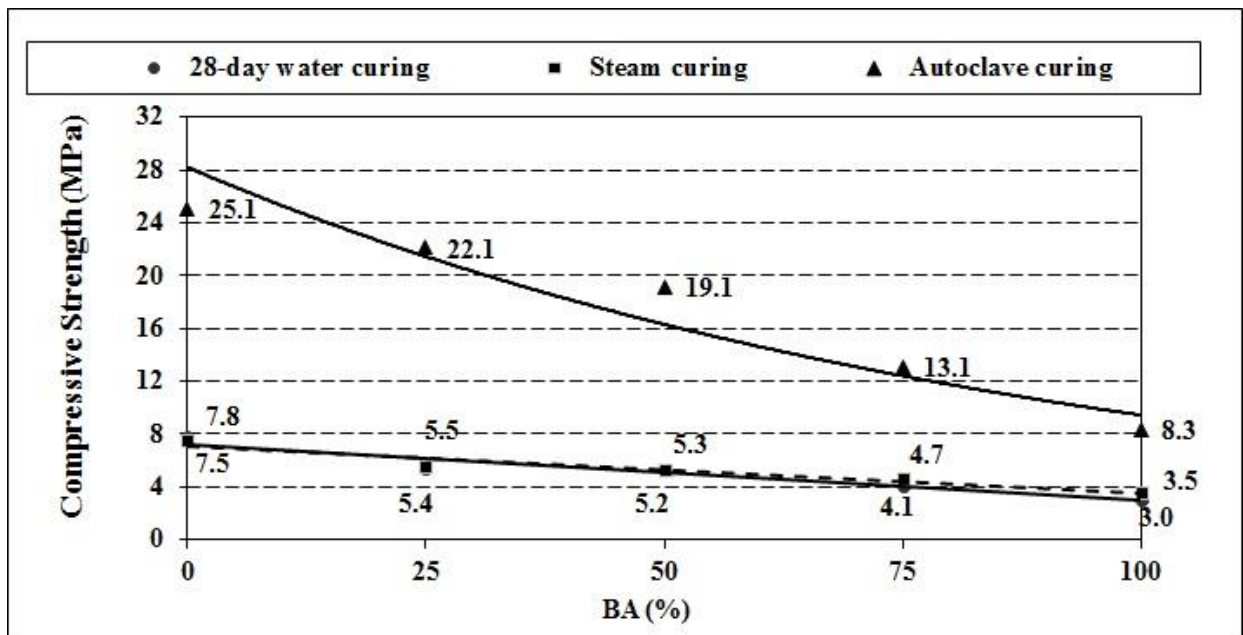


Figure 1. Compressive strength of mixtures according to BA replacement ratio as an aggregate



Figure 2. Volume stability problem of %100 BA mixtures during water curing

The compressive strength gain in air ( $20 \pm 1^\circ\text{C}$  relative humidity of  $60 \pm 10\%$ ) was given in Fig. 3. The obtained strength from 7 to 28 days is in a very high level which resulted in 9.77 and 10.51 MPa for P and BA mixtures at 28 days, respectively. The compressive strength of BA and P mixtures at 28-days is 10.95 and 13.53 MPa after water curing. The strength difference is lower than what could be expected from the air and water cured specimens. This can be attributed to the humidity conditions of the specimens at testing age. The water cured specimens were in the saturated surface dry condition while air cured ones

were in the air-dried condition at the testing age. This situation may be affected the measured strength values. Compressive strength of steam cured specimens is also shown in Fig. 3. It can be seen from the Fig. 3 that compressive strength of air cured or water cured specimens of 7 days can be reached at 2 days by steam curing. Strength gain of steam cured specimens was also continued and strength level at 28-days reached to the strength of the air or water cured ones. The effect of autoclave curing on strength gain can be followed from the Fig. 3. Autoclave curing is the most effective curing method amongst the others in regard of fast and ultimate gaining strength development. These mixtures have a compressive strength greater than 20 MPa after autoclaving at 28 days. Curing in oven increased the early strength as compared to the standard water curing. However, strength reduction is observed at 28-day. This can be explained by the drying of the specimens. It is obvious that water is necessary for hydration reaction. It was reported that hydration reaction stopped under the relative 80% humidity [30].

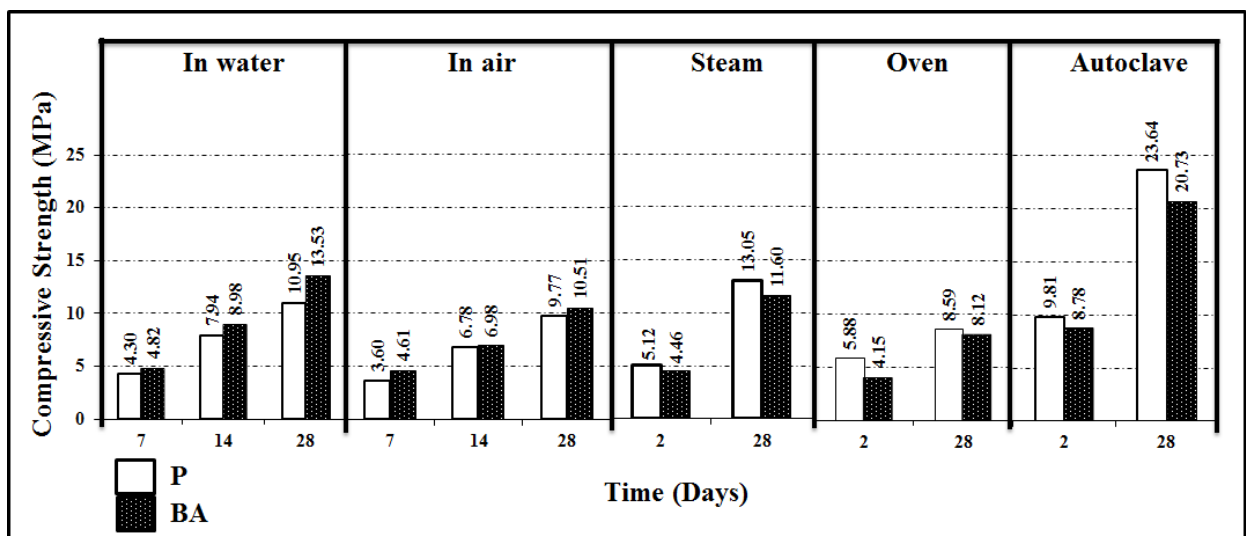


Figure 3. Compressive strength gain of mixtures after different curing regimes

### 3.2 Physical properties of the mixtures

Porosity, dry bulk density, dry specific gravity of mixtures with different curing conditions (28 days air curing in laboratory atmosphere, 28-day water curing, oven curing, steam curing, and autoclave curing) are presented in Figs. 4, 5, and 6, respectively. As shown in the Fig. 4 porosity of BA increased slightly compared to the pumice mixture. Porosity of P mixture is between 14.53-20.65% while, this ratio is between 15.25-25.58% for BA mixture. Furthermore, heat treatments (such as steam, autoclave and oven) increased the porosity. Dry bulk density is between 1.39-1.51 and 1.24-1.45 g/cm<sup>3</sup> for P and BA mixtures, respectively. Dry specific gravity is between 1.45-1.58 and 1.33-1.49 g/cm<sup>3</sup> for P and BA mixtures respectively. Generally, dry bulk density and specific gravity of BA mixture are both lower than P mixture. This behavior can be explained by lower weight unit and porous structure of bottom ash. It can be seen that the specific gravity of these mixtures are lower than the conventional cement mortar and can be used to produce the lightweight building blocks or elements.

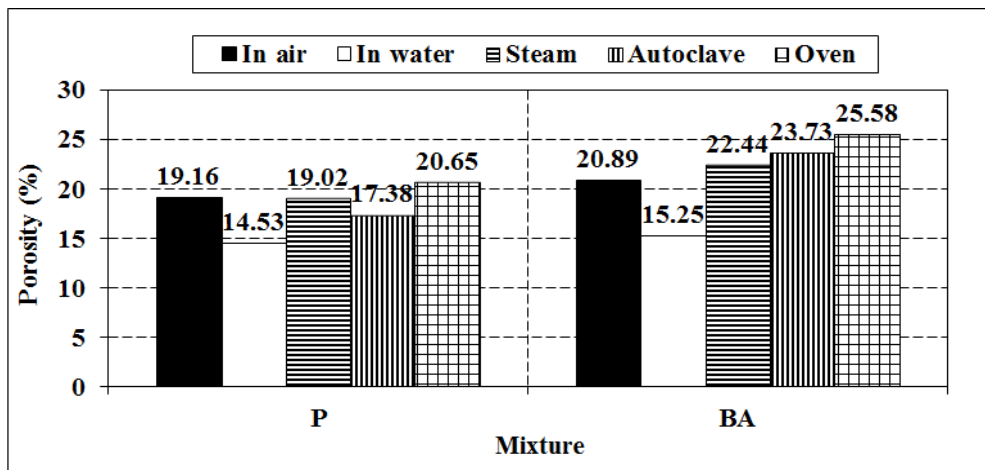


Figure 4. Porosity of mixtures after different curing regimes

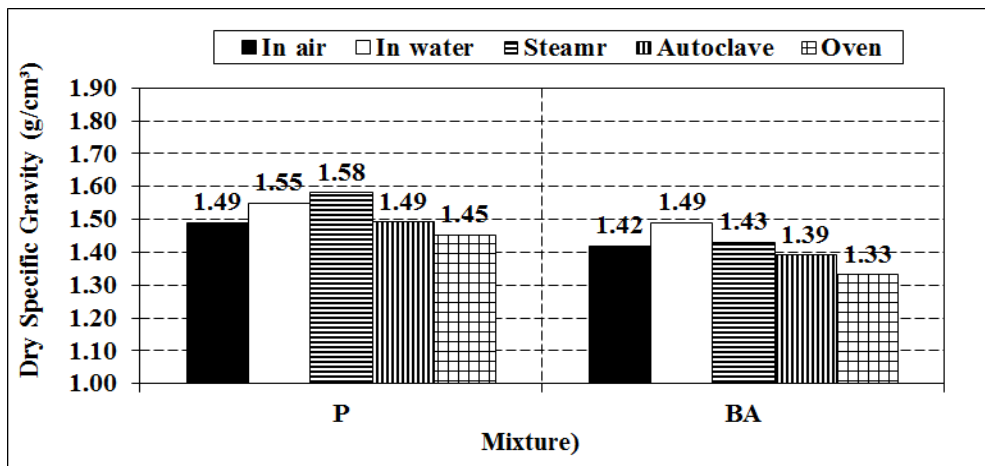


Figure 5. Dry specific gravity of mixtures after different curing regimes

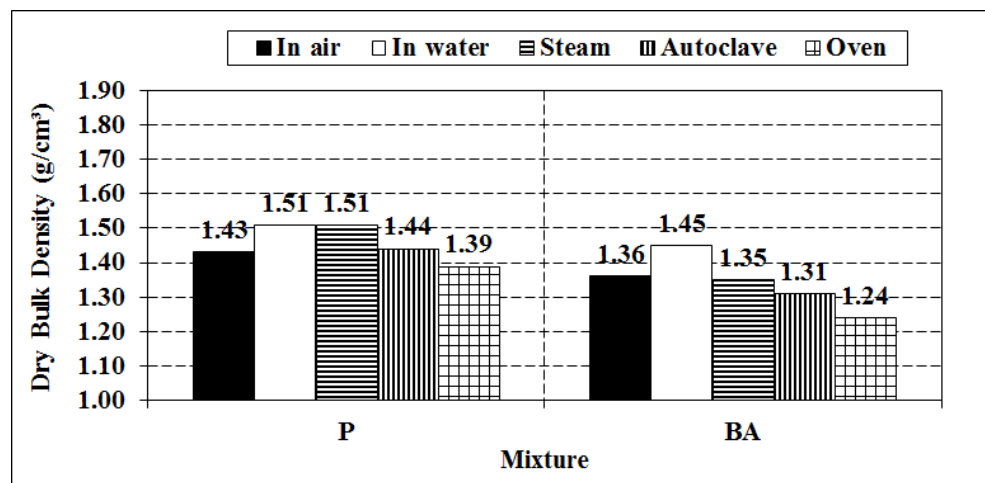


Figure 6. Dry bulk density of mixtures after different curing regimes

Capillary suction of mixtures after different curing regimes was given in Fig. 7. As can be seen from Fig.7, autoclave and water curing conditions are more effective in terms of lower capillary suction of both P and BA mixtures, while curing in oven increased the water capillary suction significantly.

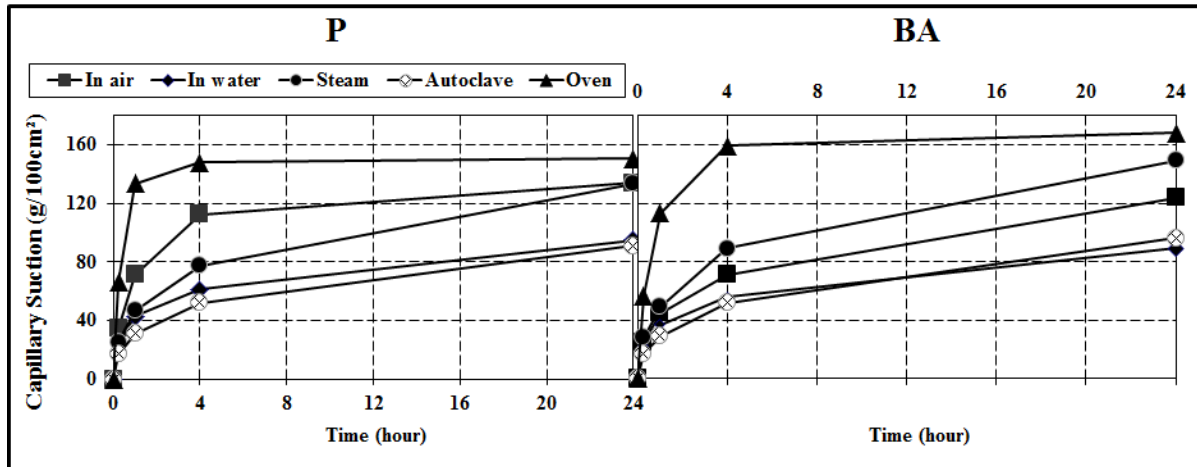


Figure 7. Capillary suction of mixtures after different curing regimes

Thermal conductivity of the autoclaved mixtures is presented in Table 5. Thermal conductivity measurement was performed immediately after autoclave curing. It can be seen that Thermal conductivity value of BA mixture is lower than P mixture. However, the thermal conductivity of both mixtures is much more less than traditional cement based mortar or concrete and can be compared with burnt clay bricks.

Table 5: Thermal conductivity of the autoclaved mixtures

Mixture	$\lambda$ , W/m.K
P	0.844
BA	0.679

### 3.3 Durability in water

One of the main problems of the BA mixture is its poor water resistance. This situation can be attributed to the expansive reaction of free CaO of BA, and relatively its high carbon content. In order to improve the dimensional stability of the mixtures, BA replacement level is limited to the 50% by weight. To determine the water resistance of these mixtures, expansion or shrinkage of mixtures kept in water or in air were measured with 25x25x285 mm mortar bar specimens. It must be noted that the mortar bars were kept in water or air after their curing periods. Fig. 8 shows expansions/shrinkage of the mixtures within time. It can be seen from the Fig. 8, the mortar bars kept in water showed expansion behavior, while the specimens that were kept in air generally showed shrinkage behavior. As shown in Fig. 8 there is no significant difference between expansion of P and BA mixtures in water. This behavior is valid in all curing conditions. In the case of steam, oven, and autoclave curing, shrinkage value of both P and BA mixtures are approximately similar after 35 days, while



higher measured shrinkage for P mixture is (0.14 %) as compared to the BA mixture (0.082 %) in air curing. The lowest shrinkage value (less than 0.03 %) was measured for specimens subjected to autoclave curing. Low shrinkage or expansion and crack free appearances in air and water exposure encompass pretty positive results. These results showed that the dimensional stabilities of these mixtures are sufficient and can be compared with the conventional cement based mortars.

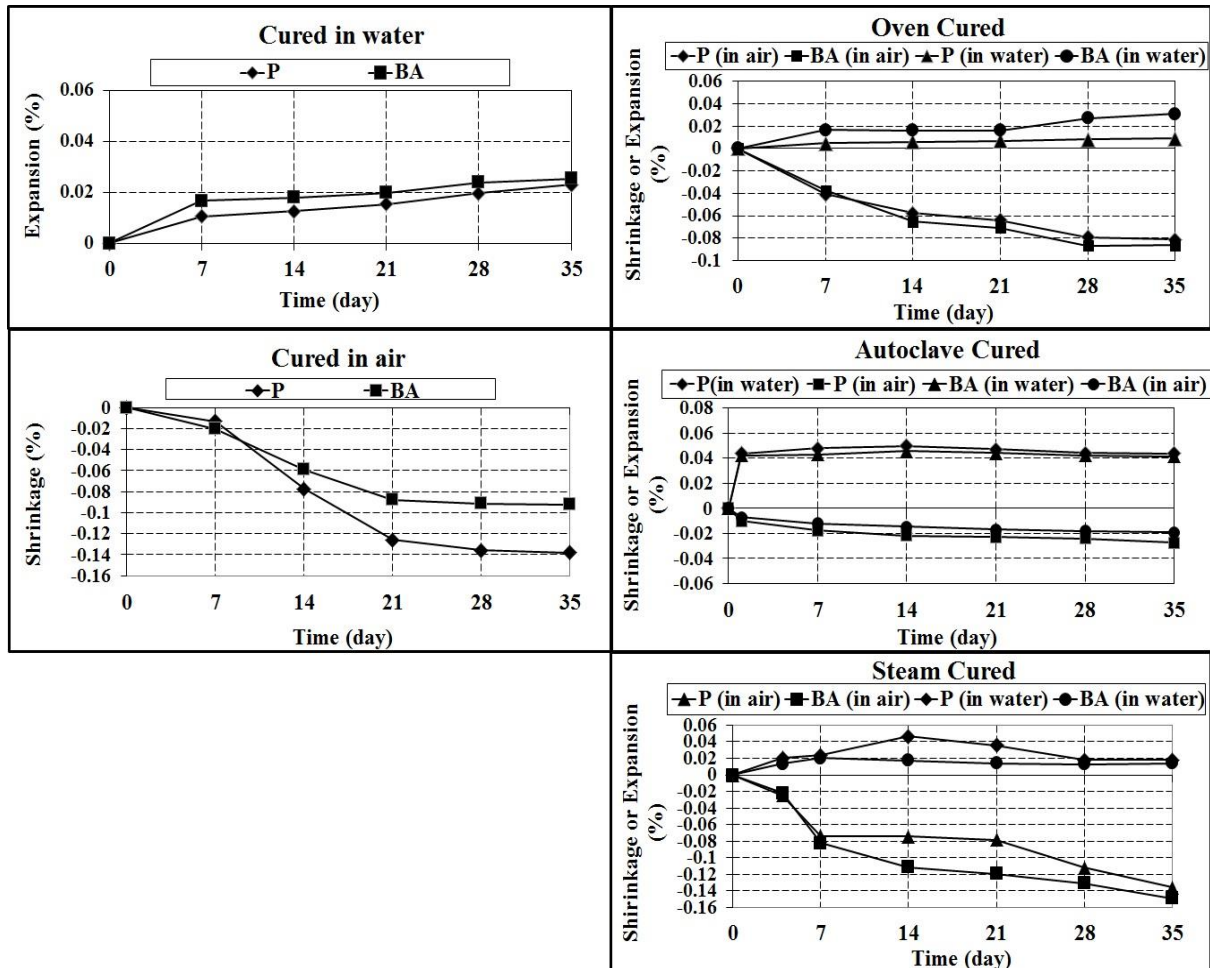


Figure 8. Shrinkage or expansion values of mixtures after different curing regimes

### 3.4 Microstructure of the mixtures

Microstructural investigations were carried out by using JEO-FEG-SEM-INCA/EDS electron microscope. The samples for SEM analysis were prepared by taking small pieces from the cube specimens, bottom ash, and pumice. Original microstructure and morphology of the hydrated mixtures were observed on fractured surfaces. Fractured small samples were mounted on the SEM stubs by using carbon paint. After that, samples were coated with carbon. The SEM study was carried out by using an accelerating voltage of 20 kV. Furthermore, polished section specimens were analyzed by BSE mode.

Fig. 9 shows the SEM images of the pumice aggregate. The porous structures of pumice

can be seen from figures. The EDS analysis showed that the main structure of pumice includes Si, Al, and K elements. This finding is in accordance with the chemical composition analysis results (Table 1). As can be seen from Figs. 10 and 11, the SEM study and the EDS analysis revealed that the bottom ash aggregate has a multiphase and porous structure. The EDS analyses of three phases of polished section specimens of bottom ash which their colors (grey, white, and black) are in high contrast with each other are presented in Fig. 11. The grey phase consists of Si (51%), Al (10 %), and C (14 %) elements. The white phase includes Fe (61 %) and Ca (20.5 %) elements while the black phase contains high C (90 %) element. It must be noted that the EDS analysis of the polished section specimens of bottom ash revealed that C element concentration is considerably in a high (56 %) level. The other main elements are Si (14%), Al (7 %), Ca (6 %), and Fe (4%).

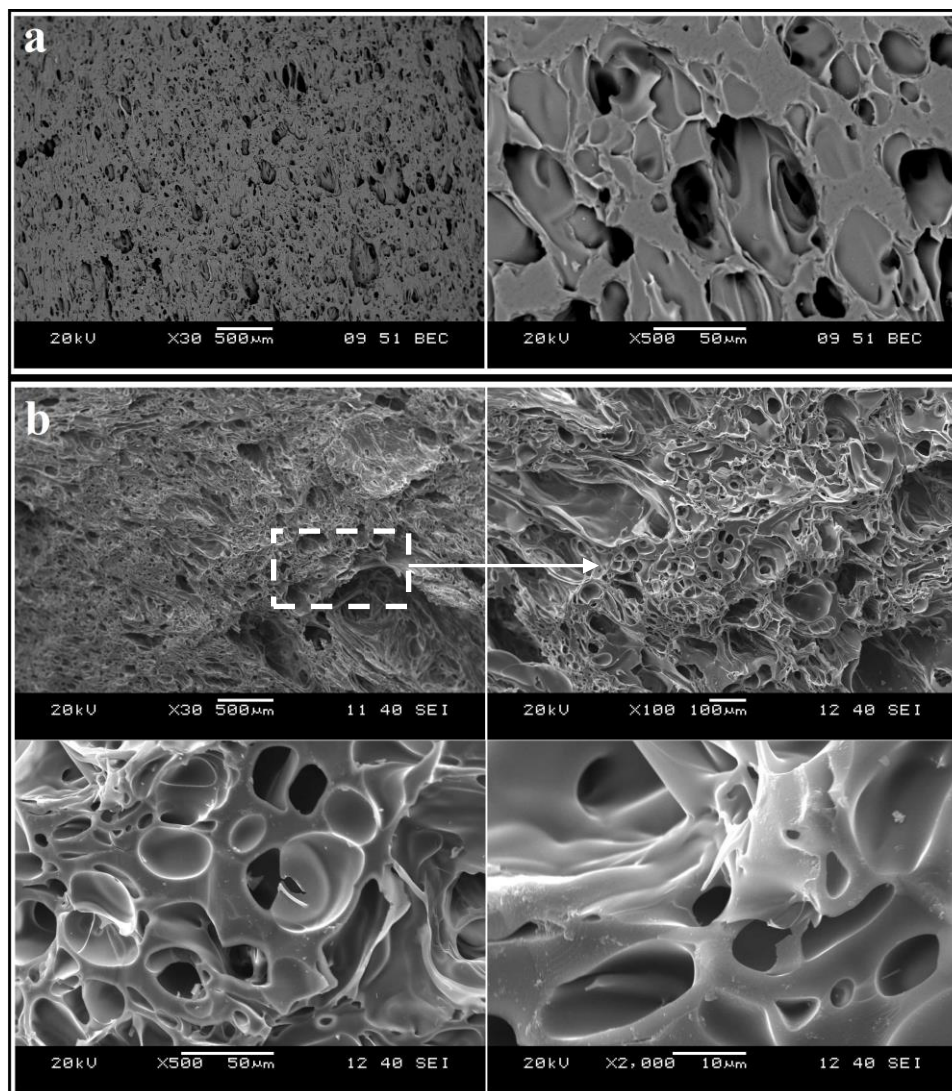


Figure 9. SEM images of the pumice a) polished section b) fractured surface

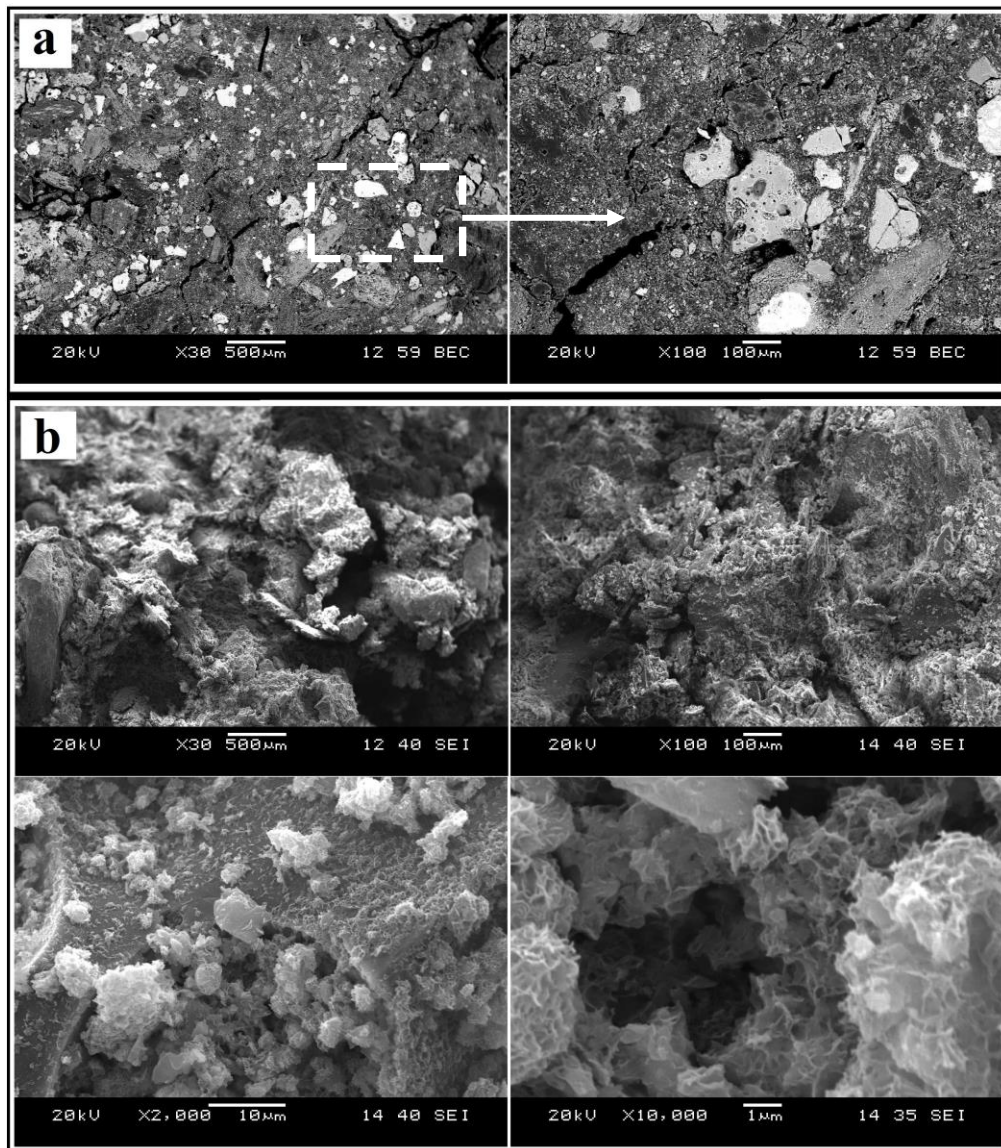


Figure 10. SEM images of the bottom ash a) polished section b) fractured surface

In order to give an opinion about the pore structure of the pumice and bottom ash, polished section specimens were prepared. The pores of polished section specimens of pumice were filled by silica fume and the bottom ash ones with quartz aggregate powder. Some images were obtained by an optical digital microscope. The images were analyzed by image processing software (ImageJ) (Fig. 12). The pumice aggregate includes 20-25 % pores which separated with each other, while the bottom ash consists of 25-30 % inhomogeneous pores (mostly connected with each other).



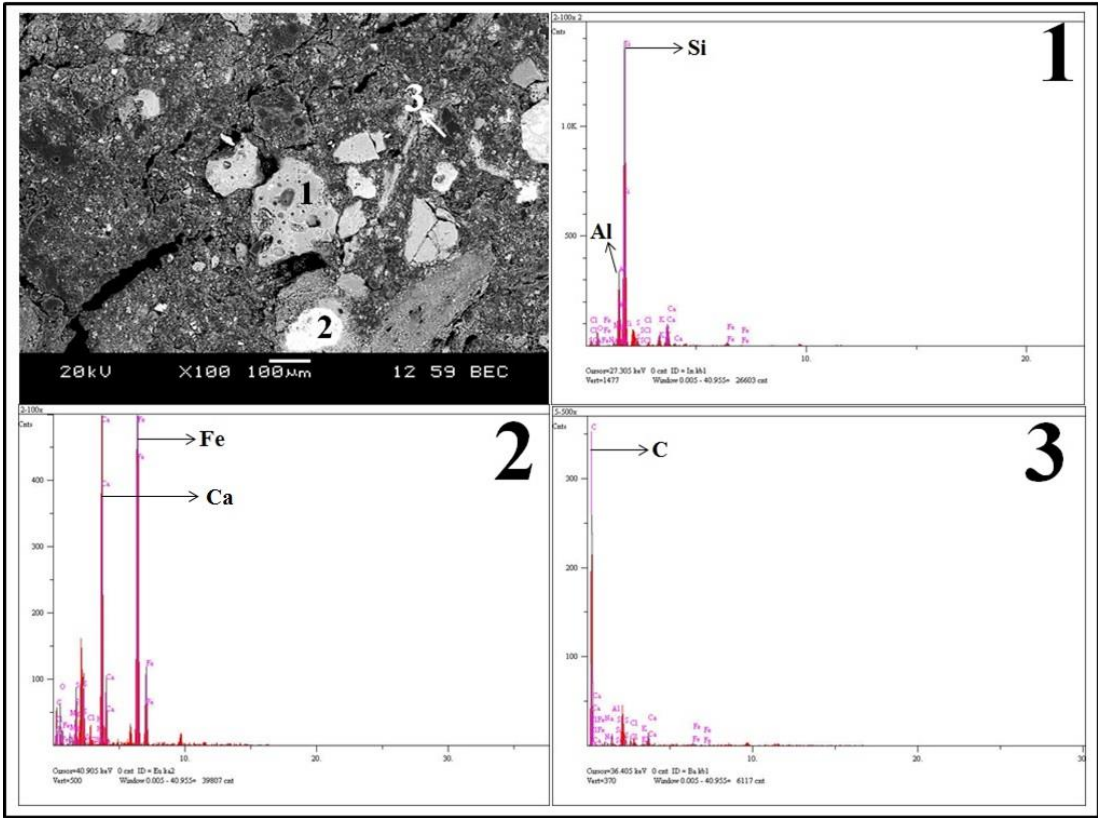


Figure 11. EDS analysis of bottom ash (Polished section specimen)

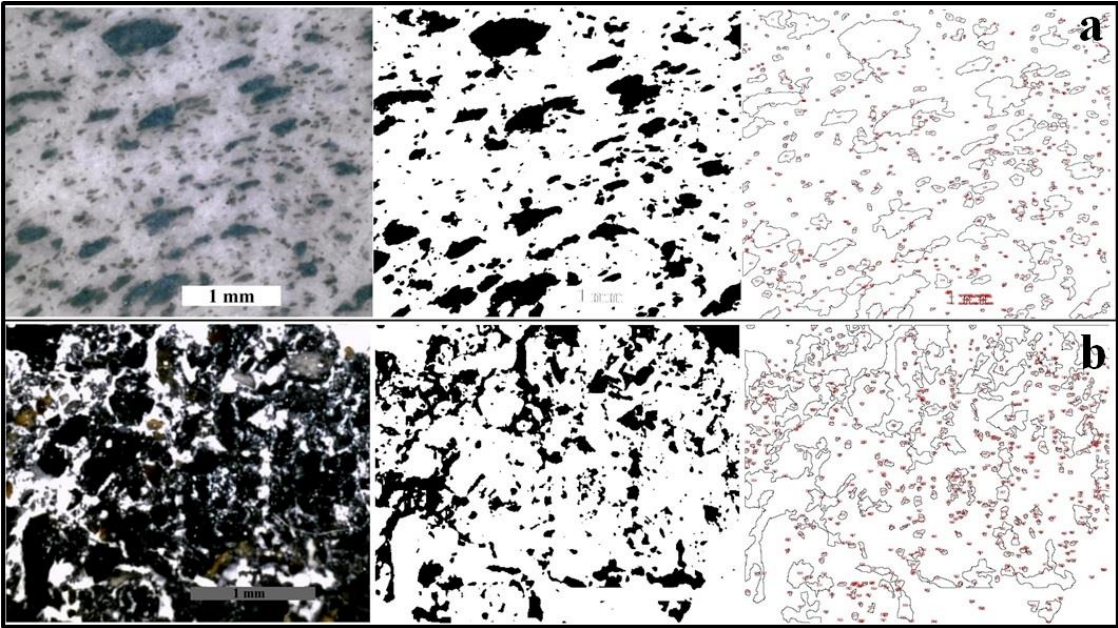


Figure 12. Image analysis (Porosity) of a) pumice b) bottom ash

Pores structure of pumice and bottom ash increased the porosity of mixtures and decreased bulk density compared to the conventional cement mortar (Figs. 13, 14). Porosity measurements are in accordance with SEM study.

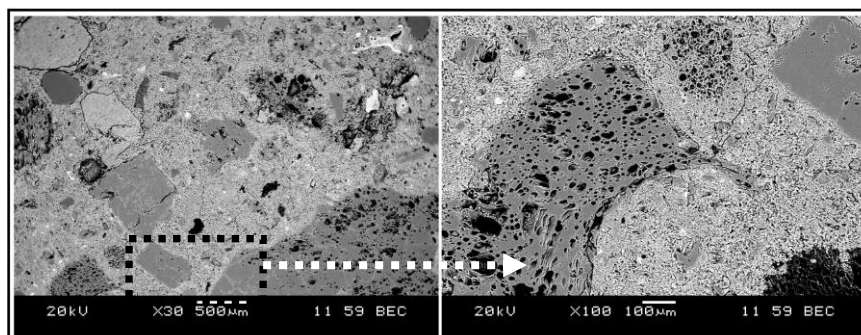


Figure 13. SEM image of polished section specimen of the BA mixture (BSE mode)

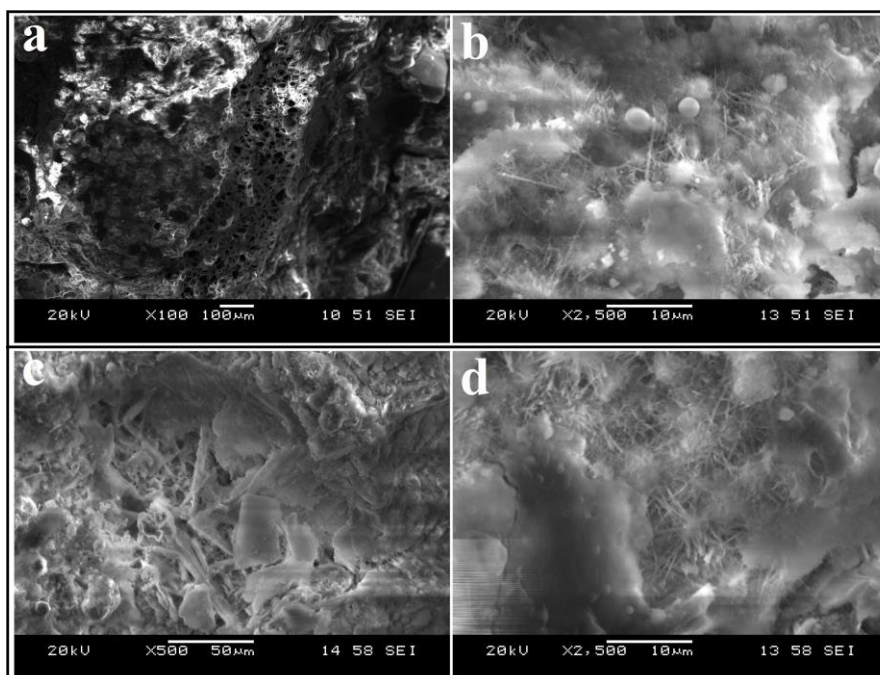


Figure 14. SEM images of P (control mixture, a, b) and BA mixture (c, d) after standard water curing

SEM study and EDS analysis showed that main binder structure consists of C-S-H (calcium-silicate-hydrate) in both mixtures. Calcium hydrate which is mainly produced by cement hydration is also detected (Fig. 15). In addition, the Ca/SiO<sub>2</sub> ratio of C-S-H phase of mixtures was decreased during autoclave curing. It is well known that the existence of SiO<sub>2</sub> sources, and high cement dosage lead to the formation of calcium silicate hydrate (C-S-H) phases with low Ca/SiO<sub>2</sub> ratio in autoclave curing [31-35]. Both P and BA mixtures include high volume (50%) fly ash which approximately consists of 50% SiO<sub>2</sub>.



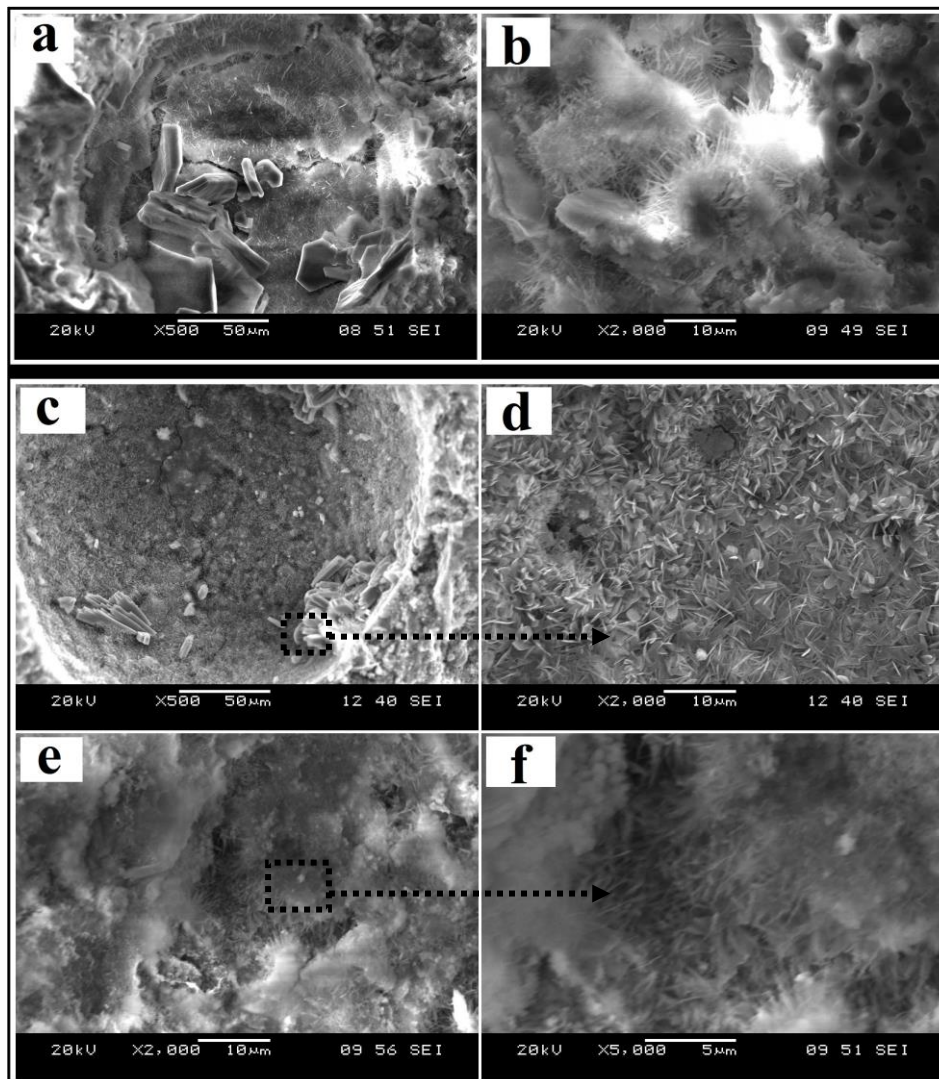


Figure 15. SEM images of P (control mixture, a, b) and BA mixture (c, d, e, f) after autoclave curing

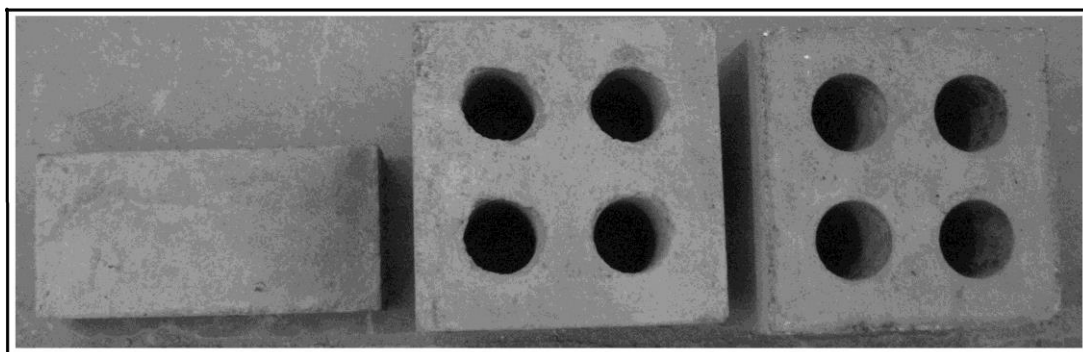


Figure 16. Photograph of hollow block and block specimens

### 3.5 Prototype building blocks

Prototypes of building blocks were prepared by using P and BA mixtures (Fig. 13). To produce hollow blocks, standard cube (150 mm) molds were modified. Four 36x39x135 mm conic steel poles were connected to moulds for producing hollows. Thus, hollow blocks with the cross section of 150x150 mm and 135 mm height were fabricated. Furthermore, 90x190x50 mm solid block elements without hollows have also been produced. Bulk density and compressive strength of these blocks at 90 days are presented in Table 6. It can be seen from Table 6 that bulk density of the blocks has been reduced approximately 350 kg/m<sup>3</sup> by creation of hallows. Prismatic solid blocks (without hollows) exhibited greater compressive strength values than hollow blocks as expected. Besides hollows, this result is due to the smaller height of it, which increases the restraining effects of the platens of the testing machine. And also, loading parallel to the hollows provided higher compressive strength values than loading perpendicular to the hollows. Compressive strength of building blocks produced from BA mix is approximately 25 % less than P mixture one. This result can be explained by higher porosity of bottom ash particles compared to the pumice. Test results indicated that both mixtures are suitable for the production of lightweight building blocks with or without hollows.

Table 6: Properties of building blocks

	<b>P</b>		<b>BA</b>	
	Block	Hollow block	Block	Hollow block
Bulk density (kg/m <sup>3</sup> )	1641	1258	1507	1190
Compressive strength (MPa)	Loading		Loading	
	// to hollows	⊥ to hollows	// to hollows	⊥ to hollows
	30.9	11.4      17.5	22.3	9.8      13.7

## 4. CONCLUSIONS

Applying the bottom ash (BA) and the fly ash in the production of lightweight building blocks were investigated in this study. Pumice aggregate was replaced by bottom ash in high volume. Fly ash was also replaced with cement in high volume. Test results indicated that;

- BA replacement level must be limited due to dimensional stability problem which was observed especially over 50% of BA replacement ratios in standard water curing.
- There is no significant difference in compressive strength of 50% BA containing and 100% pumice containing mixtures. Furthermore, autoclave curing is the most effective curing method among the others from the point of early and ultimate compressive strength development.
- Porosity of BA mixture is slightly higher than pumice mixture. Both dry bulk density and specific gravity of BA mixture are lower than P mixture due to lower unit of weight and porous structure of bottom ash. Therefore, BA mixture is suitable to produce lightweight elements

- Thermal conductivity value of BA mixture is lower than P mixture. The results of both mixtures are lower than the conventional cement mortar and in turn comparable with burn clay bricks.

- Porous structure of P and BA particles which was observed in microstructural investigation leads to an increase in the porosity of mixtures.

- Compressive strength of building blocks produced from BA mix is approximately 25 % less than P one. However, utilization of bottom ash (BA) and fly ash are definitely suitable for the production of lightweight building blocks.

These mixtures are very environment-friendly due to the utilization of solid wastes in high volume and lack of burn process compared to the clay bricks.

**Acknowledgement:** The authors would like to thank to Fatmanur Doğan for her assistance in experimental program..

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