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THE EFFECT OF USING A HIGH PROPORTION OF WASTE BOTTOM ASH INSTEAD OF SAND ON THE MECHANICAL PROPERTIES OF MORTARS

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ABSTRACT

Waste bottom ash (WBA) disposal requires large landfill areas and poses significant environmental risks due to possible leaching. Therefore, using WBA as sand replacement in mortar production is a sustainable alternative to reduce these environmental concerns. This study investigated the effects of high WBA substitution rates on the mechanical properties of mortars, including ultrasonic pulse velocity (V), flexural strength (f_f), and compressive strength (f_c), at different substitution levels (0%, 15%, 25%, 35%, 50%, 70%, and 100%) and specimen ages (28, 60 and 90 days). The study results showed that V, f_f, and f_c values decreased as the WBA substitution rate increased. However, up to a substitution level of 35%, the decrease in mechanical properties remained minimal, and this substitution level was considered applicable to the practices. Moreover, 30-35 MPa strength was obtained at 70% and 100% WBA replacement ratios. Therefore, these strength values are very close to the strength level expected from normal concrete. This study highlights that despite the variation in mortar strength, WBA can serve as an economical and environmentally friendly alternative to sand and reduce the environmental impacts of natural sand mining and landfilling.

Keywords: Waste bottom ash, Mortar, Ultrasonic pulse velocity, Compressive strength, Flexural strength.

1 INTRODUCTION

Disposing of industrial waste materials such as fly ash, slag, and waste bottom ash (WBA) [1] is a significant environmental problem. Landfill sites with large areas are needed for the disposal of such wastes. In addition, leaks that may arise from the storage of these wastes may cause various pollutants to enter groundwater. As is known, the amount of waste generated constantly increases with industrialization. Therefore, using waste as raw material in other industrial production is necessary for sustainable, environmentally friendly production.

To reduce the cost and carbon footprint of concrete/mortar production, studies have been carried out on WBA substitution instead of cement [2-14]/fine material (sand) [15-20] and WBA-blended cement production [21,22]. The fine material used in concrete/mortar production is an essential mineral resource. Therefore, using WBA instead of sand in concrete/mortar production will reduce sand consumption and protect natural resources. WBAs include substances such as CaO (%1-9.5), MgO (%0.35-2.45), SiO_2 (%45-69), Al_2O_3 (%16-19), Fe_2O_3 (%6-19), Na_2O (%0.08-2.43), K_2O (%0.33-5.3), TiO_2 (%0.84-3.27), P_2O_5 (%0.01-1) and SO_3 (%0.01-1.39) [23-25].

Yüksel et al. (2007) [17] investigated the effect of using bottom ash (BA) and granulated blast-furnace slag (GBFS) as fine aggregate in concrete on durability. GBFS, BA, and GBFS+BA were used at rates of 10%, 20%, 30%, 40%, and 50% instead of aggregate with a grain size of 3–7 mm, and it was found that GBFS and BA improved the durability properties of concrete such as high temperature and surface abrasion. Hashemi et al. (2018) [18] investigated the effect of coal bottom ash as sand replacement in mortars on microstructure and mechanical properties. It was observed that the compressive strength improved up to 40% replacement but decreased at higher replacement ratios. Günay et al. (2024) [15] expressed that chemical additives can achieve workability by using a maximum of 25% waste bottom ash instead of sand. In addition, it was determined that the compressive strength did not decrease significantly. Sharma et al. (2021) [19] stated that concrete blocks are suitable for manufacturing when replacing sand with 30% bottom ash. Singh and Siddique (2016) [20] represented that bottom ash can be used in concrete mixtures in certain proportions instead of sand. It was revealed that using 50% bottom ash instead of sand would be appropriate by using a superplasticizer in concrete production.

In the literature, using WBA instead of sand remains at a maximum rate of 50% [20]. To reduce the consumption of sand, an essential mineral, the rate of WBA use should be increased. The use of WBA instead of sand primarily causes workability problems. The workability problem can be solved by adding water to the mixture in addition to chemical additives. However, the negative effects of water addition on strength should be determined. Therefore, the effect of using high rates of WBA instead of sand on strength was investigated in the study. In addition to the WBA displacement rate, the specimen's age was also considered. The study aims to reveal the usability of waste bottom ashes instead of fine aggregate (sand) in concrete/mortar production and the potential to be converted into an economic input. Therefore, workability, ultrasonic pulse velocity, compressive and flexural strengths were investigated.

2 MATERIALS AND METHODS

2.1 Materials

Portland cement (PC) (CEM I 42.5 R), CEN standard sand (SS), 2 mm under-sieve waste bottom ash (WBA), distilled water (W), and chemical additives were used in the production of mortar samples. PC and SS comply with TS EN 197-1 [26] and TS EN 196-1 [27] standards, respectively. The chemical analysis and physical properties of PC and WBA are given in Table 1 [14]. Granulometry curves of WBA and SS are shown in Figure 1 [14]. The size of waste bottom ash grains varies from 2.000 mm to 0.075 mm. The strength activity index (specimen age; 28 days) of 75 µm under-sieve WBA is 79.8% [14], and it meets the boundary condition (%79.8 > %75 [28]). A liquid high-performance superplasticizer based on modified polycarboxylate polymer was used as the chemical additive.

Table 1. Chemical analysis and physical properties of cement and waste bottom ash [14].

Chemical Composition (by weight, %)	Portland cement	Waste bottom ash
SiO_2	19.535	41.05
CaO	64.342	8.80
Al_2O_3	4.605	17.21
Fe_2O_3	3.091	12.48
MgO	0.895	5.32
Alkali (Na_2O + 0.658 K_2O)	1.022	5.13
Cl^-	0.013	0.008
SO_3	3.365	1.96
Loss on ignition	2.548	7.59
Insoluble residue	0.285	0.45
Physical properties		
Initial setting (minutes)	123	123
Final setting (minutes)	123	123
Total expansion (mm)	123	123
Density (g/cm^3)	123	123
Specific surface (cm^2/g)	123	123
45 µm sieve residue (%)	123	123
90 µm sieve residue (%)	123	123

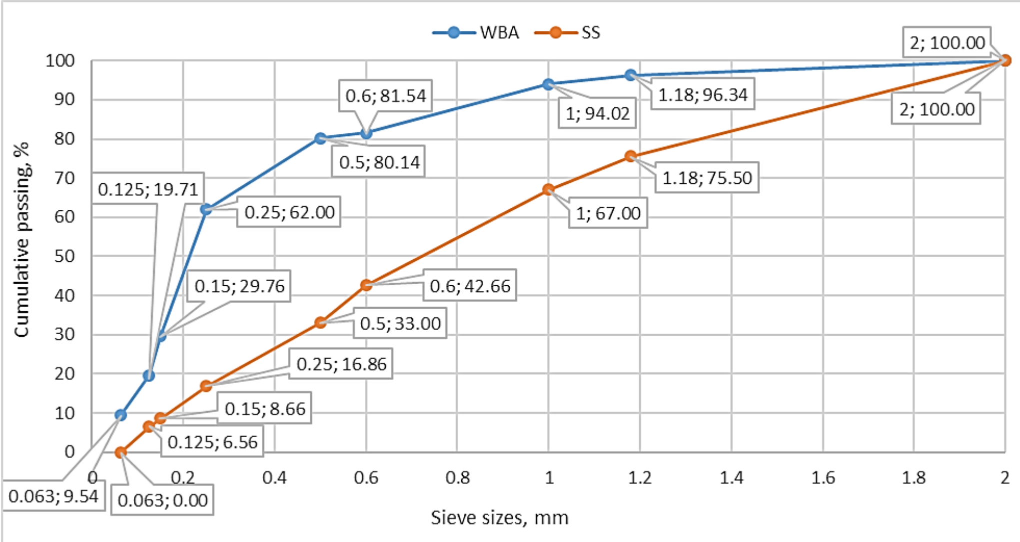

Figure 1. Granulometry curves of WBA and CEN standard sand [14].

The waste bottom ash's particle shape and surface texture properties were determined by scanning electron microscope (SEM) (Figure 2). As seen in Figure 2, WBA particles have an angular, rough, and porous structure.

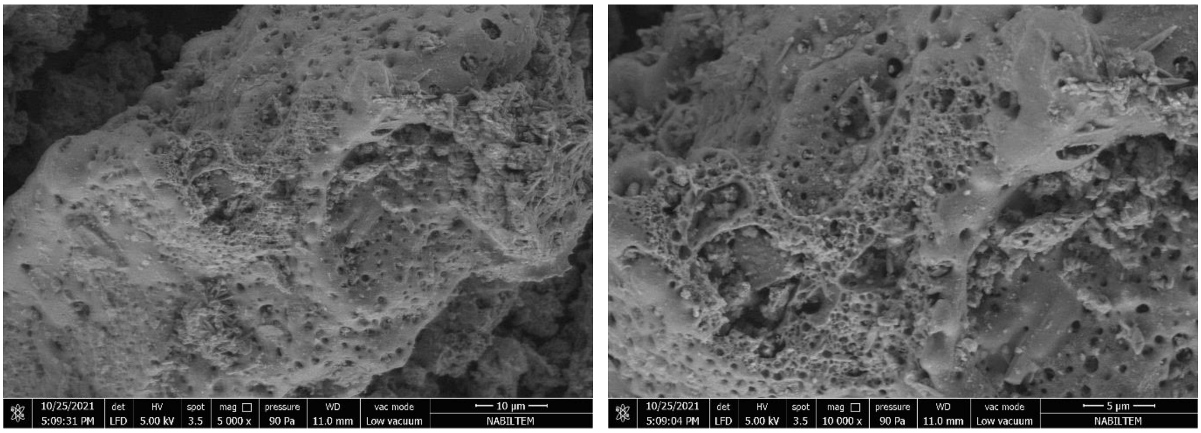

Figure 2. SEM images of waste bottom ash.

2.2 Methods

In the study, the effects of WBA replacement ratio (substitution of WBA by weight instead of SS) and specimen age on ultrasonic pulse velocity (V), flexural strength (f_f), and compressive strength (f_c) of mortars were investigated. The variation intervals were selected as 0%, 15%, 25%, 35%, 50%, 70%, and 100% for the WBA replacement ratio and 28, 60 and 90 days for specimen age. It is reported in the literature [29] that fc decreases gradually up to 50% WBA substitution ratio. However, the level of decrease in f_c at higher WBA substitution rates has not been demonstrated. Therefore, the increase was kept at about 10% to demonstrate the gradual decrease in f_c up to 50% WBA substitution rate. If the WBA substitution rate is between 50% and 100%, the increase was preferred to be 20% to 30% to reduce the number of experiments since the final target is 100%. Production was carried out at $3 \cdot 7 = 21$ trial points in total, with seven trial points for each specimen age. The experimental results were obtained as the average of tests conducted on six 40×40×160 mm prismatic specimens. Consequently, a total of 126 specimens were produced for the study.

Since the particle shape properties of WBA and SS are different, the desired workability (flow-table value) cannot be provided by using only superplasticizers at high WBA replacement ratios. Previous studies have indicated that, in mortars where WBA was used instead of SS, the desired workability could be achieved using chemical additives at approximately 25% WBA replacement ratio [18]. Therefore, the desired workability in the study was provided by adding chemical additives and additional water to the mixture. The extra water amount was selected to make the W/(PC+k·WBA) ratio 50%. The k-value increases as the WBA replacement ratio rises. However, the k-value is the same at 70% and 100% WBA replacement ratio (0.6). This shows that the effect level of SS on workability is minimal when the WBA replacement ratio is above 70%. The constituent materials of the mortar specimens produced depending on the WBA replacement ratio are given in Table 2.

Table 2. Constituent materials.

WBA replacement ratio (%)	PC (g)	SS (g)	W (g)	WBA (g)	Superplasticizer (by weight of PC+k·WBA) (%)	k -	W/(PC+k·WBA) (%)
0	900	2700	450	0	0	0.00	
15	900	2295	501	405	1.08	0.25	
25	900	2025	568	675	1.37	0.35	
35	900	1755	639	945	1.44	0.40	50
50	900	1350	787.5	1350	1.61	0.50	
70	900	810	1017	1890	1.28	0.60	
100	900	0	1260	2700	1.86	0.60	

Note: *Constituent materials are given for six specimens with dimensions of 40×40×160 mm.*

Mortar specimens were produced according to the TS EN 196-1 standard [27]. Workability (flow-table test), ultrasonic pulse velocity, flexural, and compressive tests were carried out according to TS EN 1015-3 [30], TS EN 12504-4 [31], and TS EN 196-1 [27], respectively. In addition, the internal structure of the specimens with WBA replacement ratios of 0%, 25%, 50%, and 100% was determined by scanning electron microscope (SEM).

3 RESULTS AND DISCUSSION

3.1 Mechanical Properties

The results obtained at the test points are given in Table 3. The flow-table values of the mortar specimens vary between 11.9-17.3 cm. Workability could be achieved with a superplasticizer and additional water as the WBA replacement ratio increases. The WBA grains' shape properties (porous structure) are the most crucial reason for decreased flow-table value [32]. In literature, 100% sand was replaced with CBA, resulting in up to 34% reduction in the flowability of mortar [29,33]. As the WBA replacement ratio increases, workability can be achieved with superplasticizer and additional water.

Table 3. Run points and experimental results.

Run point	WBA replacement ratio (%)	Specimen age (day)	Flow-table value (cm)	V (km/s)	f_f (MPa)	f_c (MPa)
1	0	28	17.0	4.505	7.84	48.70
2	15	28	13.9	4.242	7.70	53.31
3	25	28	13.5	4.101	6.85	49.66
4	35	28	12.4	3.954	6.80	46.38
5	50	28	12.8	3.749	6.03	42.76
6	70	28	13.9	3.468	4.54	34.95
7	100	28	13.8	3.261	3.38	33.41
8	0	60	17.0	4.567	7.22	54.53
9	15	60	14.3	4.269	7.88	53.33
10	25	60	13.3	4.118	7.74	54.83
11	35	60	11.9	3.959	7.34	50.23
12	50	60	12.4	3.750	5.84	40.19
13	70	60	13.4	3.477	4.29	32.07
14	100	60	14.3	3.251	3.80	31.49
15	0	90	17.3	4.539	7.18	58.51
16	15	90	14.2	4.244	8.65	60.54
17	25	90	13.8	4.068	8.00	58.47
18	35	90	12.5	3.935	6.80	54.13
19	50	90	12.3	3.762	6.87	40.48
20	70	90	13.5	3.492	5.92	31.64
21	100	90	13.0	3.289	4.80	33.39

Figures 3, 4, and 5 show the variations of V, f_f, and f_c, respectively, depending on the WBA replacement ratio. Moreover, the graphs give the k-values determined experimentally depending on the WBA replacement ratio.

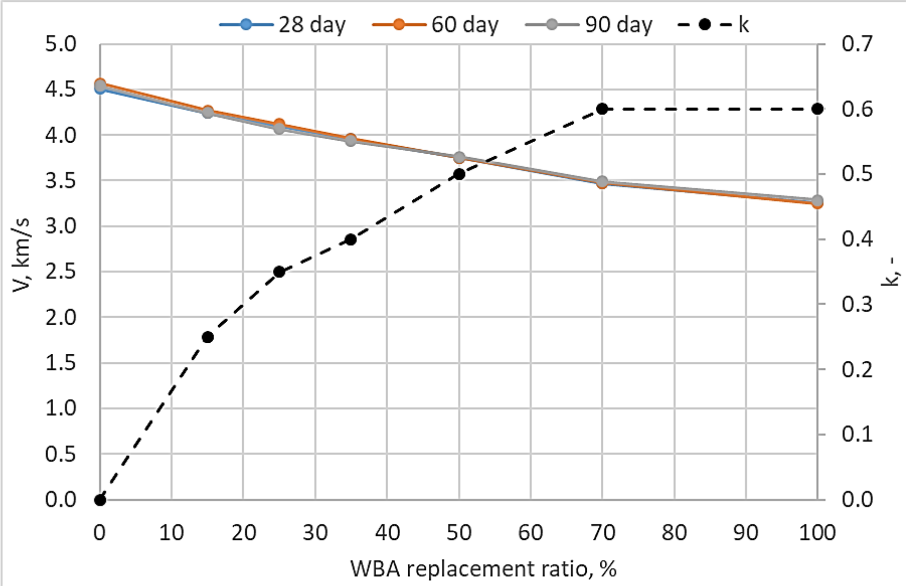

Figure 3. Experimental results for V.

Figure 3 shows that V decreases across all specimen ages as the WBA replacement ratio increases. In addition, specimen age didn't create a variation in V. The decrease in V is proportional to the increase of the voids at the specimens. Since the water requirement for workability increases with the rise in WBA, the void content in the specimens also rises, explaining the reduction in V.

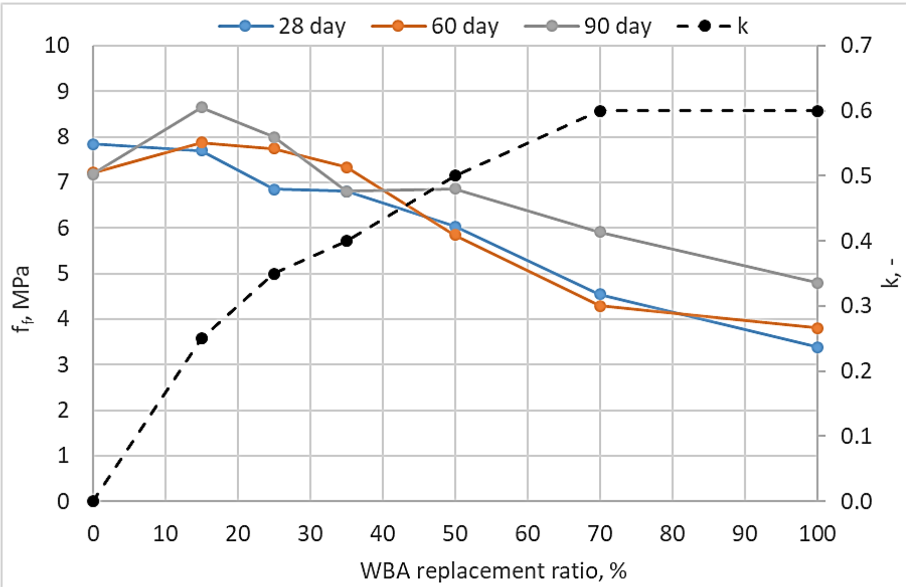

Figure 4. Experimental results for f_f.

The literature states that f_f increases up to a 20% displacement rate and decreases at higher displacement rates [34]. However, in Figure 4, when the WBA replacement ratio is increased up to 35%, it is seen that f_f changes in the range of 7-8 MPa. However, when the increase in the WBA replacement ratio exceeds 35%, f_f decreases. This decrease is higher in 28 and 60-day specimens than in 90-day specimens. Since the amount of < 63 μm grains in the mixture increases with the rise in WBA addition, it can be said that the pozzolanic properties of the WBA are more effective on the f_f at high specimen ages. The WBA replacement ratio of up to 40% didn't cause a significant variation in the f_f value at all specimen ages.

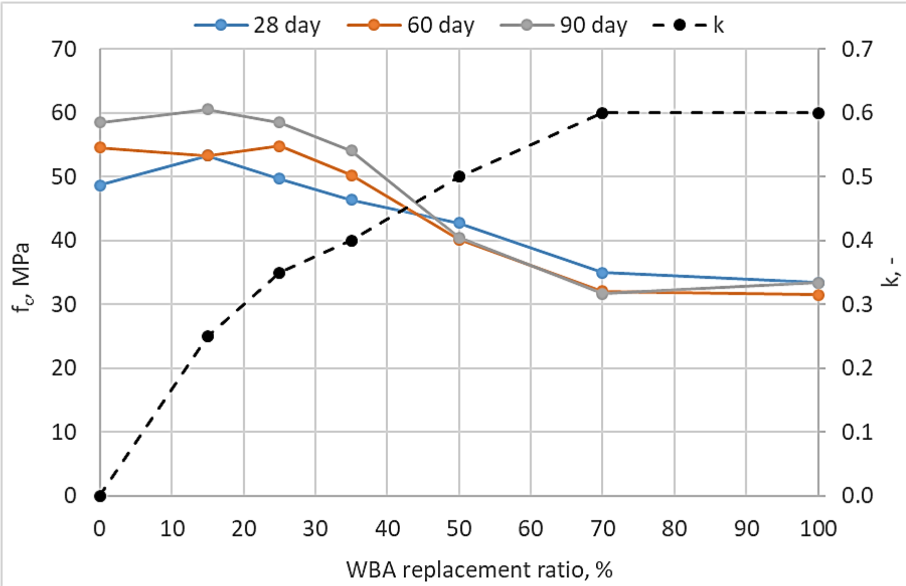

Figure 5. Experimental results for f_c

In Figure 5, it is generally seen that f_c decreases as the WBA replacement ratio increases. Torkittikul et al. stated that f_c values gradually decreased to 50% WBA replacement ratio [29]. However, other studies reported that f_c decreased systematically in the 20% to 40% WBA substitution ratio [18,34-36]. This study showed no significant change in f_c at all specimen ages up to 35% WBA replacement ratio. WBA exhibits pozzolanic properties because it contains a high amount of silica (SiO_2). Pozzolanic reactions occur when the active silica in the pozzolan reacts with water and portlandith (cement hydrates compound, $Ca(OH)_2$) to form new, stronger compounds. However, these reactions take a certain period and do not affect early-age strength but contribute to late-age strength. Therefore, f_c increased with increasing sample age, and the maximum f_c was obtained in 90-day specimens. Specimen age didn't affect f_c at values above 35% of the WBA replacement ratio. Other studies reported that f_c decreased systematically in the 20% to 40% WBA substitution ratio. However, this rate was 35% in this study. It is seen that there is no decrease in f_c in the range of 70%-100% of the WBA replacement ratio. Although the k-value is constant (0.6) in this range, the amount of water increases by 243 g due to the increased WBA in the mixture. The fact that f_c does not decrease due to the increase in the amount of water in the mix can be explained as the pozzolanic effect of WBA [18] contributing to the strength with increasing under 63 μm sieve material in the blend due to the high WBA content. In 28, 60, and 90-day specimens, f_c decreases by 4.76%, 7.89%, and 7.49% at a 35% WBA replacement ratio. However, at a 100% WBA replacement ratio, f_c decreases by 31.40%, 42.25%, and 44.85%, respectively. Using high WBA, the decrease in f_c can be minimized using different chemical additives and ratios. The high decrease rate in f_c at high specimen ages (60 and 90 days) is due to the high f_c value at low WBA replacement ratios. The high f_c at low WBA replacement ratios can be explained by the reduction of the voids formed due to the low water content in the mixture with the filler effect of WBA, i.e. the formation of a more compact structure and the pozzolanic effect of WBA.

3.2 Microstructure

The microstructures were determined by SEM analysis on 90-day samples with 0%, 25%, 50%, and 100% WBA replacement ratios. Figure 6 shows SEM images for 0%, 25%, 50%, and 100% WBA replacement ratios.

It is observed that a compact internal structure is formed in the specimens with a 25% WBA replacement ratio (Figure 6 (b)). Despite the increasing amount of water depending on the WBA replacement ratio, the filler effect of the fine material coming from the WBA and the pozzolanic reactions depending on the age of the specimen cause the formation of a compact internal structure compared to the specimens with a 0% WBA replacement ratio. This explains the small increases in f_c up to 25% WBA replacement.

When a high WBA replacement ratio is used (≥ 40%), due to the porous structure of WBA, the pore size in the paste increases to approximately 100 μm [18]. Also, at 100% WBA replacement ratios, the permeable pore size increases by approximately 37% compared to 0% WBA mixtures [29]. At high WBA replacement ratios, in addition to the voids formed due to WBA's porous and irregular shape, the high amount of water used for workability also increases the pore amount in the mortar. Therefore, a porous internal structure is observed in specimens with a 100% WBA replacement ratio as in Figure 6 (d). In addition, when Figure 6 (d) is examined, it is observed that cracks form in the internal structure. Both the high pore amount and crack formations explain the high decrease in strength.

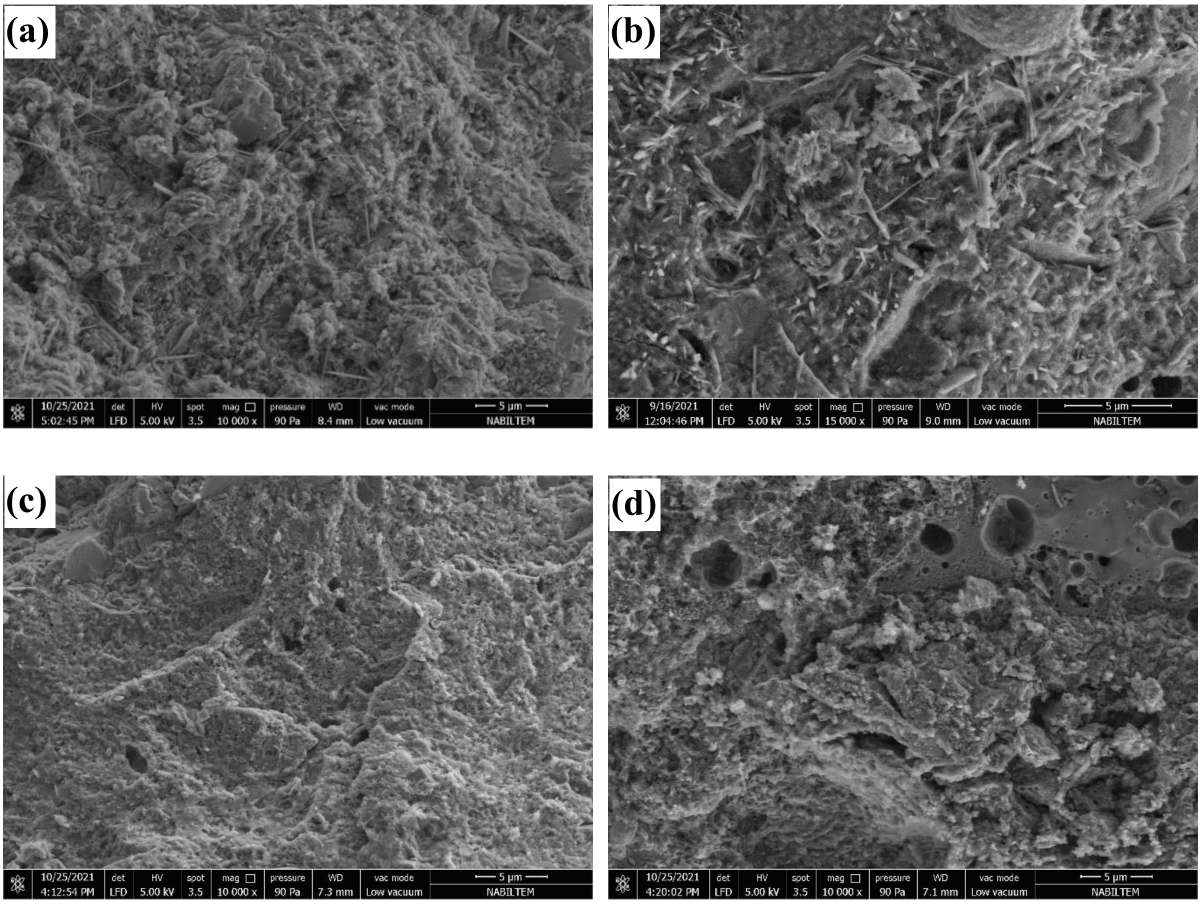

Figure 6. (a) SEM images for WBA replacement ratios; (a) %0, (b) %25, (c) %50, and (d) %100.

4 CONCLUSION

In this study, the effects of waste bottom ash instead of standard sand on the mechanical properties of mortars were investigated at different specimen ages. The results obtained are given below.

According to the study results, compressive strength was obtained similarly to the reference specimen in samples with 15%, 25% and 35% WBA replacement ratios. Accordingly, it can be said that replacing SS with 35% WBA will not cause any strength loss. 30-35 MPa strength was obtained at 70% and 100% WBA replacement ratios. As it is known, there is a linear relationship between mortar and concrete strength [37]. Therefore, 30-35 MPa values are sufficient for the strength level expected from normal concretes. However, it should be noted that CEM I 42.5 R cement was used in this study. Given the environmental damage caused by sand quarrying and WBA waste disposal and considering potential durability issues related to porosity, the use of high WBA in concrete with 30-35 MPa strength could be considered.

The use of WBA in construction has environmental advantages, such as preserving natural sand resources, reducing waste and carbon footprints during sand extraction, and reducing reliance on landfills. Using WBA also provides economic benefits as it reduces waste management costs in the industries where it is produced and reduces the cost of sand in the applications where it is used. In addition, the usability of WBA in non-load-bearing structures and mortars encourages sustainable construction practices.

In conclusion, 25% - 35% WBA can be used instead of fine material (sand). In addition, low-strength structures or elements can be produced using high amounts of WBA. However, the negative effects of voids caused by the high-water content must also be considered. Therefore, the material's behavior under adverse environmental influences should also be examined in future studies.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

First and second authors: Conceptualization, Methodology, Validation, Formal Analysis, Writing- Original Draft Preparation, and Writing- Reviewing and Editing. All authors: Data curation, Visualization, and Investigation.

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