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EFFECT LEVELS OF REPLACEMENT RATIO AND SPECIMEN AGE ON THE MECHANICAL PROPERTIES OF MORTARS CONTAINING WASTE BOTTOM ASH

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Abstract

The coarse solid residue formed at the bottom of combustion boilers is called waste bottom ash (WBA). The most important difficulties that can arise when storing WBA are the potential for leaching of hazardous substances and the high space requirement. For these reasons, there is an urgent need to investigate alternative materials capable of substituting for sand, a natural mineral extensively used in concrete and mortar production. This study aimed to evaluate the feasibility of changing the amount of WBA in concrete and mortar formulations in order to reduce sand consumption in the construction industry and transform WBA into a valuable economic resource for the sector. For this purpose, bottom ash was taken from a landfill in Thrace, an industrially dense region. Effects of the variables of the replacement ratio (B) of WBA in mortar mixtures and the sample age (A) of the formed mortar on the ultrasonic pulse velocity (V), flexural strength (f_f), and compressive strength (f_c) of mortar were determined using analysis of variance (ANOVA), and models were created for V, f_f, and f_c. Notably, there was no decrease in the f_c value at 25% B, while an increase in the fc value was achieved at 15% B. The R^2 values for the models were 0.99, 0.92, and 0.95 for V, f_f, and f_c, respectively. The study concludes that WBA can effectively serve as a substitute for standard sand in mortar mixtures at specific ratios.

Key words: compressive strength, flexural strength, mortar, sand, waste bottom ash

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1. Introduction

Disposal of waste, including fly ash, slag, waste bottom ash (WBA) (Konak, 2018), and other by-products resulting from coal combustion, constitutes a significant environmental challenge. Typically, these materials are disposed of through landfilling, a practice that demands extensive land resources. Additionally, an important environmental problem associated with these materials is their potential to pollute groundwater. With increasing of industrialization, the amount of waste generated is always on rise. Therefore, use of wastes as a raw material in another industrial process is crucial for sustainability and environmentally friendly production.

The characteristics of WBA depend on the type of coal, combustion technology, and furnace type (Kaya, 2010). The temperature and combustion technology used during the combustion process affect the physical and chemical composition of the ash and can change the types and proportions of minerals present in the ash. Additionally, combustion conditions can also affect the reactivity of the resulting ash, thus determining the ability of the ash to react with cement or other materials (Vouk et al., 2018). The composition of WBA includes substances such as SiO_2 (%45-69), Al_2O_3 (%16-19), Fe_2O_3 (%6-19), CaO

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(%1-9.5), MgO (%0.35-2.45), 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) (Bhatt et al., 2019; Mohammed et al., 2021; Singh and Siddique, 2013). The specific gravity and loss of ignition (950 °C) of WBA are reported to be 1.47-2.78 (Prakash and Sridharan, 2009) and 0.61-12.8 (Prakash and Sridharan, 2009; Singh and Siddique, 2013), respectively.

In recent years, many studies have been conducted on the use of coal bottom ash as a substitute for cement or sand in mortar and concrete for various purposes, such as dam construction, highways, and other construction projects, owing to its cost-effectiveness and low density (Klangvijit and Sookramoon, 2018; Koçak, 2011; Pantiru et al., 2023; Ramzi et al., 2016). Many studies have shown that coal ash has advantageous properties such as low specific gravity, low compressibility, high consolidation ratio, high strength, high volume stability, and pozzolanic activity (Prakash and Sridharan, 2009). The main components of concrete and mortar are cement, sand, water, and aggregates. Many studies have been conducted on the use of WBA as a substitute for cement and the production of cement mixed with WBA to reduce costs and carbon footprint in concrete and mortar (Abdulmatin et al., 2018; Al Biajawi et al., 2022; Argiz et al., 2017, 2018; Ibrahim, 2019; Mangi et al., 2019a, 2019b, 2019c; Oruji et al., 2017; Pantiru et al., 2023; Velardo et al., 2023).

Sand is an important mineral resource used in concrete and mortar. Therefore, the use of WBA instead of sand in concrete and mortar can reduce sand consumption and contribute to the preservation of natural resources. There is a wide range of studies in which WBA has been utilized as a substitute for both cement and sand in the production of mortar and concrete. Yüksel et al. (2007) investigated the effect of using BA, granulated blast furnace slag (GBFS), and a combination of both as fine aggregates in concrete to the durability of the concrete. GBFS, BA, and GBFS+BA were used instead of 3-7 mm-sized aggregates at ratios of 10%, 20%, 30%, 40%, and 50%. The results of the study showed that GBFS and BA improved certain durability properties of concrete, such as high-temperature resistance and surface wear. Hashemi et al. (2018) examined the effect of using coal bottom ash (BA) as a fine aggregate substitute in mortar on microstructure and mechanical properties. The use of BA and silica sand at up to 40% of the total fine aggregate improved the compressive strength of the mortar. However, at higher replacement ratios, the compressive strength decreased due to the increased porosity of the mortar. Sharma et al. (2021) examined the feasibility of substituting bottom ash (BA) sourced from three distinct locations within coal-fired thermal power plants with sand, at proportions of 30%, 40%, and 50%, for the production of concrete blocks. The results indicated that the production of concrete blocks containing 30% bottom ash was suitable. Konak (2018) examined the effects of using bottom ash and granulated blast furnace slag instead of fine aggregate at rates of 0%, 25%, 50%, 75%, and 100% in concrete on the mechanical properties of concrete. Changes in elasticity modulus, stress-strain behavior, compressive strength, and toughness were investigated in concrete specimens. The study concluded that bottom ash and granulated blast furnace slag could be used as a replacement for fine aggregate in concrete. Singh and Siddique (2016) investigated the strength properties of concrete produced by replacing sand with coal bottom ash. Two different concrete strengths were used in the study, and bottom ash was used at ratios of 0%, 20%, 30%, 40%, 50%, 75%, and 100% to replace sand in the mixture for each concrete strength. The 90-day-old specimens containing bottom ash showed compressive and tensile strengths at the same level as the reference specimens. However, specimens containing bottom ash displayed lower elasticity modulus and reduced abrasion resistance. The study concluded that bottom ash can be used in certain ratios in concrete mixtures instead of sand, without using superplasticizer in concrete production, 30% replacement with bottom ash is suitable, while in structural concrete production, 50% replacement with bottom ash using superplasticizer is appropriate. Additionally, it was mentioned that coal bottom ash can be used instead of sand at 100% in concrete applications where workability is not an issue, such as paving blocks, hollow blocks, sidewalks, etc. Saleh et al. (2023) in their study, bottom ash was substituted for cement at 10%, 20% and 30% of the total weight of the mortar, while it was substituted for fine aggregate at 30%, 40% and 50% of the total weight of sand. In the results of the study, it was stated that when bottom ash was used as a cement substitute, the compressive strength of the mortar decreased as the amount of bottom ash increased, and when it was used instead of aggregate, the compressive strength increased. In another study, the effects of using bottom ash in construction materials on the performance of cement-based materials under various curing temperatures were investigated. The hydration reactivity of bottom ash was improved by increasing the grinding and curing temperature. According to the study results, finer CBA particles and higher curing temperature showed positive effects on improving the properties of cement materials (Guan et al., 2023). Li et al. (2022) in their study, mortar was obtained by using bottom ash instead of sand at three replacement rates of 10%, 20% and 30%. In the study, high-performance mortar containing bottom ash was tested for mechanical properties such as hardened density, compressive and flexural strength, resistance to NaOH solution and heavy metal leaching. The study showed that bottom ash can be used instead of sand in the development of high-performance mortar.

As seen in the studies, WBA was used as a replacement for fine materials, and the changes in selected properties were investigated based on the substitution rate. This study examines the economic potential of integrating WBA to replace different proportions of fine aggregate (sand) in concrete and mortar, especially for applications in the construction industry. Moreover, the effect levels of main, interaction, second-degree terms of replacement ratio, and specimen age on the mechanical properties were also obtained.

Therefore, the workability, ultrasonic pulse velocity, flexural strength, and compressive strength of mortar specimens containing WBA instead of fine aggregate were determined. The main purpose of this study is to determine the most appropriate WBA replacement rates for sand in mortar. The outcomes of this study aim to minimize the disposal of WBA to landfills and encourage its use without need for landfilling. As a result, it aims to reduce landfill space requirements and contribute to mitigating the environmental consequences associated with leaching after storage.

2. Materials and methods

2.1. Material

CEM I 42.5 R (PC) (in compliance with TS EN 197-1 (TSE, 2002)), standard sand (SS, Fig. 1a) (in compliance with TS EN 196-1 (TSE, 2016)), waste bottom ash (WBA, Fig. 1b), chemical admixture, and distilled water were used in the production of mortar specimens containing WBA. The chemical analysis and physical properties of PC and WBA are given in Table 1. WBA was obtained from the solid waste disposal site in Çorlu, Tekirdağ, where only inert solids can be stored (Class III). This site has been receiving wastes since June 2008. Initially, only mixed municipal wastes were accepted, and then, since it is the only landfill area in the region, non-hazardous wastes originating from industries have also started to be accepted to the area.

The supplied WBA was sieved through a 2 mm sieve aperture size, and the 2 mm undersize WBA grains were used in the mortar (Fig. 1b). The grain-size distribution curves of the WBA and the SS used in mortar are shown in Fig. 2 (fineness modulus, k_{WBA}= 3.27, k_{SS}= 5.50). As seen in Fig. 2, the grain size of the waste bottom ash varies in the range of 2.000 mm - 0.075 mm (Kaya, 2010). The 28-day strength activity index of the WBA below 75 μm was determined in accordance with TS EN 450-1 standard (TSE, 2013) (Table 2) and meets the specified limit condition (%79.8 > %75).

The particle shape and surface texture characteristics of the WBA were determined using the scanning electron microscopy (SEM) imaging technique (Fig. 3). SEM analysis was conducted by using FEI Quanta FEG 250. As shown in Fig. 3, the WBA particles have an angular, rough, and porous structure.

2.2. Method

In the experimental design, replacement ratio, and specimen age were selected as the independent variables, and ultrasonic pulse velocity (*V*), flexural strength (f_f), and compressive strength (f_c) were chosen as the response variables. The workability of fresh mortar specimens was determined by the flow-table value, and the flow-table value was kept within a certain range by using a modified polycarboxylate polymer-based liquid high-performance superplasticizer chemical additive.

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

	Cement	***Waste bottom ash***
Chemical composition (wt. %)		
Silica (SiO_2)	19.535	41.05
Calcium oxide (CaO)	64.342	8.80
Aluminum oxide (Al_2O_3)	4.605	17.21
Iron oxide (Fe_2O_3)	3.091	12.48
Magnesium oxide (MgO)	0.895	5.32
Alkali (Na_2O + 0,658 K_2O)	1.022	5.13
Chloride (Cl^-)	0.013	0.008
Sulfate (SO_3)	3.365	1.96
Loss on ignition	2.548	7.59
Insoluble residue	0.285	45.77
Physical properties		
Initial setting time (minutes)	195	-
Final setting time (minutes)	270	-
Total expansion (mm)	1.0	-
Density (g/cm^3)	3.11	2.37
Specific surface area (cm^2/g)	4530	-
Residue on 45 μm sieve (%)	1.6	-
Residue on 90 μm sieve (%)	0.2	-

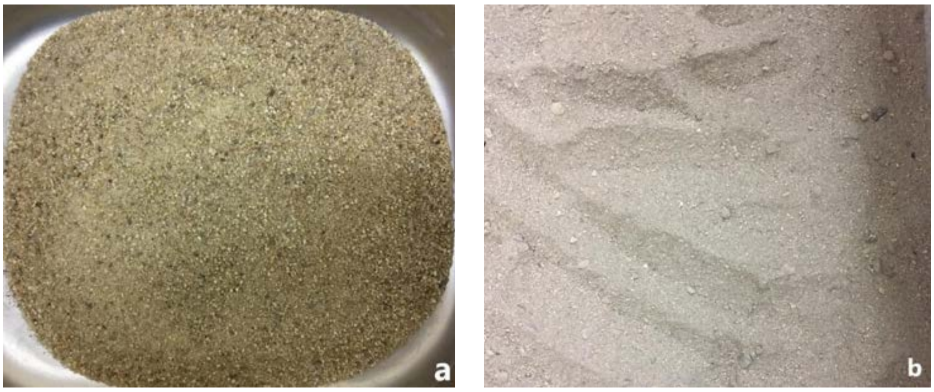


Fig. 1. a) The standard sand grains, b) the undersize WBA grains from 2 mm

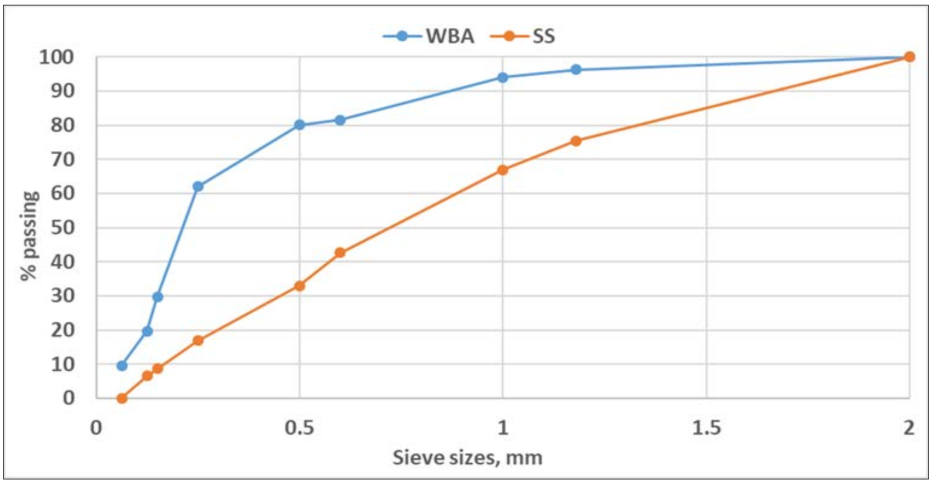


Fig. 2. The grain-size distribution curves of the WBA and SS

Table 2. The 28-day strength activity index of WBA

Specimen code	*Mixture ratio*	*PC (g)*	*WBA (g)*	*f_c (MPa)*	*Strength activity index (%)*	*Limits* (%)*
Ref	100% PC	900	-	48.7	-	-
WBA	25% WBA+ 75% PC	675	225	38.9	79.8	75

** TS EN 450-1 (TSE, 2013)*

Compared to SS particles, the ATK particles were found to have a higher angularity, rougher, and more porous surface texture (Fig. 3). Therefore, in fresh mortars with a water/cement ratio of 0.5, the desired workability (flow-table value) was achieved by using a chemical additive. The desired flow-table value (11 cm-17 cm) was achieved in specimens with the highest 25% replacement ratio by using a chemical additive. However, workability could not be achieved by using a high percentage of chemical additives at higher replacement ratios. Therefore, WBA replacement ratios of 0%, 15%, and 25% were selected. The microstructure of mortar specimens was revealed using SEM imaging techniques. Moreover, the effects of replacement ratio and specimen age on the response variables (V, f_f, and f_c) were determined using ANOVA. The ANOVA was performed using the "Design Expert V.13" computer program (Stat-Ease, 2021). ANOVA is a statistical method used to analyze and compare means among multiple groups (Sawyer, 2009). ANOVA evaluates differences between groups by examining the share of variance between groups in the total variance (Tabachnick and Fidell, 2007). If the between-group variance is greater than expected, this indicates a significant difference between groups.

To determine the usability of WBA as a replacement for SS, 54 (3·3·6) 40×40×160 mm prism mortar specimens were produced. The selected variation intervals for replacement ratio and specimen age are at 0%, 15%, and 25% by weight of SS and at 28, 60, and 90 days, respectively. The mortar constituent materials and codes used in specimen production are given in Table 3.

The mortar specimens were produced according to TS EN 196-1 (TSE, 2016). The specimens were cured initially at 24-hour sealing curing and in lime-saturated water at 20±1 °C until the testing date.

The workability of mortars was determined using the flow-table test in accordance with TS EN 1015-3 (TSE, 2000). The ultrasonic pulse velocity test was performed in accordance with TS EN 12504-4 (TSE, 2012), while the flexural and compressive strength tests were carried out according to TS EN 196-1 (TSE, 2016). Moreover, the microstructure of the bottom ash-substituted mortars was analyzed using scanning electron microscopy (SEM).

3. Experimental results

The run points and the results obtained at the run points are presented in Table 4. Six specimens were produced for each run point, and the average of the results from these six specimens was considered as the experimental result for that specific run point.

The flow-table test results of the mortar specimens were obtained as 17.05 cm, 16.24 cm, and 12.60 cm for the reference, WBA-SS%15, and WBA-SS%25 sample codes, respectively. As expected, due to the particle shape and surface texture, using WBA instead of SS reduces the workability (slump value) of the mortar specimens. Especially after the replacement ratio of 15%, the required flow-table value for workability could only be achieved by using a very high amount of chemical admixture. However, in terms of workability, it is stated that specimens with a 30% replacement ratio can be produced without using a superplasticizer, and specimens with a 50% replacement ratio can be produced using a superplasticizer (Singh and Siddique, 2016).

Due to the variability of the WBAs' physical properties, the water requirements for workability are shown variation. Variations of V, f_f, and f_c according to the replacement ratio are shown in Fig. 4. At a 25% replacement ratio, V decreases by 7.91%, 9.63%, and 7.71% for 28, 60, and 90 days, respectively. When the replacement ratio is 15%, f_f increases, but when the replacement ratio increases from 15% to 25%, f_f decreases. At a 25% replacement ratio, the f_f value of the 28 and 60-day-old specimens decreases compared to the reference specimen results. However, the f_f value in 90-day-old specimens was higher than in the reference specimens.

At a 15% replacement ratio, f_c increases by approximately 28% at all specimen ages due to the filler effect of the WBAs. While f_c values in specimens with a 25% replacement ratio were obtained similar to those in specimens with a 0% replacement ratio, they were lower than the f_c values of specimens with a 15% replacement ratio. The ratio of decrease in the f_c value is less in 90-day-old specimens due to the slow pozzolanic reactivity of WBAs. Due to WBA's high strength activity index, the total amount of binder in the mixture (cement + WBA) increases with the addition of WBA instead of standard sand. Therefore, one of the reasons for the increase in strength in WBA specimens is that WBA exhibits pozzolanic activity. It is mentioned in the literature that WBA can be utilized as a substitute for fine aggregate at replacement ratios of 40% (Hashemi et al., 2018), 30% (Sharma et al., 2021), and 50% (Singh and Siddique, 2016). However, in the context of this study, the maximum replacement ratio is 25% due to the inability to achieve appropriate workability. The variation in replacement ratios is attributed to the diverse physical and chemical properties of the WBAs employed. Therefore, in production processes where WBA is intended as a substitute for fine aggregate, it is recommended to conduct preliminary trial productions.

4. Statistical analysis

The effect levels of the specimen age (A) and the replacement ratio (B) on the V, f_f, and f_c were determined by ANOVA. The ANOVA results are given in Table 5. As seen in Table 5, the models obtained for all response variables (V, f_f, and f_c) are significant ($p_{model-V}$ < 0.0001, $p_{model-ff}$ = 0.0202, and $p_{model-fc}$ = 0.0014).

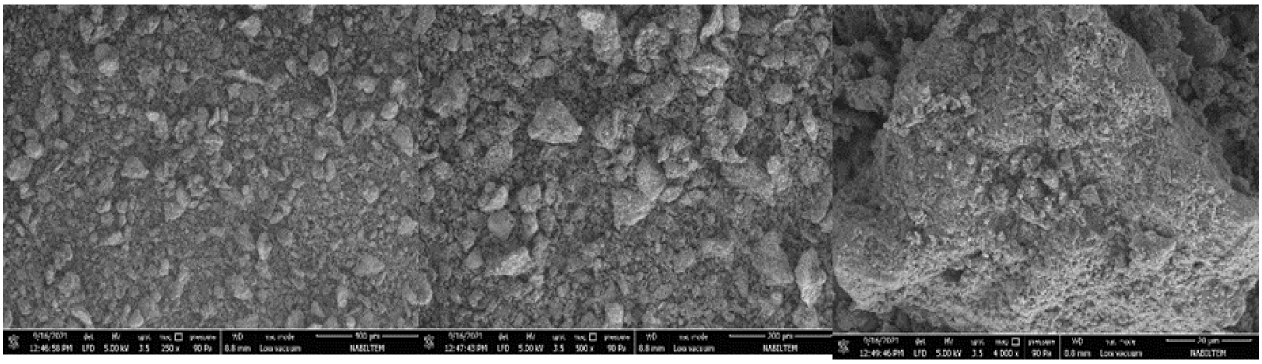


Fig. 3. SEM images of WBA

Table 3. Mortar constituent materials and specimen code

Code	*PC, g*	*SS, g*	*Water, g*	*WBA, g*	*Superplasticizer (by weight of PC+WBA), %*
Ref	450	1350	225	0.0	0
WBA-SS-%15	450	1147.5	225	202.5	1.73
WBA-SS-%25	450	1012.5	225	337.5	5.96

Note: *Constituent materials are given for 3 specimens.*

Table 4. Run points and experimental results

Run point	Factor 1	Factor 2	Response 1	Response 2	Response 3
	A:Specimen age	B:Replacement ratio	V	f_f	f_c
	day	%	km/s	MPa	MPa
1	28	0	4.505	7.841	48.701
2	28	15	4.378	8.228	64.441
3	28	25	4.149	5.859	51.960
4	60	0	4.567	7.218	54.533
5	60	15	4.394	8.633	68.846
6	60	25	4.128	5.995	54.082
7	90	0	4.539	7.184	58.508
8	90	15	4.424	8.397	73.509
9	90	25	4.189	7.652	67.077

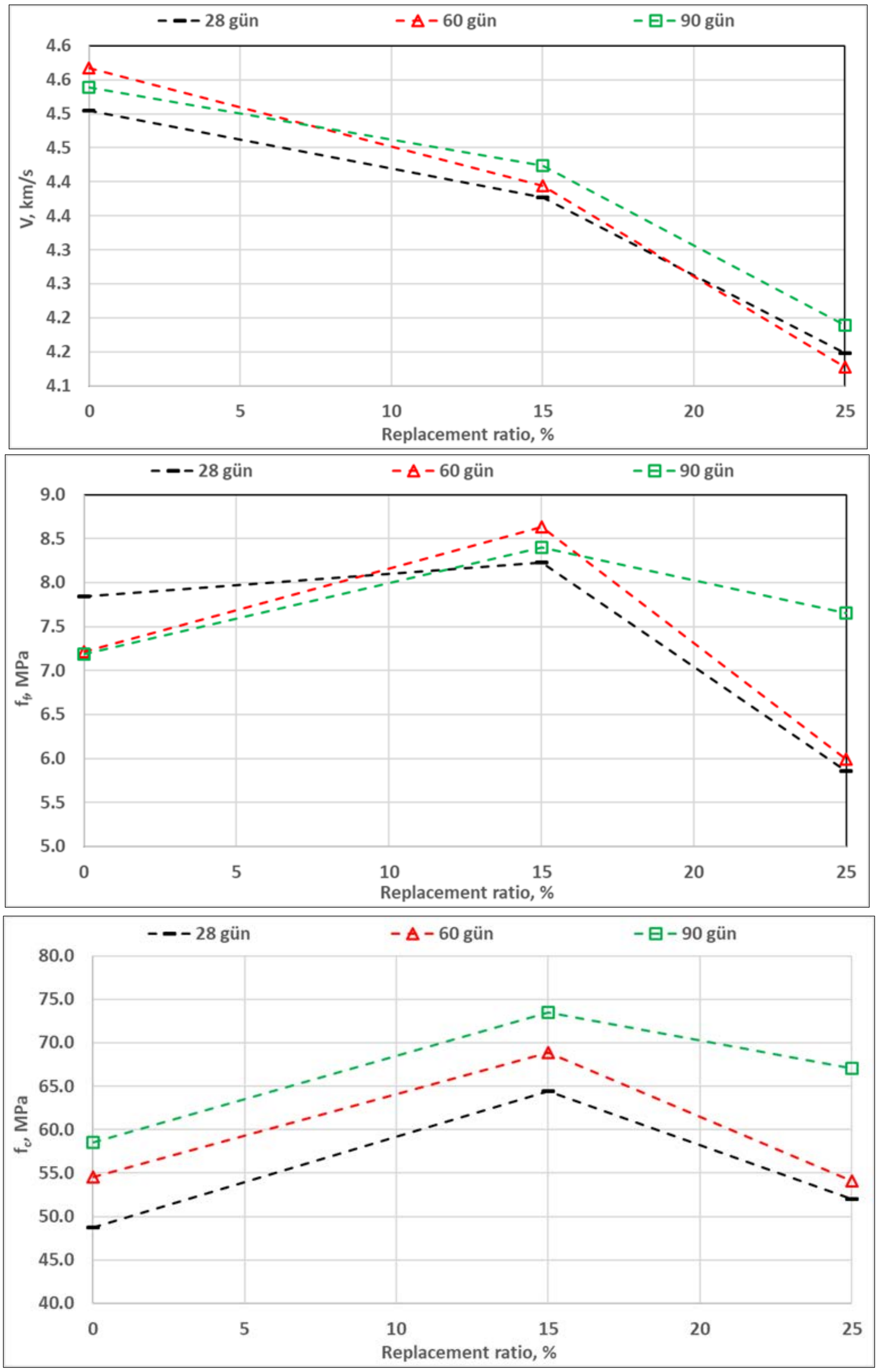


Fig. 4. Variations of V, f_f, and f_c according to the replacement ratio

A (p_A = 0.0821), and B (p_B < 0.0001) main terms have a significant effect on the *V* in the selected variation intervals. However, the significant effect level of the B main term is much higher than that of A. Moreover, the second-degree term B^2 also has a significant effect on *V*. B main term has a significant effect (p_B = 0.0499) on the f_f. Moreover, AB interaction and B^2 second-degree terms have significant effects on f_f. The A main term has a significant effect level (p_A = 0.0029) on the f_c. In addition, the B^2 second-degree term also has a significant effect on f_c. The models for the response variables are given in Eqs. (1-3), respectively. Furthermore, the suitability of each model for the response variables was determined by the fit statistics and is presented in Table 6.

$$V = 4.49875 + 0.000645 \cdot A - 0.000156 \cdot B - 0.000604 \cdot B^2 \quad (1)$$

$$f_f = 8.20620 - 0.013346 \cdot A + 0.132017 \cdot B + 0.001521 \cdot AB - 0.010349 \cdot B^2 \quad (2)$$

$$f_c = 43.10623 + 0.182153 \cdot A + 2.27546 \cdot B - 0.084951 \cdot B^2 \quad (3)$$

As seen in Table 6, the predictability of all response variables is high (R^2 > 0.9155) and the highest and lowest R^2 were obtained for V (0.9889) and f_f (0.9155), respectively. The difference between adjusted-R^2 and predicted-R^2 for *V* and f_c response variables is less than 0.2 (Stat-Ease, 2021), indicating that the added terms have a high effect level on the response variables. However, the difference between adjusted-R^2 and predicted-R^2 for the f_f is greater than 0.2, that some of the added terms may not have a significant effect on this response variable. Additionally, the adequate precision value obtained for all response variables is > 4 (Stat-Ease, 2021), signifying that the models have generated a substantial effect within the chosen design space.

The interaction, contour, 3D, and predicted-actual value plots for changes in *V*, f_f, and f_c with respect to replacement ratio and specimen age are shown in Figs. 5-7, respectively. As seen from Fig. 5, the value of V decreased as the replacement ratio increased. The variation in V due to specimen age was low. No significant decrease was observed in *V* up to a replacement ratio of 10%, while at a higher replacement ratio, the decrease in *V* was significant. The predicted and actual values overlap with adjusted-for curvature, indicating a high R^2 value (approximately 0.99).

Figure 6 shows that there is a tendency for an increase in the value of f_f up to a 15% replacement ratio. The highest value of f_f was observed between the replacement ratio of 5% and 15%, showed no significant variation. The specimen age didn't cause a significant change in f_f for all replacement ratios. The use of 15% WBA instead of SS did not cause any decrease in f_f for all specimen ages. Therefore, it was seen that mortars containing 15% WBA can be used in practice instead of SS, and even mortars containing WBA up to a higher replacement ratio (~%25) can be used due to their high resistance at an advanced age. The predicted and actual values overlap with adjusted-for curvature, indicating that the predictability of f_f is also high ($R^2 \cong 0.92$).

In all specimen ages, an increase in f_c value was observed up to a 15% replacement ratio compared to reference specimens. However, a decrease in f_c values was observed in specimens with a 25% replacement ratio when compared to the 15% replacement ratio, across all specimen ages. While an increase in f_c value was observed in 90-day specimens containing WBA replacement compared to 0% WBA replacement specimens, there was no change in 28-day and 60-day specimens. The maximum f_c value was attained in 90-day specimens with a 15% replacement ratio. As the specimens age increased, the amount of WBA that were utilized in the production of mortar specimens (at high replacement ratios) also increased. High strengths were achieved at approximately 7.5-22.5% replacement ratios in 90-day specimens. The substitution of 25% WBA instead of SS did not cause any loss in f_c value at all specimen ages. The predicted and actual values overlapped the adjusted-for curvature, and the deviation was quite low. This indicates that the predictability of f_c is high ($R^2 \cong 0.95$).

5. Microstructure

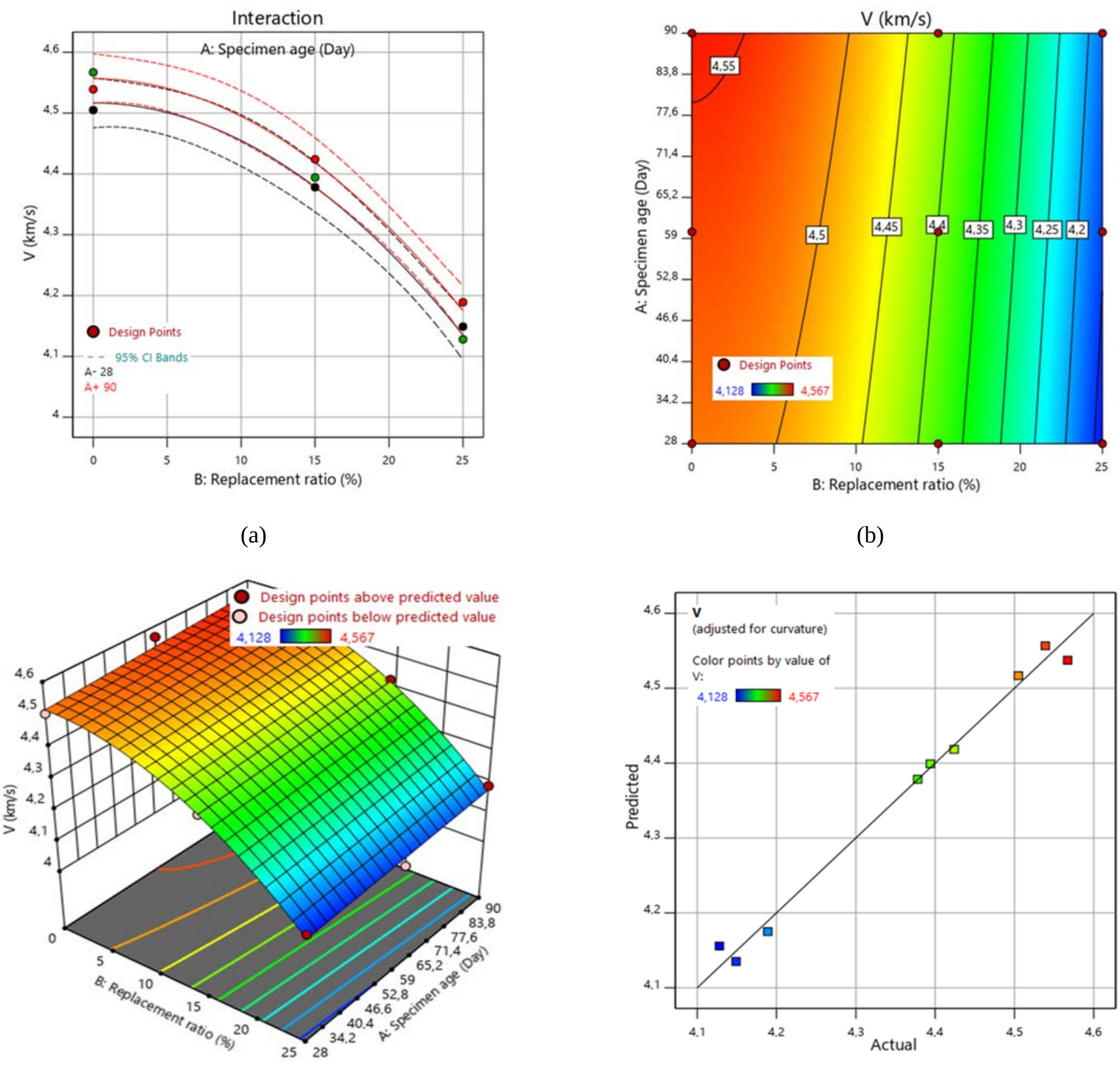
The microstructure in the mortar specimens with WBA additions was determined by SEM analysis on 90-day specimens that have a 0%, 15%, and 25% replacement ratios. The SEM images for 0%, 15%, and 25% replacement ratios are shown in Figs. 8-10, respectively.

Table 5. ANOVA for response variables

	V			f_f			f_c		
Source	***F-value***	***p-value***	***Significance***	***F-value***	***p-value***	***Significance***	***F-value***	***p-value***	***Significance***
Model	148.40	< 0.0001	Significant	10.84	0.0202	Significant	28.69	0.0014	Significant
A-Specimen age	4.71	0.0821		1.11	0.3524		29.56	0.0029	
B-Replacement ratio	429.66	< 0.0001		7.72	0.0499		3.33	0.1275	
AB	-	-		8.47	0.0436		-	-	
B²	31.90	0.0024		28.62	0.0059		49.50	0.0009	

Table 6. Fit statistics

Response	*Standard deviation*	*Mean*	R^2	*Adjusted-R^2*	*Predicted-R^2*	*Adequate precision*
V, km/s	0.0226	4.36	0.9889	0.9822	0.9684	28.0451
f_f, MPa	0.4076	7.45	0.9155	0.8310	0.5092	9.8096
f_c, MPa	2.5400	60.18	0.9451	0.9122	0.8243	15.5107

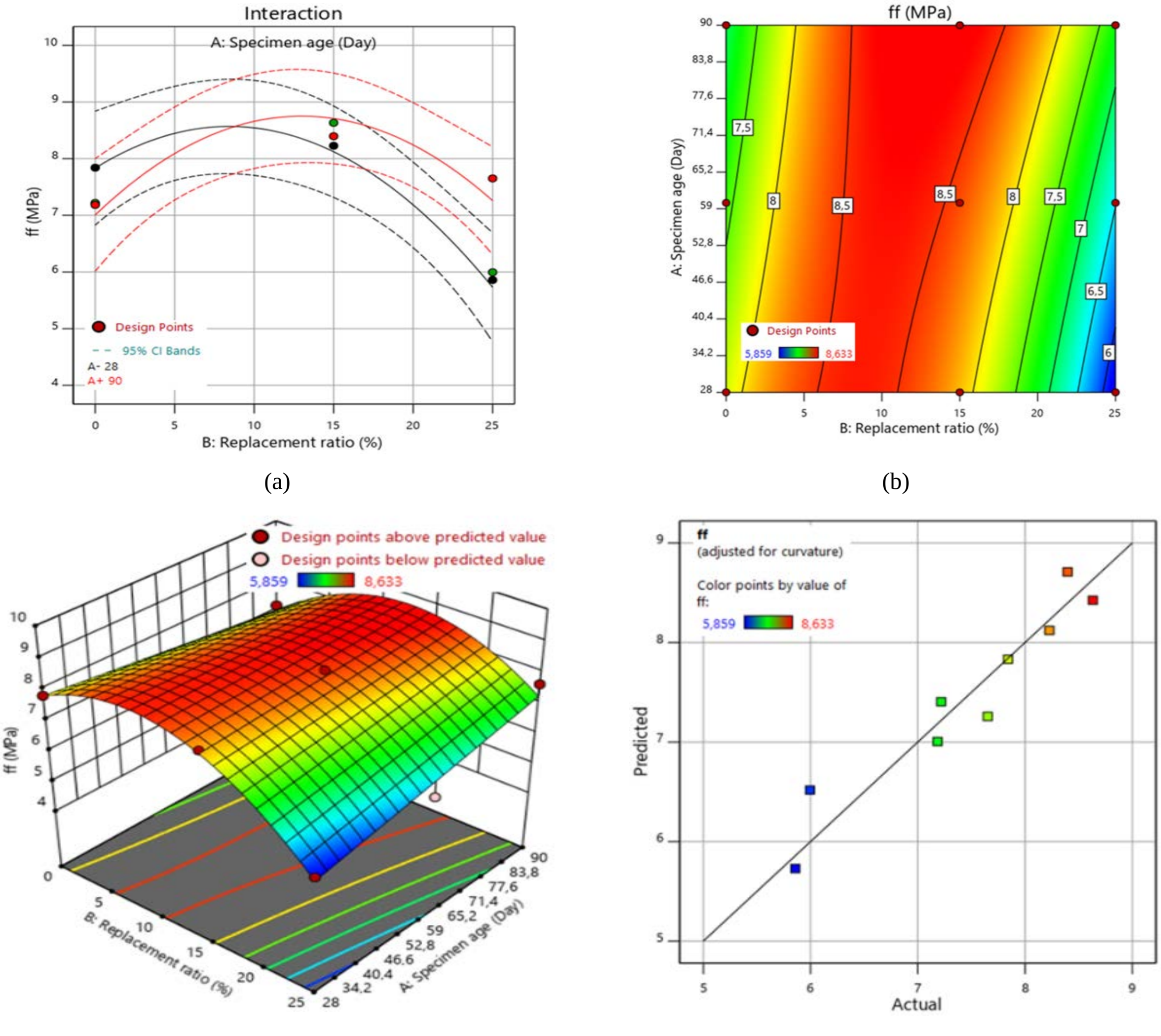


(a) (b) (c) (d)

Fig. 5. Interaction (a), contour (b), 3D (c) and predicted-actual plots (d) for *V*

SEM image of the reference specimen shows that the formation of CSH (calcium silicate hydrate) gels, ettringite, and portlandite resulting from cement hydration are observed. Moreover, unhydrated cement particles are also present.In the microstructure analysis of the ATK-SK%15 specimen, a dense formation of CSH and tobermorite gels was observed. This observation elucidates the 15 MPa difference in compressive strength between this sample and the reference sample. Conversely, in the microstructure analysis of the WBA-SS%25 specimen, the presence of CSH, the formation of cracks, and unhydrated WBA particles were observed due to the higher concentration of WBA.

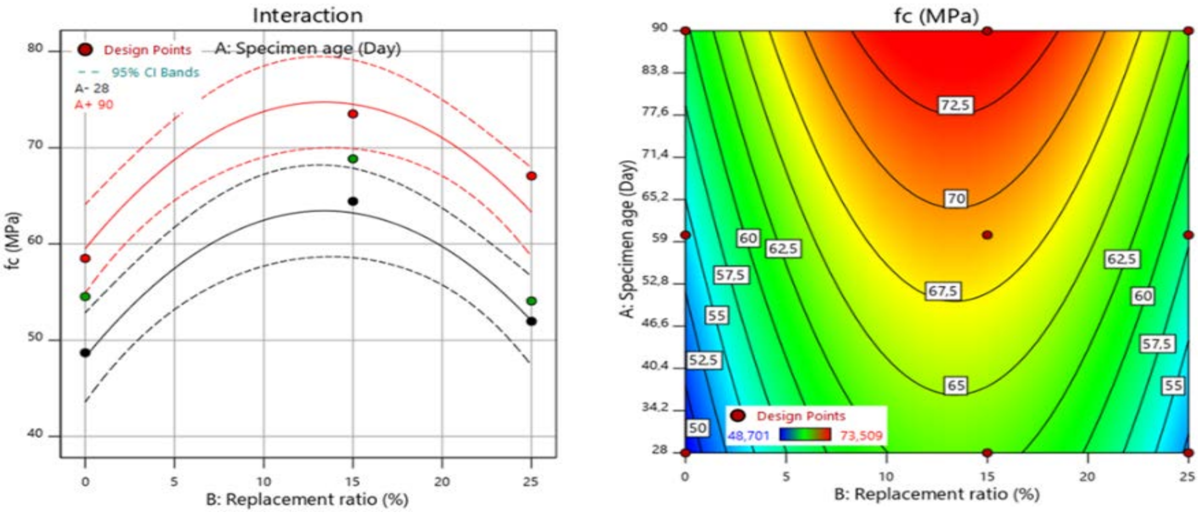
The microstructure of the WBA-SS%25 specimen was denser than that of the reference specimen, but less dense than that of the WBA-SS%15 specimen. This result explains the 8.6 MPa higher compressive strength of the WBA-SS%25 specimen, and the 6.4 MPa lower compressive strength of the WBA-SS%15 specimen compared to the reference specimen.



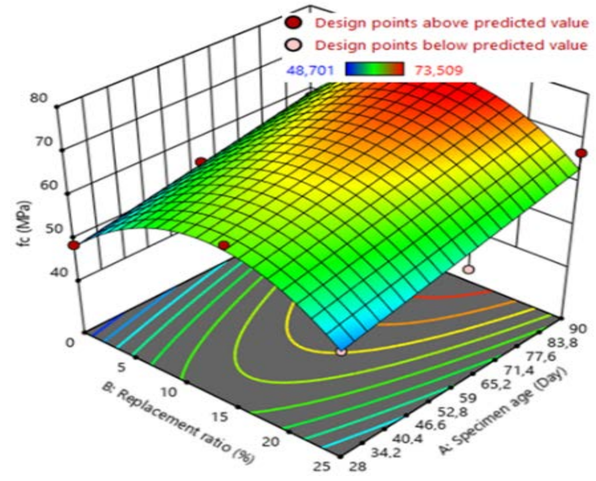
(a) (b)

(c) (d)

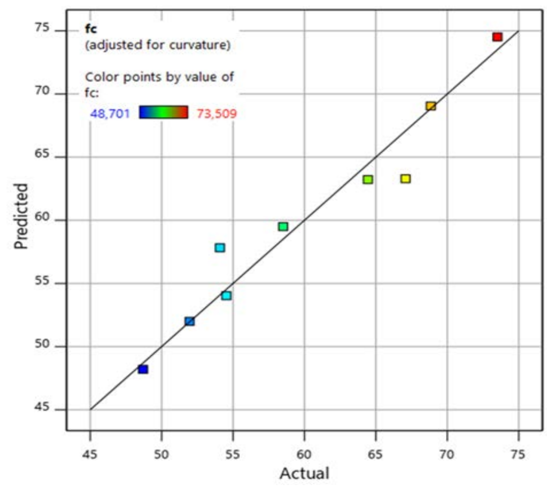
Fig. 6. Interaction (a), contour (b), 3D (c) and predicted-actual (d) plots for f_f



(a) (b)



(c)



(d)

Fig. 7. Interaction (a), contour (b), 3D (c) and predicted-actual (d) plots for f_c

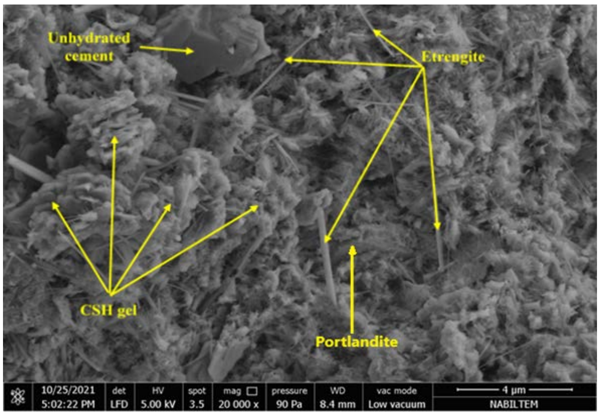


Fig. 8. SEM image for 0% replacement ratio

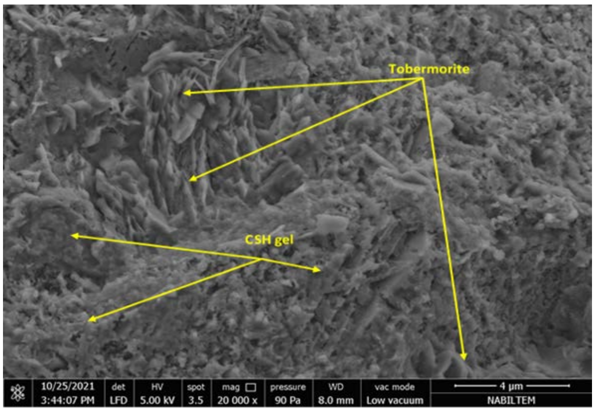


Fig. 9. SEM image for 15% replacement ratio

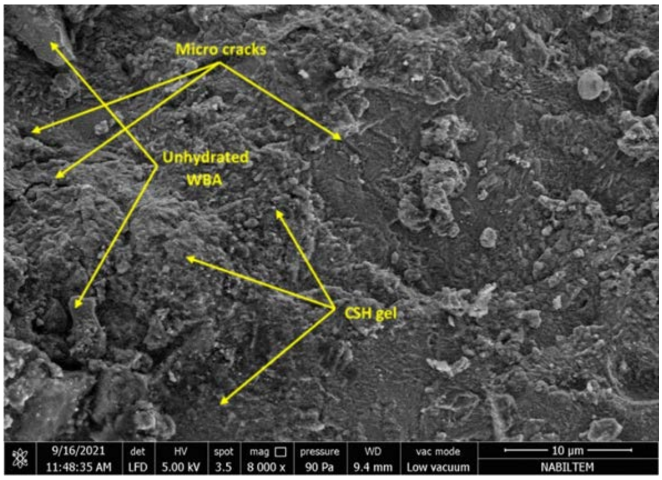


Fig. 10. SEM image for 25% replacement ratio

6. Conclusions

In this study, the usability of WBA in various ratios instead of sand in mortar composition was investigated. For this purpose, the effects replacement ratios (B) and specimen age (A) of mortar on ultrasonic pulse velocity (V), flexural strength (f_f), and compressive strength (f_c) of mortar values were investigated in detail. The effects of B and A variables on the V, f_f, and f_c of mortar containing WBA were determined using ANOVA. The results obtained within the scope of the study are presented below:

- The predictability of the models obtained for the V, f_f, and f_c is high (R^2, 0.9889, 0.9155, 0.9451, respectively).
- Specimen age (A) has a significant effect on V, and f_c ($p_V = 0.0821$, $p_{fc} = 0.0029$), but it does not have a significant effect on f_f ($p_{ff} = 0.3524$).
- Replacement ratio (B) has a significant effect on V, and f_f ($p_V < 0.0001$, $p_{ff} = 0.0499$), but its effect on V is much higher. B does not have a significant effect level on f_c at the selected variation intervals of effect variables.
- Although specimen age (A), and replacement ratio (B) have a significant effect on V, V is more sensitive to replacement ratio (B).
- f_f increases up to 15% replacement ratio, but it decreases at higher replacement ratios, and at 25% replacement ratio, similar results to specimens with 0% replacement ratio are obtained for f_f. Therefore, using 25% WBA instead of standard sand does not cause a significant change in f_f.
- The f_c value of 28-day, and 60-day specimens using 25% WBA instead of SS does not show a significant change compared to specimens with 0% replacement. A higher f_c value was obtained for the 90-day specimens. The f_c value of specimens with 15% replacement was high for all ages.
- If the workability can be provided by using a chemical additive, using 25% WBA instead of SS in practice does not pose a problem for strength (f_f and f_c).

The study concluded that waste bottom ash can be used in certain ratios in mortar mixtures instead of standard sand and 25% replacement with WBA was suitable by using a chemical additive within the selected variation intervals of the effect variables. The different factors affecting the properties of WBA (type of coal, burning temperature etc.) also change the properties of WBA. Therefore, it is necessary to determine appropriate usage ratios for the WBA that will be used in the construction sector by conducting preliminary studies. In addition, it is necessary to investigate the using WBA at high replacement ratios to minimize SS consumption

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