KSÜ Mühendislik Bilimleri Dergisi, 25(3), 2022
Araştırma Makalesi

KSU J Eng Sci, 25(3), 2022
Research Article

Kahramanmaras Sutcu Imam University
Journal of Engineering Sciences

Geliş Tarihi : 10.07.2022
Kabul Tarihi :11.08.2022

Received Date :10.07.2022
Accepted Date : 11.08.2022

MECHANICAL PROPERTIES OF MORTARS CONTAINING WOOD BOTTOM ASH INSTEAD OF CEMENT

ÇİMENTO YERİNE ODUN TABAN KÜLÜ İÇEREN HARÇLARIN MEKANİK ÖZELLİKLERİ

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ABSTRACT

Carbon dioxide (CO_2) released into the atmosphere during the production of Portland cement (PC) is one of the important factors causing global warming. Therefore, studies are carried out on different materials to reduce PC consumption. The effect levels of the wood bottom ash (WBA) ratio and specimen age on the response variables (compressive strength, flexural strength, and ultrasonic pulse velocity) were investigated in this study. Mortar specimens were produced using PC, WBA, CEN standard sand, and distilled water. The produced specimens were cured in water until the test day. WBA ratios are 0%, 5%, 10%, 20%, 35% and 50% by weight of binder. As a result, it was determined that the optimum WBA ratio was 5%. In addition, R^2 values of response variables were found to be high (ultrasonic pulsed wave velocity; 0.8925, flexural strength; 0.9356, compressive strength; 0.9404) by analysis of variance (ANOVA). This shows that the models have a high correlation. Moreover, the terms added to the models have a significant effect on the responses.

Keywords: Wood bottom ash, ultrasonic pulse velocity, flexural strength, compressive strength, ANOVA

ÖZET

Portland çimentosu (PÇ) üretimi sırasında atmosfere salınan karbondioksit (CO_2), küresel ısınmaya neden olan önemli faktörlerden biridir. Bu nedenle PÇ tüketimini azaltmak için farklı malzemeler üzerinde çalışmalar yapılmaktadır. Bu çalışmada, değişkenlerin (odun taban külü (OTK) oranı ve numune yaşı) tepki değişkenleri (ultrasonik atımlı dalga hızı, eğilmede çekme ve basma dayanımı) üzerindeki etki düzeyleri araştırılmıştır. Harç numuneleri; PÇ, OTK, CEN standart kum ve distile su kullanılarak üretilmiştir. Üretilen numuneler, deney gününe kadar suda kür işlemine tabi tutulmuştur. OTK ilave oranları bağlayıcı ağırlığınca %0, %5, %10, %20, %35 ve %50'dir. Sonuç olarak, optimum OTK kullanım oranının %5 olduğu tespit edilmiştir. Ek olarak, varyans analizi (ANOVA) ile tepki değişkenlerinin R^2 değerlerinin yüksek olduğu (ultrasonik atımlı dalga hızı; 0.8925, eğilme dayanımı; 0.9356, basınç dayanımı; 0.9404) bulunmuştur. Bu durum, modellerin yüksek bir korelasyona sahip olduğunu göstermektedir. Ayrıca modellerdeki terimler, tepki değişkenleri üzerinde önemli bir etkiye sahiptir.

Anahtar Kelimeler: Odun taban külü, ultrasonik atımlı dalga hızı, eğilmede çekme dayanımı, basınç dayanımı, ANOVA.

ToCite: CİHAN, M. T., & AVŞAR, Y. E., (2022). MECHANICAL PROPERTIES OF MORTARS CONTAINING WOOD BOTTOM ASH INSTEAD OF CEMENT. *Kahramanmaraş Sütçü İmam Üniversitesi Mühendislik Bilimleri Dergisi*, 25(3), 491-502.

INTRODUCTION

Concrete is produced by over annually 7 billion tons in the world (Topçu, 2021). While the amount of concrete produced in EU countries in 2020 was 253 million m^3 (ERMCO, 2020), 95 million m^3 in Turkey (THBB, 2020). Concrete has many advantages (Erdoğan, 2015) as well as some disadvantages. The crucial disadvantage of concrete in sustainable production is the amount of carbon dioxide (CO_2) released in producing Portland cement (PC) used as a binder. The cement industry is estimated to be responsible for approximately 8% of the amount of CO_2 released worldwide (Preston, 2018). Using different materials has become popular to reduce the amount of cement in concrete due to intense energy consumption and harmful environmental effects.

As a result of the combustion of coal in coal-fired boilers, different types of coal ash such as fly ash (FA), coal bottom ash (CBA), and boiler slag are formed. The heavy and coarse particles that dropped at the bottom of the boiler furnace are called CBA (Singh, 2018). The amount of the CBA is the majority of industrial waste generated from coal-fired thermal power plants (Baite et al., 2016; Nikbin et al., 2016; Kim and Lee, 2015). It has a large, porous, light, glassy, and granular structure and is grayish (Abubakar and Baharudin, 2012). It is used as cement raw material, concrete additive, infrastructure stabilization material, and filler (ECOBA, 2016).

There have been some studies about cement replacement with the CBA (Khongpermgoson et al., 2020; Oruji et al., 2017; Aydın, 2016; Kim and Lee, 2011). The wood is used as fuel in some industrial areas (industrial facilities that burn pulp, paper, and wood or power plants that burn wood), and wood bottom ash (WBA) is formed as a by-product. While most of the WBA is disposed of in landfills, the remaining part is used by replacing fine aggregate, coarse aggregate, and PC due to its pozzolanic properties (Akinyemi, 2021).

Adamu (2017) obtained compressive strength for 28 and 90 days as 21.2 and 31.4 MPa, respectively, for the samples used 20% and 5% WBA for PC and a w/c ratio of 0.55. Raheem and Adenuga (2013) determined that using 10% WBA for PC in concrete with a w/c ratio of 0.5 increased the workability. In addition, they obtained compressive strength for 28 days as 19.1 and 21.1 MPa, respectively, for the samples containing 5% and 10% WBA. Nader et al. (2020) studied the effect of 0-50% WBA replacement for PC on compressive strength. As a result, the compressive strength was obtained as 18.2 and 11.8 MPa, respectively, for mortar samples containing 10% and 20% WBA. Ulewicz and Jura (2017) investigated the optimum composition ratio of FA and WBA. WBA/FA composition ratios are 90/10, 80/20, 10/90, and 20/80, and the usage ratio for PC is 20%. As a result, the highest compressive strength for 28 days was 68.5 MPa, obtained from a composition ratio of 10/90. Ghorpade (2012) investigated the change in compressive strength of concrete depending on the WBA ratio (0%-30%) and sample age (28 and 90 days). The compressive strength was obtained as 39.1-44.3 MPa and 39.6-50.6 MPa, respectively, for 28 and 90 days. As a result, the optimum WBA ratio was determined as 10%. Chowdhury et al. (2015) investigated the mechanical and structural properties of concrete containing partially WBA instead of PC. The highest compressive, flexural, and tensile strengths for 28 days are 36.5, 5.63, and 3.24 MPa, respectively. The increase in w/c and WBA ratio decreased the strength, slightly. In addition, it was determined that WBA could be replaced for PC without adversely affecting the strength properties of concrete since it contains amorphous silica. Ramos et al. (2013) investigated the mechanical strength, carbonation resistance, and ASR expansion of mortars containing partially WBA instead of PC. Increasing the WBA ratio in the mortar was not affected the mechanical properties. In addition, it decreased the ASR expansion and increased the carbonation depth. Akinyemi et al. (2020) investigated the effect of WBA in improving the properties of cement mortar modified with banana fiber and polymer additives. As a result, using more than 10% WBA reduced the tensile strength. In addition, it has been determined that the samples prepared with 10% WBA have significant thermal insulation properties.

Models with high estimation accuracy were obtained depending on terms of the effect levels of the WBA ratio and specimen age on the response variables (compressive strength, ultrasonic pulse velocity, and flexural strength) in the study. It is aimed to balance the ecosystem, alleviate the burden on natural resources, reduce PC consumption, and minimize carbon footprint thanks to the efficient using WBA.

MATERIAL AND METHOD

In this study, the effects of wood bottom ash (WBA) ratio and specimen age on the compressive strength, flexural strength, and ultrasonic pulse velocity were investigated.

Material

PC (CEM I 42.5 R), WBA, standard sand, and distilled water were used to produce the mortar samples. The physical and chemical properties of PC are given in Table 1, and SEM images of the PC are shown in Figure 1. Figure 1 shows that the cement grains are angular, and the grain surfaces are smooth. In addition, no porous structure is observed in the cement grains (Figure 1).

Table 1. Properties of the PC

Chemical, %										
SiO_2-Solute	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Cl	Insoluble Residue	NaO/K_2O	Loss of Ignition	F. CaO – Free Lime
19.78	62.65	5.25	3.59	0.84	3.24	0.04	0.97	0.57/0.75	2.44	1.21

Physical						
Specific Gravity, gr/cm^3	Setting Time, min.		Volume Expansion, mm	Fineness		
	Start	Finish		Specific Surface, cm^2/gr	Sieve Residue (45µm), %	Sieve Residue (90µm), %
3.16	119	170	1	3550	3.1	0.2

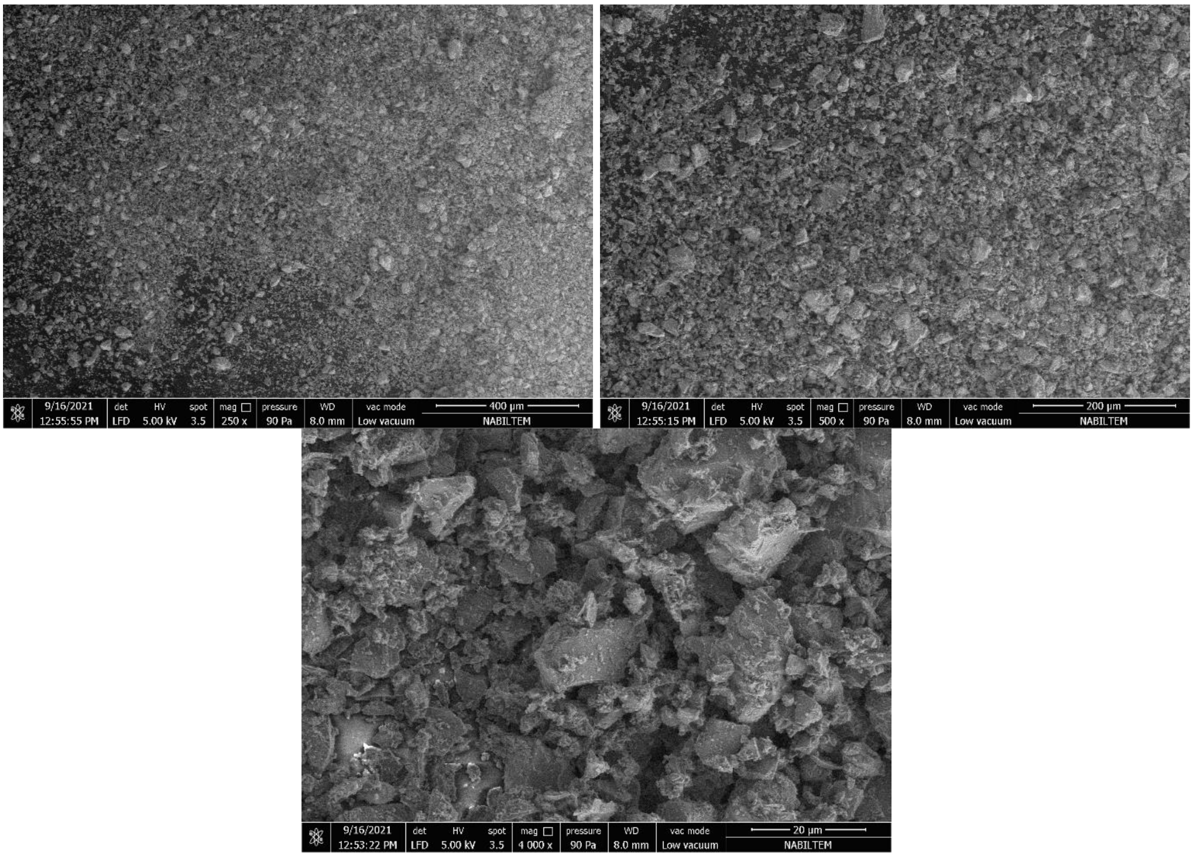

Figure 1. SEM Images of the PC

In the study, WBA obtained from the furniture industry in the Thrace region was used. Wood bottom ash was obtained by burning pine, oak, and poplar woods. Firstly, WBA was ground by the Los Angeles abrasion machine. 75-micron WBA (Figure 2) was used in the production of mortar. The chemical properties of WBA are given in Table 2, and SEM images of WBA grains are shown in Figure 3. WBA grains have an angular, porous, and rough structure (Figure 3). In specimens with a high WBA ratio and a constant water/cement ratio, the workability decreases due to the increased water requirement from the grain structure of WBA.

Figure 2. Undersize WBA Grains from 75-Micron

Table 2. The Chemical Properties of WBA

SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O/K_2O	Loss of Ignition
11.74	33.14	4.64	2.53	5.75	1.51	1.01/1.89	17.07

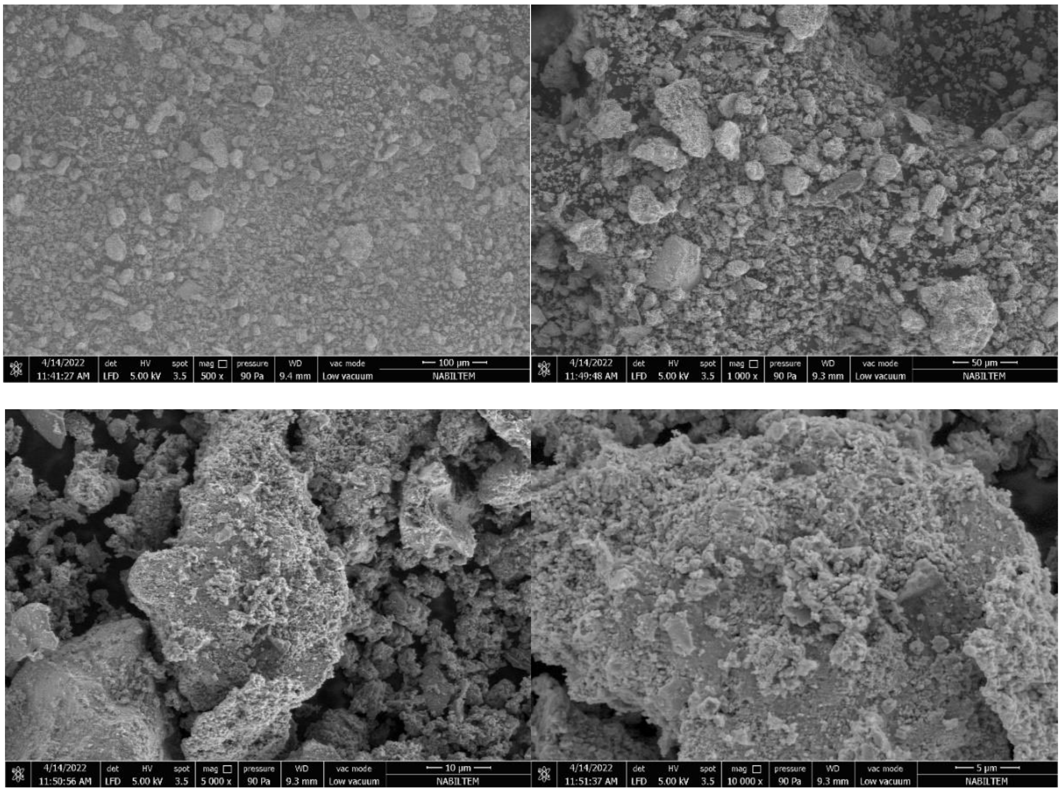

Figure 3. SEM Images of WBA Grains

Method

In the study, 72 mortar specimens (40×40×160 mm) were produced according to the TS EN 196-1 (2016). The produced samples were cured in water until the test day. WBA ratios are 0%, 5%, 10%, 20%, 35% and 50% by weight of binder. The experimental design is given in Table 3. The workability, compressive strength, flexural strength, and ultrasonic pulse velocity of the specimens containing partially WBA were determined.

Table 3. The Experimental Design

Codes	Number of samples	WBA ratio by weight of PC	Sample age	PC	Water	Sand	WBA
	Piece	%	Day	g	g	g	g
Ref-28	6	0	28	900	450	2700	0
TKÇ-%5-28	6	5	28	855	450	2700	45
TKÇ-%10-28	6	10	28	810	450	2700	90
TKÇ-%20-28	6	20	28	720	450	2700	180
TKÇ-%35-28	6	35	28	585	450	2700	315
TKÇ-%50-28	6	50	28	450	450	2700	450
Ref-60	6	0	60	900	450	2700	0
TKÇ-%5-60	6	5	60	855	450	2700	45
TKÇ-%10-60	6	10	60	810	450	2700	90
TKÇ-%20-60	6	20	60	720	450	2700	180
TKÇ-%35-60	6	35	60	585	450	2700	315
TKÇ-%50-60	6	50	60	450	450	2700	450
TOTAL	72	-	-	8640	5400	32400	2160

The workability of the mortar specimens was determined according to the TS EN 1015-3 (2000). The flow-table test is shown in Figure 4. Flow-table values of mortars with WBA are approximately 11.75-16.5 mm (~15.75 mm in reference samples). 5% and 10% WBA have increased the flow-table value by 1 mm (~16.5), while 50% WBA reduced by 4 mm (~11.75).

Figure 4. Flow-Table Test

Flexural strength (f_f, MPa) was determined according to TS EN 196-1 (2016) by applying 3-point loading (Figure 5a). The compressive strength was determined by the test (Figure 5b) performed according to the TS EN 196-1 (2016) on half prisms divided into two parts during the flexural test.

Figure 5. Flexural Strength (a) and Compressive Strength (b) Tests

The effect levels of the WBA ratio and sample age on the compressive strength, ultrasonic pulse velocity, and flexural strength were determined by ANOVA, and models were created for actual values. Design Expert V13 Trial" (StatEase, 2021) program was used for the Experimental design and ANOVA. The variation of the effect variables is given in Table 4.

Table 4. The Variation of the WBA Ratio and Specimen Age

	Factor	Units	Type	Minimum	Maximum	Coded low	Coded High	Mean	Std.*
A	WBA ratio	%	Numerical	0.00	50.00	-1 ↔ 0.00	+1 ↔ 50.00	20.00	17.94
B	Specimen age	day	Numerical	28.00	60.00	-1 ↔ 28.00	+1 ↔ 60.00	44.00	16.34

*Std., standard deviation

EXPERIMENTAL RESULTS

The run point values were obtained by taking the average of the test results of the 3 specimens (24 run points and 72 specimens). The variations of compressive strength, flexural strength, and ultrasonic pulse velocity depending on the WBA ratio are shown in Figure 6. Compressive strength, ultrasonic pulse velocity, and flexural tensile decreased in 28 and 60-day specimens with the increase in WBA ratio (increase in void ratio). A little increase was shown in flexural strength and compressive strength of 28-day specimens with 5% WBA. However, this increase does not affect the decreasing trend of the strengths. Compressive strength, ultrasonic pulse velocity, and flexural strength at 28 and 60-day specimens decrease moderately up to 35% WBA. However, at a 50% WBA ratio, the decrease observed in the 28-day specimens is greater than in the 60-day specimens. It shows that the effect of WBA on mechanical properties increases in advanced ages. In the literature, experiments have been carried out on 28 and 90 days of samples, and the WBA ratios used range from 0% to 30%. The obtained compressive strengths decrease in 28-day specimens with the increase in WBA ratio. However, an increase in compressive strength is observed with the increase in WBA ratio in advanced age samples. Therefore, the experimental results obtained within the scope of the study are compatible with the literature.

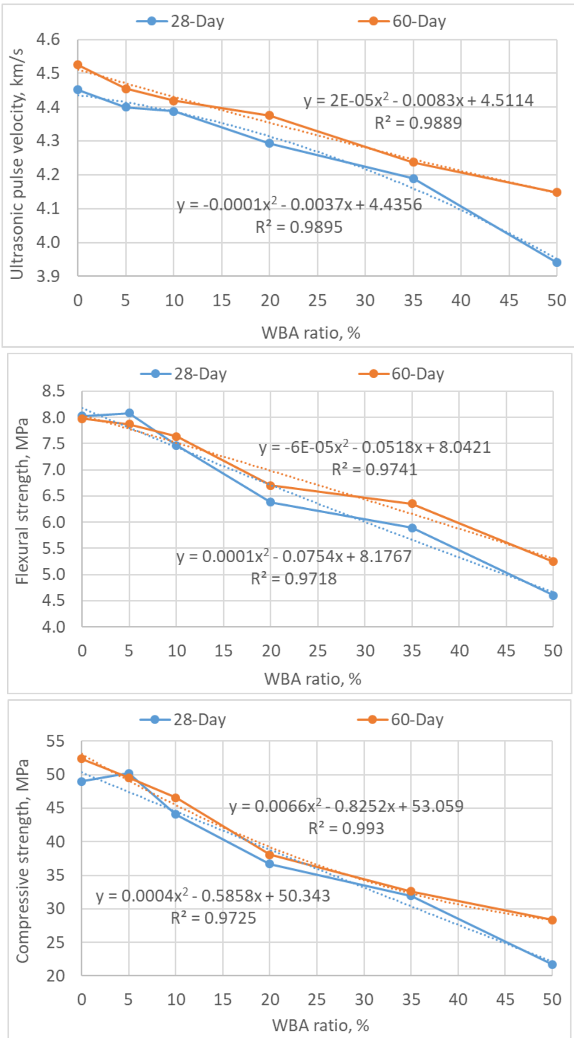

Figure 6. The Variations of Flexural Strength, Ultrasonic Pulse Velocity, and Compressive Strength Depending on the WBA Ratio

Run points of the experimental design and the results of the tests are given in Table 5. The design summary of the responses is given in Table 6.

Table 5. Runs Points and the Results of the Response Variables

Runs	A: WBA ratio	B: Specimen age	Ultrasonic pulse velocity	Flexural strength	Compressive strength
	%	Gün	km/s	MPa	MPa
1	0	28	4.396	8.000	48.367
2	5	28	4.376	8.067	50.133
3	10	28	4.344	7.833	44.517
4	20	28	4.222	6.167	34.417
5	35	28	4.149	6.033	31.150
6	50	28	3.941	4.600	21.417
7	0	28	4.507	8.050	49.625
8	5	28	4.424	8.100	50.250
9	10	28	4.432	7.100	43.675
10	20	28	4.364	6.600	39.000
11	35	28	4.229	5.750	32.700
12	50	28	3.941	-	22.050
13	0	60	4.563	8.050	54.400
14	5	60	4.482	7.800	49.275
15	10	60	4.444	7.950	45.475
16	20	60	4.392	6.700	39.000
17	35	60	4.248	6.250	32.950
18	50	60	4.071	5.250	24.500
19	0	60	4.486	7.900	50.350
20	5	60	4.428	7.950	49.850
21	10	60	4.394	7.325	47.650
22	20	60	4.360	6.700	37.100
23	35	60	4.225	6.450	32.225
24	50	60	4.225	-	32.225

Table 6. The Summary of the Response Variables

Response	Units	Observations	Analysis	Minimum	Maximum	Mean	Std.	Model
Ultrasonic pulse velocity	km/s	24	Polynomial	3.94	4.562	4.318	0.166	Linear
Flexural strength	MPa	22	Polynomial	4.6	8.1	7.028	1.042	2FI
Compressive strength	MPa	24	Polynomial	21.416	54.4	40.095	9.872	Linear

The effect levels of the WBA ratio and specimen age on the responses were obtained by ANOVA. In addition, the response models were created. ANOVA for compressive strength, flexural strength, and ultrasonic pulse velocity are shown in Table 7.

Table 7. ANOVA for Compressive Strength, Flexural Strength, and Ultrasonic Pulse Velocity

Source	Compressive strength		Flexural strength		Ultrasonic pulse velocity	
	p-value	Significance	p-value	Significance	p-value	Significance
Model	< 0.0001	significant	< 0.0001	significant	< 0.0001	significant
A-WBA ratio	< 0.0001	significant	< 0.0001	significant	< 0.0001	significant
B-Specimen	0.036	significant	0.0358	significant	0.0019	significant
AB	-	-	0.0531	significant	-	-
Lack of fit	0.1551	not significant	0.2368	not significant	0.6187	not significant

The models' p-values of the compressive strength, ultrasonic pulse velocity, and flexural strength determined with ANOVA are < 0.0001, and therefore, the obtained models are significant. The p-values of the terms are less than 0.05, indicating that the terms significantly affect the response variable. The p-values over 0.1 indicate that the terms are not significant (do not significantly affect the response variable) (StatEase, 2021). It is seen that the terms A and B are significant for all response variables. In addition, the term AB (p-value=0.0531) in the model obtained for the flexural strength was added to the model since its p-value was nearly equal to the 0.05 significance level.

The lack of fit is used to obtain two or more observations (replication) on the response (StatEase, 2021). In the experimental design, two replicates were performed for each run. The determination of whether the two experimental results were compatible with each other was carried out with the lack of fit test. It is desired that the lack of fit is not significant, and it was determined that the lack of fit was insignificant for all response variables.

The obtained models at selected variation intervals of the variables for compressive strength, ultrasonic pulse velocity, and flexural strength are given in Equation (1), Equation (2), and Equation (3), respectively. The fit statistics of the responses are shown in Table 8.

$$\text{Ultrasonic pulse velocity} = 4.28 - 0.2118 \cdot A + 0.0414 \cdot B \tag{1}$$

$$\text{Flexural strength} = 6.55 - 1.55 \cdot A + 0.154 \cdot B + 0.2005 \cdot AB \tag{2}$$

$$\text{Compressive strength} = 37.45 - 13.24 \cdot A + 1.15 \cdot B \tag{3}$$

When the equations are examined, it is seen that the WBA ratio has a negative (-) effect, and the specimen age has a positive (+) effect. Therefore, response variable values decrease with the increase in WBA ratio and increase with the increase in specimen age. In addition, it can be said that the absolute effect of the WBA ratio in all response variables is greater than the specimen age.

Table 8. The Fit Statistics of the Models

Response	Units	Standard deviation	Mean	R^2	Adjusted R^2	Predicted R^2	Adequate precision
Ultrasonic pulse velocity	km/s	0.0573	4.32	0.8925	0.8823	0.8503	25.0087
Flexural strength	MPa	0.2857	7.03	0.9356	0.9249	0.9136	28.6889
Compressive strength	MPa	2.52	40.1	0.9404	0.9347	0.9183	32.2722

R^2 values for the response variables were obtained as 0.8925, 0.9356, and 0.9404, respectively. It shows that the models have a high correlation. The adjusted R^2 value shows that both the sufficiency of the model and the added terms to the model have a significant effect on the responses (StatEase, 2021). A high adjusted R^2 value is desirable and should not show wide deviations from the predicted R^2 value. Also, the results of the adjusted R^2 minus predicted R^2 is under 0.2 (StatEase, 2021) indicates that the prediction error of the data estimated from the models is appropriate. The adjusted R^2 minus predicted R^2 values of the ultrasonic pulsed wave velocity, flexural strength, and compressive strength are 0.032, 0.0113, and 0.0164, respectively.

The desirable adequate precision should be greater than 4 (StatEase, 2021). The adequate precision value of the compressive strength, ultrasonic pulse velocity, and flexural strength are 32.2722, 25.0087, and 28.6889 respectively. This indicates that the models form sufficient signals in the selected variation ranges.

Contour and 3D graphs of ultrasonic pulse velocity, compressive strength, and flexural strength are shown in Figure 7, Figure 8, and Figure 9, respectively. The maximum ultrasonic pulse velocity was obtained in the maximum specimen age with the minimum WBA ratio, and the minimum ultrasonic pulse velocity was obtained in the minimum specimen age with the maximum WBA ratio (Figure 7). The maximum flexural strength was obtained with the minimum WBA ratio. Specimen age was not affected the maximum flexural strength. The minimum flexural strength was obtained in the minimum specimen age with the maximum WBA ratio (Figure 8). The maximum compressive strength was obtained in the maximum specimen age with the minimum WBA ratio, and the minimum compressive strength was obtained in the minimum specimen age with the maximum WBA ratio (Figure 9).

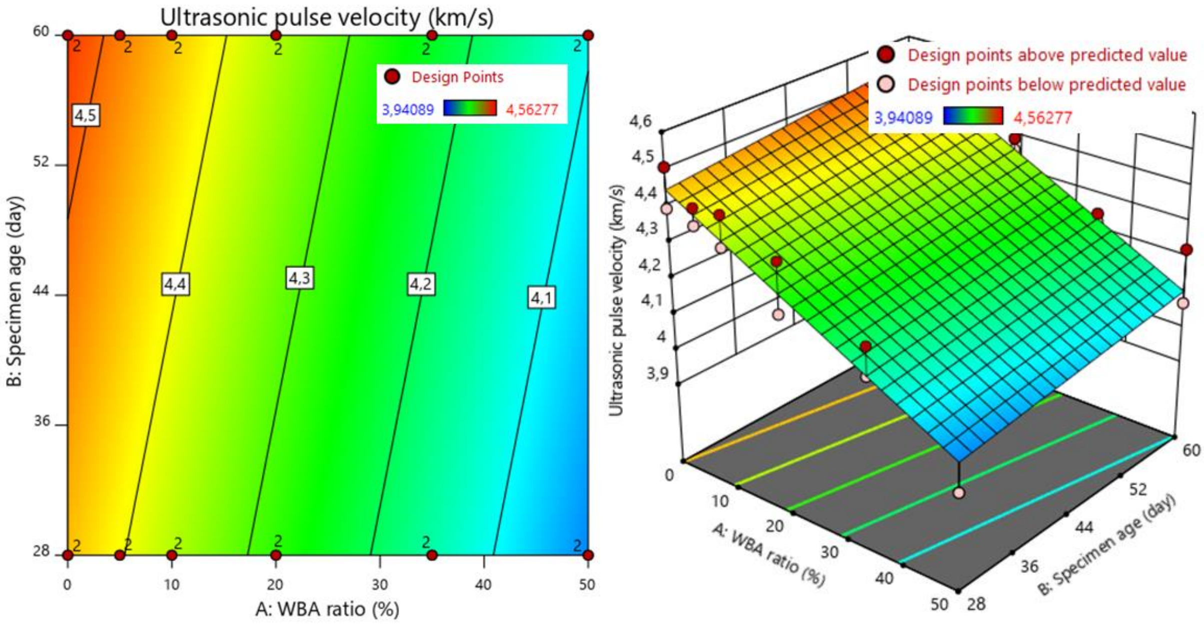

Figure 7. Contour and 3D Graphs of Ultrasonic Pulse Velocity

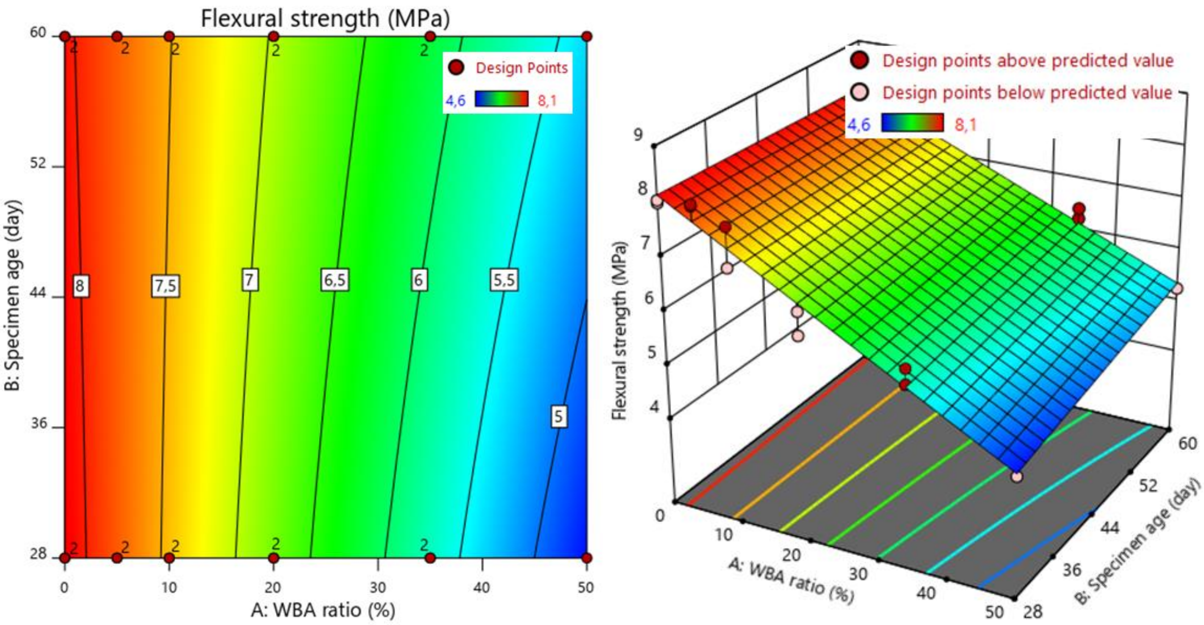

Figure 8. Contour and 3D Graphs of Flexural Strength

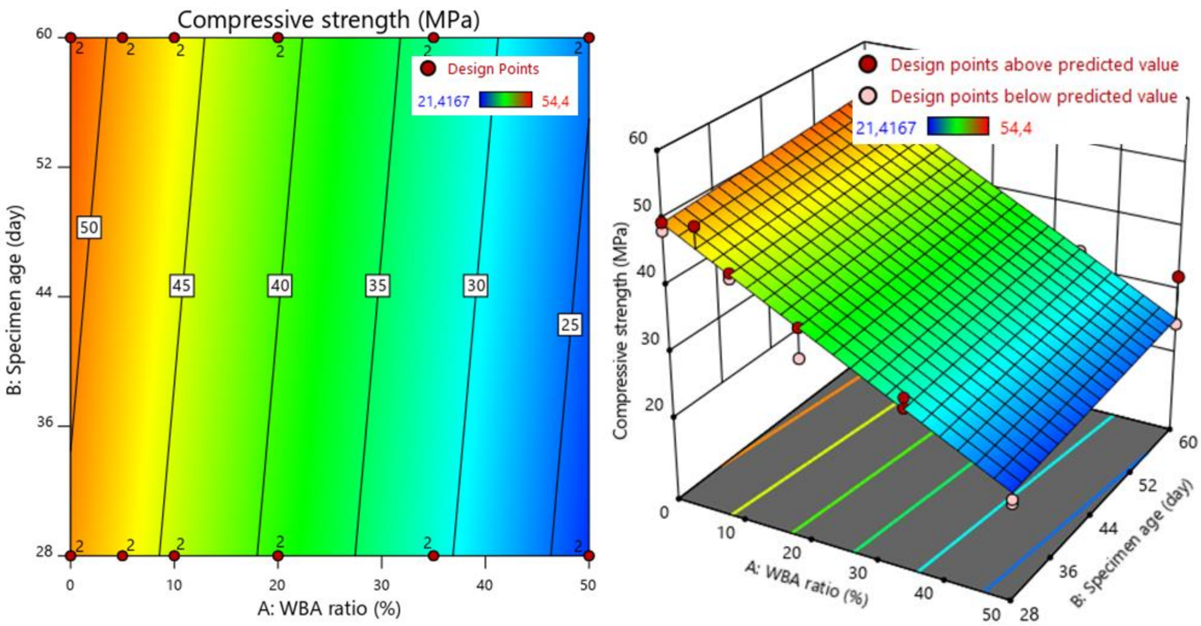

Figure 9. Contour and 3D Graphs of Compressive Strength

The predicted and the actual values (runs) of compressive strength, ultrasonic pulse velocity, and flexural strength are shown in Figure 10. The predicted results determined by the models obtained for the responses overlap the experimental results (Figure 10).

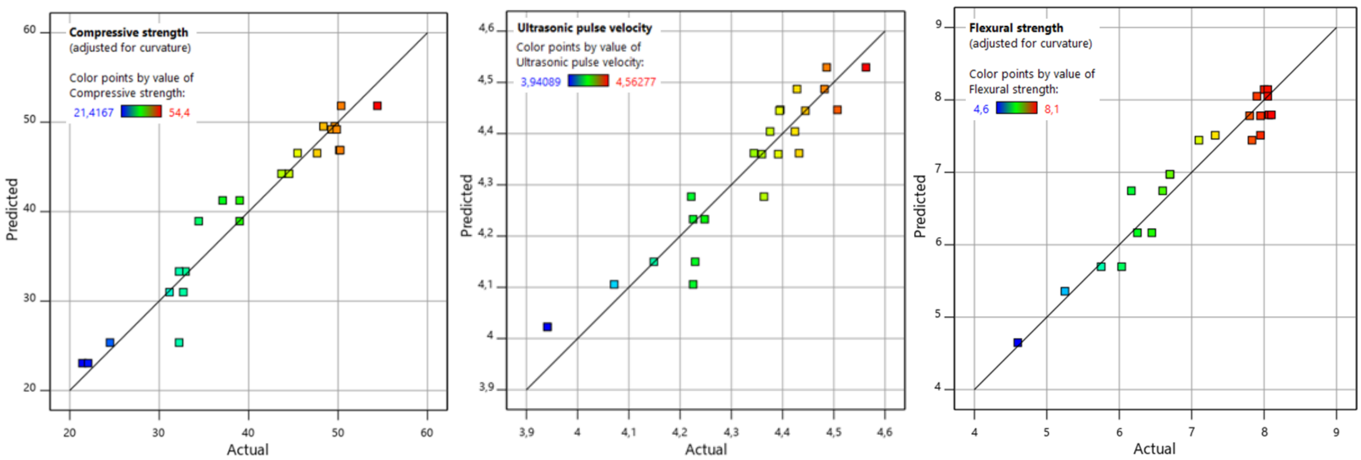

Figure 10. Actual and Predicted Values of Compressive Strength, Ultrasonic Pulse Velocity, and Flexural Strength

CONCLUSION

In the study, the effect of the PC with the replacement for WBA on the mechanical properties of mortars was investigated. Firstly, the effect of each effect variable on response variables was examined. Then, taking into account the interaction terms, their effect level on the response variables was determined. The results are summarized below.

- Up to 5% WBA ratio increases the flexural and compressive strength at 28-days slightly, while more than 5% WBA ratio decreases them.
- It is seen that the increase in the WBA ratio decreases the flexural and compressive strength at 60 days.
- An increase in the WBA ratio decreases the ultrasonic pulse velocity at 28 and 60-days. It shows that the increase in the WBA ratio raises the porosity.
- In mortars with a 50% WBA ratio, the decrease in compressive strength, ultrasonic pulse velocity, and flexural strength of the 28-day samples is higher than the 60-day samples. It shows that WBA is more effective on the mechanical properties of mortars at advanced ages.

- It is seen that the models obtained for compressive strength, ultrasonic pulse velocity, and flexural strength are significant.
- R^2 values of the response variables (UPV; 0.8925, f_f; 0.9356, f_c; 0.9404) were found to be high. It shows that the models have a high correlation. Adjusted R^2 values of the response variables (UPV; 0.8823, f_f; 0.9249, f_c; 0.9347) were found to be high. It shows that both the adequacy of the obtained models and the terms in the models have a significant effect on the response variables. Adjusted R^2 - predicted R^2 values of the response variables (UPV; 0.032, f_f; 0.0113, f_c; 0.0164) are greater than 0.2. It shows that the prediction error of the estimated data from the models is adequate.
- The fact that the adequate precision value for the responses is above the desired value (UPV; 25.0087 > 4, f_f; 28.6889 > 4, f_c; 32.2722 > 4) indicates that the models form sufficient signals in the selected variation ranges.

It can be said that the ratio of WBA that can be used in 28-day mortar samples is 5%, and this rate is higher at later ages in mortar samples. The predictability of compressive strength, flexural strength, and ultrasonic pulse velocity of WBA-added mortars are high ($R^2 > 0.90$). Therefore, the predictability of response variable models can be further increased by increasing the number of effect variables and narrowing the controllable ranges of variation selected.

ACKNOWLEDGMENTS

All authors thanks to Tekirdağ Namık Kemal University.

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