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Effect of waste concrete powder on slag-based sustainable geopolymer composite mortars

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ABSTRACT

In this study, the effect of waste concrete powder (WCP) on slag-based geopolymer composite mortars was investigated. Blast furnace slag (BFS) and WCP were used as binders in geopolymer mortars. WCP was substituted into the geopolymer mortar composites at rates of 10%, 20%, 30%, and 40% by weight of slag. Sodium hydroxide (NaOH) solution was used as the alkali activator in the mixtures and the solution activator concentration was chosen as 16 molars (M). After the prepared mortars were cured at 100°C for 24 hours, they were subjected to flexural strength (f_{fs}), compressive strength (f_{cs}), and ultrasonic pulse velocity (UPV) tests. Results showed that f_{fs}, f_{cs}, and UPV decreased with the increase in WCP replacement ratio. These decrements were seen clearly, especially after the 20% replacement ratio. However, despite these decrements, the compressive strengths of all groups were found to be above 50 MPa. In addition, it is thought that environmental pollution can be reduced by using WCP in geopolymer composite mortars.

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1. Introduction

The developments in concrete technology and the rapid increase in the global population have also increased housing needs. As a result of this situation, ordinary Portland cement (OPC) has become the world's most widely used construction material. A high number of raw materials and energy are consumed during the production of OPC (Li et al. 2019; Tahwia et al. 2022, Toklu 2021). It is also stated that OPC production is responsible for 7% of the world's greenhouse gas emissions (Meyer 2009; Sevim and Sengul 2021; Toklu and Şimşek 2018). These reasons have led researchers to work on developing more environmentally friendly and alternative binders to OPC (Sahmaran et al. 2013; Mehta and Siddique 2017; Demir et al. 2018; Sevim and Demir 2019). Developed as an alternative to OPC, geopolymer binders have been studied with increasing interest in recent years, as they consume less energy and emit less CO2 compared to OPC (Provis 2014; Geraldo et al. 2017; Alhawat et al. 2022).

It has been stated that geopolymers have many advantages such as superior mechanical properties (Mahmoodi et al. 2022), high resistance to elevated temperature (Çelikten et al. 2020), acid (Thokchom et al. 2009), and sulfate effects (Bhutta et al. 2013), as well as environmentally friendly properties. Geopolymers are produced as a result of the chemical reaction between aluminosilicate sources (precursors) such as metakaolin, blast furnace slag (BFS), fly ash (FA), and alkaline activators such as NaOH, Na_2SiO_3 (Rakhimova 2020; Öztürk and Atabey 2022). These aluminosilicate sources, widely used in geopolymers' production, were formerly seen as industrial by-products or waste. However, these products are no longer considered waste due to their successful and widespread use for years (Ulugöl et al. 2021). This situation has led researchers to investigate the use of different waste materials in geopolymer composites (Shoaei et al. 2019; Mahmoodi et al. 2021a).

Construction and demolition waste (CDW), which is responsible for most of the global solid waste production,

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has become a rapidly growing problem worldwide. While the 28 member countries of the European Union produced approximately 1.65 tons of CDW per capita in 2012, the United States of America produced approximately 1.7 tons of CDW per capita in 2015 (Ulugöl et al. 2021). Uncontrollable CDW production will continue to threaten the health of living things and the environment day by day (Wang et al. 2014). Geopolymers have been produced using some CDW products (concrete, glass, tiles, bricks, etc.).

Öztürk and Atabey (2022) produced geopolymer mortars containing recycled ceramic sanitaryware waste powder (CSW). NaOH as alkali activators in four different molars (10, 12, 14, and 16 M) and two different water/binder (w/b) ratios (0.45 and 0.50) were used in the mixtures. The increase in NaOH concentration increased the workability of the CSW-added mortars while decreasing their porosity and water absorption. The highest strength values were obtained from geopolymer mortars produced with 16 M NaOH and a 0.45 w/b ratio. Ahmari et al. (2012) investigated the combined use of waste concrete powder and F class FA as geopolymeric binders. The results showed that no significant improvement in compressive strength was achieved with the use of waste concrete powder alone, while there was an increase in compressive strength when used together with F class FA. Tahwia et al. (2022) produced ultra-high performance geopolymer concrete by using crushed glass (CG), ceramic (CC) and crumb rubber (CR) wastes as aggregates in geopolymer mortars. According to the results, it was observed that the mechanical and microstructural properties of the mixtures decreased significantly with the inclusion of CC and CR and increased with the inclusion of CG. A denser microstructure was obtained by incorporating CG into the mixtures.

In this study, the effect of waste concrete powder (WCP) on slag-based geopolymer composite mortars was investigated. Blast furnace slag (BFS) and WCP were used as binders in geopolymer mortars. WCP was substituted into the geopolymer mortar composites at rates of 10, 20, 30, and 40% by weight of slag. Sodium hydroxide (NaOH) solution was used as the alkali activator in the mixtures and the solution activator concentration was chosen as 16 molars (M). After the prepared mortars were cured at 100°C for 24 hours, they were subjected to flexural strength (f_{fs}), compressive strength (f_{cs}), and ultrasonic pulse velocity (UPV) tests. Finally, the obtained results were compared with control geopolymer mortars without waste concrete powder replacement.

2. Materials and Method

In the preparation of geopolymer mortars, standard sand defined by CEN (Committee of European Norms) in TS EN 196-1 was used. The sand was obtained from the local source in Turkey. BFS was selected according to ASTM C989 (ASTM 2014b). WCP was obtained by grinding the materials collected from the landfill. The ground material was used after sieving through the 75 µm sieve. The chemical oxide composition and physical properties of BFS and WCP are given in Table 1. NaOH in the form of white pellets with a purity of about 99% was used as an alkali activator in the mixtures.

Table 1. Chemical oxide composition and physical properties of BFS and WCP.

Chemical composition (%)	BFS	WCP
SiO_2	35.97	26.38
Al_2O_3	16.05	5.23
Fe_2O_3	0.66	2.06
MgO	5.43	9.45
CaO	37.38	32.96
Na_2O	0.38	0.51
K_2O	0.81	0.75
TiO_2	0.58	0.23
Physical properties		
Relative density (g/cm^3)	3.06	2.69
Loss on ignition (LOI)	1.18	21.98

Mixing ratios of geopolymer mortars are given in Table 2. Fresh geopolymer mortars prepared per TS EN 196-1 were filled in molds with dimensions of 40×40×160 mm in two stages and compressed on the shaking table. It was then cured in an oven at 100°C for 24 hours. Ultrasonic pulse velocity (UPV) test was conducted per ASTM C 597-16 standard for the geopolymer mortars whose curing process was completed. Table 3 shows the classification of the quality of concrete as a function of the ultrasonic pulse velocity (Whitehurst 1951; Qasrawi 2000). Afterward, the flexural strengths of the samples were determined per TS EN 196-1. In addition, the compressive strength test was conducted on the broken parts of the prismatic samples after the flexural strength test.

Table 2. Mixing ratios of geopolymer mortars.

Mixture Code	BFS (g)	WCP (g)	WCP ratio (%)	Water (g)	Sand (g)	NaOH (g)	Molarity (M)	Curing time (hour)	Curing temperature (°C)
Ref	450	0	0	192.60	1350	144	16	24	100
WCP10	405	45	10						
WCP20	360	90	20						
WCP30	315	135	30						
WCP40	270	180	40						

Table 3. Quality of concrete as a function of the ultrasonic pulse velocity (Whitehurst 1951).

UPV (km/h)	>4.5	3.5–4.5	3.0–3.5	2.0–3.0	<2.0
Quality	Excellent	Good	Doubtful	Poor	Very poor

3. Results and Discussion

3.1. Flexural strength (f_{fs})

The f_{fs} test results performed per the TS EN 196-1 standard are shown in Fig. 1(a). For the mixtures with each code, the average of the results of three samples was taken as the final f_{fs} results. The percentage of decrease in f_{fs} results of slag-based geopolymer mortars incorporating WCP compared to control geopolymer mortars without WCP is shown in Fig. 1(b).

When the f_{fs} results given in Fig. 1 are examined, it is seen that the f_{fs} results vary between 12.05 and 10.45 MPa. The f_{fs} results of the WCP10, WCP20, WCP30, and WCP40 decreased by 2.84, 4.07, 7.80, and 13.27%, respectively, compared to the Ref mortars. The rate of decrease in f_{fs} results increased with the increase of the WCP replacement ratio. BFS particles provide the formation of calcium alumina silicate hydrate (C-A-S-H) and/or calcium silicate hydrates in the geopolymeric gel system (Rakhimova and Rakhimov 2015; Mahmoodi et al. 2021b). As the amount of WCP in the mixtures increases, the amount of BFS decreases. As a result of this situation, the hydrated element density in the matrix of geopolymer mortars decreases. Tan et al. (2020) stated in their study that the geopolymer samples became much denser with the addition of BFS. These conditions can be shown as the reason for the decrease in f_{fs} results with the increase in WCP replacement ratio.

3.2. Compressive strength (f_{cs})

The f_{cs} test results performed per the TS EN 196-1 standard are shown in Fig. 2(a). The f_{cs} test was performed on two pieces of samples obtained as a result of the f_{fs} test. For the mixture with each code, the average of the results of six samples was taken as the final f_{cs} result. The percentage of decrease in f_{cs} results of slag-based geopolymer mortars incorporating WCP compared to control geopolymer mortars without WCP is shown in Fig. 2(b).

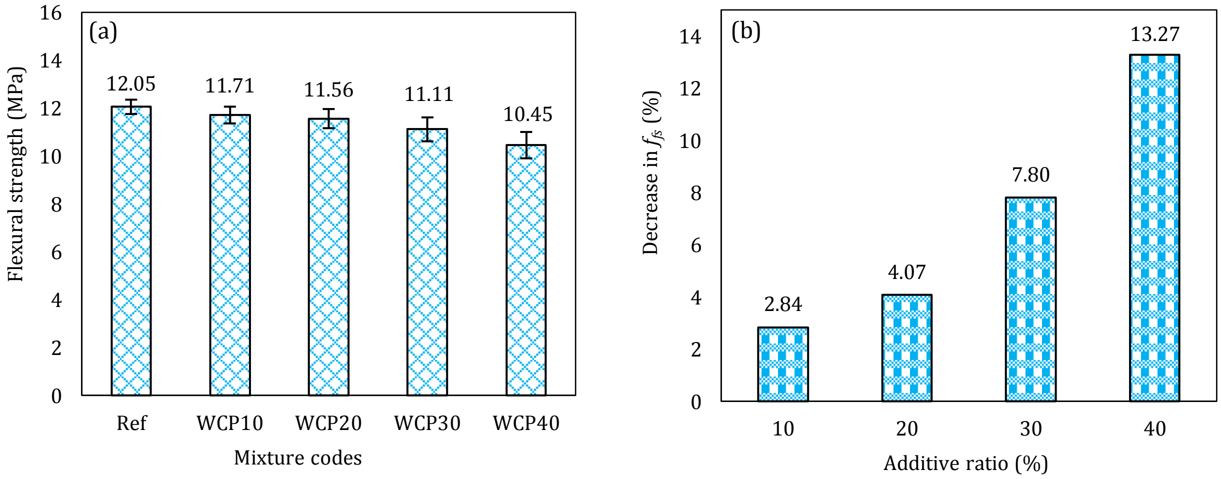

Fig. 1. (a) The f_{fs} test results;(b) The percentage of decrease in f_{fs} results.

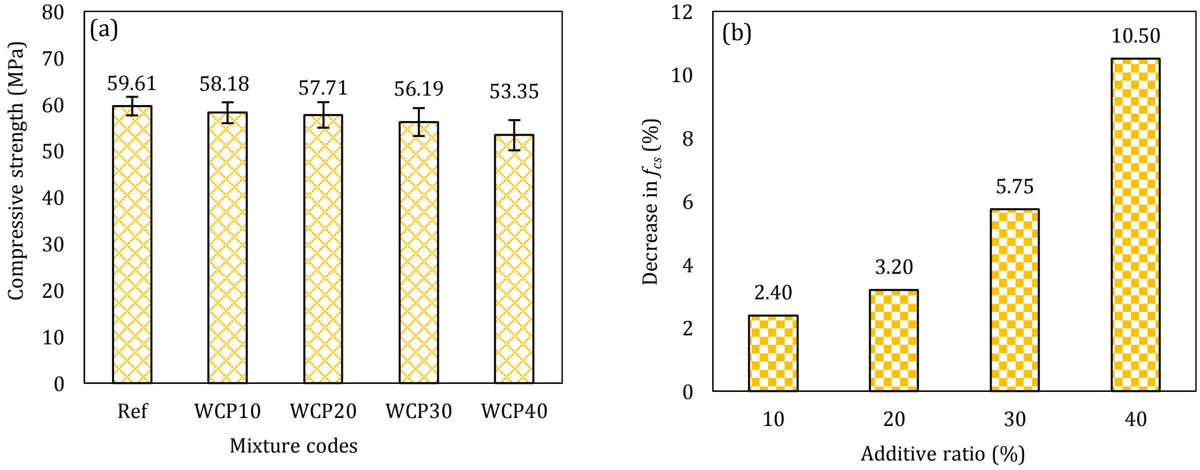

Fig. 2. (a) The f_{cs} test results; (b) The percentage of decrease in f_{cs} results.

When the f_{cs} results given in Fig. 2 are examined, it is seen that the f_{cs} results vary between 59.61 and 53.35 MPa. The f_{cs} results of the WCP10, WCP20, WCP30, and WCP40 decreased by 2.40, 3.20, 5.75, and 10.50%, respectively, compared to the Ref mortars. As in the f_{fs} results, the rate of decrease in the strengths increased with the increase of WCP replacement ratio in the f_{cs} results. However, considering the results obtained from the f_{cs} results, the f_{cs} results of all mixture groups remained above 50 MPa. This value is quite sufficient for many building applications. It has been noted that the slag adds more calcium oxide to the geopolymer matrix. Free calcium in the geopolymer matrix increases the reaction rate and the geopolymerization process due to the formation of C-A-S-H gel in the early stage (Puligilla and Mondal 2013; Tan et al. 2020). The reason for the decrease in f_{cs} results as a result of the increase in the replacement ratio of WCP in the geopolymer mortars can be explained in this way.

3.3. Ultrasonic pulse velocity (UPV)

The results of the UPV test performed per the ASTM C 597-16 standard are shown in Fig. 3(a). For the mixture with each code, the average of the results of three samples was taken as the final UPV results.

When the UPV results given in Fig. 3 are examined, it is seen that the UPV results vary between 4.55 and 4.29 km/h. The UPV results of the WCP10, WCP20, WCP30, and WCP40 decreased by 1.39, 2.75, 3.74, and 5.70%, respectively, compared to the Ref code mortars. As in the f_{fs} and f_{cs} results, the rate of decrease in the strengths increased with the increase of WCP replacement ratio in the UPV results. According to the Whitehurst (1951) classification, Ref mortars are in the "excellent" class, while WCP substituted mortars are in the "good" class. Song et al. (2019) reported that in geopolymer mortars, the slag can fill the pores and voids, thus increasing the strength of the matrix. For this reason, it was thought that the porosity of geopolymer mortars increased with the increase of WCP replacement ratio, and this situation caused decreases in UPV results. Fig. 4 shows the correlations between f_{fs} and f_{cs} results and UPV results. Linear regression was used to correlate the f_{fs} and f_{cs} results with the UPV results and the equations obtained are given on the graphs in Fig. 4. As seen in Figs. 4(a-b), R^2 values were obtained as 0.9641 and 0.9566, respectively. These values can mean good confidence in the correlation.

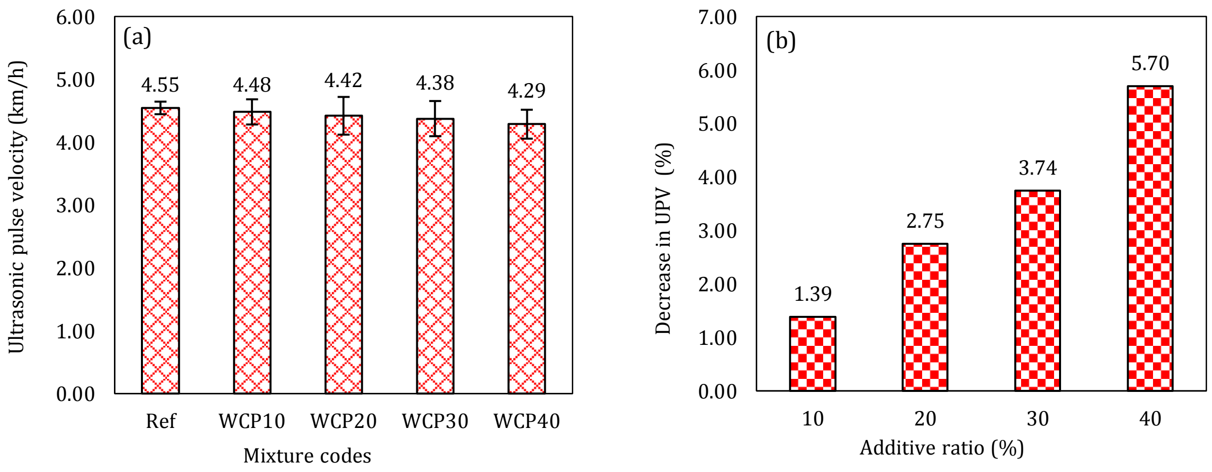

Fig. 3. (a) The UPV test results; (b) The percentage of decrease in UPV results.

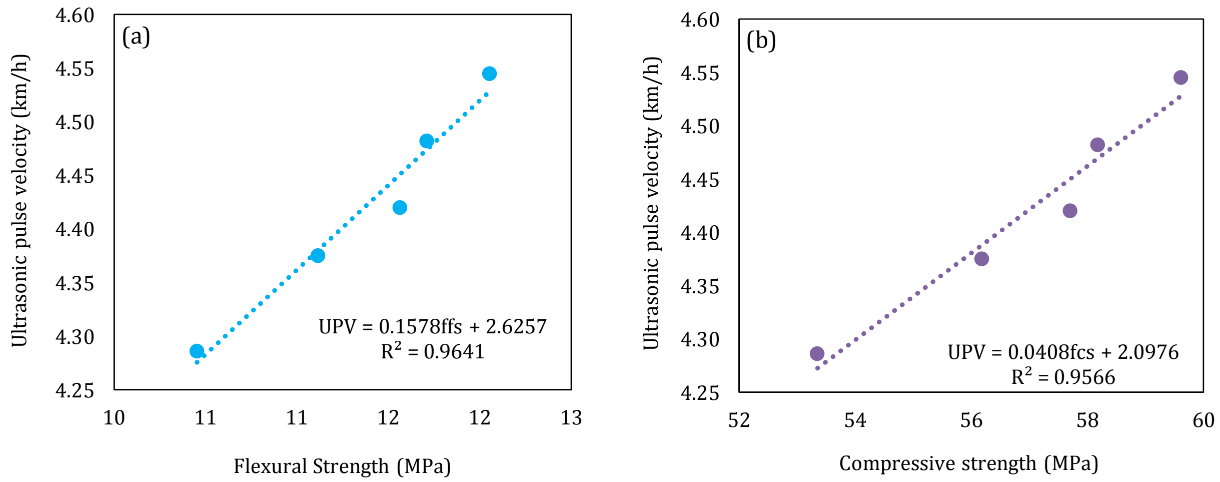

Fig. 4. Relationship between (a) f_{fs} and UPV; (b) f_{cs} and UPV.

4. Conclusions

In this study, the effect of waste concrete powder (WCP) on slag-based geopolymer composite mortars was investigated. Blast furnace slag (BFS) and WCP were used as binders in geopolymer mortars. WCP was substituted into the geopolymer mortar composites at rates of 10%, 20%, 30%, and 40% by weight of slag. Sodium hydroxide (NaOH) solution was used as the alkali activator in the mixtures and the solution activator concentration was chosen as 16 molars (M). After the prepared mortars were cured at 100°C for 24 hours, they were subjected to flexural strength (f_{fs}), compressive strength (f_{cs}), and ultrasonic pulse velocity (UPV) tests. The following results were obtained from this study:

- With the increase in WCP replacement ratio, decreases in f_{fs} ranging from 2.84 to 13.27% were observed. It has been determined that the decreases in f_{fs} results are seen more clearly when the replacement ratio rises above 20%. The highest strength loss was observed in geopolymer mortars with 40% WCP, and this rate was determined as 13.27%.
- f_{cs} results also decreased with the increase of WCP replacement ratio, similar to f_{fs} results. There were decreases in f_{cs} results between 2.40 and 10.50%. The lowest result in f_{cs} was obtained from geopolymer mortars with 40% WCP and was measured as 53.35 MPa. Although this result is 10.50% lower than reference mortars, it is a remarkably high value for many construction applications.
- When the UPV results were examined, it was seen that there were decreases between 1.39 and 5.70% with the increase in the WCP replacement ratio. However, according to the Whitehurst (1951) classification, mortars with WCP were found to be in the "good" class.
- Finally, it was determined that the relations between flexural strength & ultrasonic pulse velocity and compressive strength & ultrasonic pulse velocity parameters exhibited a remarkably high coefficient of determination (R^2).

When the results from the study are evaluated in general, it has been determined that WCP can be used in the remarkably high ratio (up to 40% replacement rate) in geopolymer mortars. Although it is seen that WCP replacement causes decreases in strength, it has been determined that the results are quite sufficient for many building applications. In addition, it has been observed that a high amount of WCP as a waste material can be disposed of using geopolymer mortars. In this way, environmental pollution will be reduced, and a sustainable environment will be contributed. In further studies, the effect of WCP can be examined by changing the molarity, curing temperature, and curing time parameters.

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Conflict of Interest

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