NÖHÜ Müh. Bilim. Derg. / NOHU J. Eng. Sci., Erken Görünüm / InPress

Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi
Niğde Ömer Halisdemir University Journal of Engineering Sciences

Araştırma makalesi / Research article

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Statistical analysis of mechanical properties of waste glass powder substituted glass fiber mortars by ANOVA

Atık cam tozu ikameli cam elyaf içeren harçların mekanik özelliklerinin ANOVA ile istatistiksel analizi

Mehmet Timur Cihan [1,*], Veysel Akyüncü[2]

[1,2] Tekirdağ Namık Kemal University, Çorlu Engineering Faculty, Department of Civil Engineering, 59860, Tekirdağ Türkiye

Abstract

Using waste in the cement and concrete industry helps reduce costs and the need for large storage spaces for waste disposal. In particular, disposing of waste glass powder (WGP) from the glass industry requires significant storage capacity. Therefore, utilizing WGP as a raw material in construction is both an environmentally and economically viable solution. This study examined the workability, flexural strength, compressive strength, and splitting tensile strength of glass fiber-reinforced mortars containing WGP. A face-centered composite design was used to determine 13 test points. The fiber ratio was selected at 0%, 0.3%, and 0.6% by weight of the mixture, while WGP substitution levels were 0%, 7.5%, and 15% by weight of cement. The results indicate that adding glass fiber and WGP reduces flow value, flexural strength, compressive strength, and splitting tensile strength. However, at higher glass fiber ratios, the negative effect of WGP on flow value and compressive strength is less pronounced. The R^2 values for flow value, flexural strength, compressive strength, and splitting tensile strength were 0.9983, 0.9586, 0.9069, and 0.8526, respectively, indicating a strong correlation between the tested parameters and the predictive model.

Keywords: Glass fiber, Waste glass powder, ANOVA, Flow value, Flexural strength, Compressive strength, Splitting tensile strength

Öz

Atıkların çimento ve beton endüstrisinde kullanılması, maliyetin ve atık bertarafı için büyük depolama alanlarına olan ihtiyacın azaltılmasına yardımcı olur. Özellikle cam endüstrisinden çıkan atık cam tozunun (WGP) bertaraf edilmesi önemli bir depolama kapasitesi gerektirmektedir. Bu nedenle, WGP'nin inşaatta hammadde olarak kullanılması hem çevresel hem de ekonomik açıdan uygulanabilir bir çözümdür. Bu çalışmada, WGP içeren cam lif takviyeli harçların işlenebilirliği, eğilmede çekme, basınç ve yarmada çekme dayanımları incelenmiştir. Yüzey merkezli kompozit tasarım 13 test noktasını belirlemek için kullanılmıştır. Lif oranı karışımın ağırlığına göre %0, %0.3 ve %0.6 olarak seçilirken, WGP ikame seviyeleri çimentonun ağırlığına göre %0, %7.5 ve %15 olarak belirlenmiştir. Sonuçlar, cam lif ve WGP ilavesinin yayılma değerini, eğilmede çekme, basınç ve yarmada çekme dayanımını azalttığını göstermektedir. Bununla birlikte, daha yüksek cam lif oranlarında, WGP'nin yayılma değeri ve basınç dayanımı üzerindeki olumsuz etkisi daha az belirgindir. Yayılma değeri, eğilmede çekme, basınç ve yarmada çekme dayanımı için R^2 değerleri sırasıyla 0.9983, 0.9586, 0.9069 ve 0.8526 olup test edilen parametreler ile tahmini model arasında güçlü bir korelasyon olduğunu göstermektedir.

Anahtar kelimeler: Cam lifi, Atık cam tozu, ANOVA, Yayılma değeri, Eğilmede çekme dayanımı, Basınç dayanımı, Yarmada çekme dayanımı

1 Introduction

As sustainability becomes a priority in the construction industry, emphasis is being placed on recycling waste to produce environmentally friendly cement-based or cement-free materials [1]. Glass is versatile due to its properties, such as transparency and inertness [2]. The glass is completely recyclable. However, there are still limitations due to quality criteria in glass production [1]. Therefore, non-recyclable glass waste is disposed of in landfills [1]. The amount of glass landfilled worldwide is estimated at approximately 200 million tons annually [3]. In addition, approximately 400000 tons of glass waste is buried annually in the three largest cities of Turkey (Istanbul, Izmir, and Ankara) [4].

Waste glass cullet is used as an aggregate source (coarse aggregate [5] or fine aggregate [6,7]) in the construction industry [8,9]. However, it is known that they have adverse effects, such as a decrease in workability/strength [6,7] and alkali-silica reaction (ASR) [10]. In addition, waste glass powder (WGP) is also used for sustainable production in the construction industry. In particular, it is used for geopolymer production [11] and lightweight aggregate manufacturing [12,13].

Concrete is the most widely used building material and has low tensile strength. Different types of fibers, such as steel, polypropylene, aspect, and glass [14], are used to improve the tensile strength of concrete [15]. Glass fibers

* Sorumlu yazar / Corresponding author, e-posta / e-mail: mehmetcihan@nku.edu.tr (M. T. Cihan)
Geliş / Recieved: 01.10.2024 Kabul / Accepted: 24.02.2025 Yayımlanma / Published: xx.xx.20xx
doi: 10.28948/ngmuh.1558323

delay the development of micro-cracks in the early age of concrete and thus increase the tensile strength and toughness of concrete [16]. The mechanical properties of glass fiber reinforced concretes generally depend on the fiber content, water/cement ratio, void content, sand content, fiber distribution, fiber length, and curing conditions. Glass fiber is chosen to help prevent shrinkage cracks from forming.

In mortars using glass fiber with a length of 12 mm and a diameter of 14 µm, compressive strength decreases with increasing fiber ratio, but flexural strength increases [17–19]. Using more than 0.5% glass fiber (l/d-length/diameter of 6-8 mm/78 µm) in shotcrete reduces tensile strength in bending [20]. In the case of using glass fiber with an l/d of 3 mm/12-13 µm in mortars, no significant change is observed in flexural and compressive strengths [21].

In studies with high controllable and uncontrollable effect variables, central composite design is frequently used within the scope of response surface methodology [22]. A face-centered composite design was preferred within the scope of this study. This design determines the optimum effect levels of controllable variables on the response variable. One of the most important advantages of the face-centered composite design is that it increases applicability by keeping the experimental points within cubic boundaries [22]. This feature prevents the experimental conditions from reaching extreme values. This allows data to be produced for the desired variation intervals of controllable effect variables. In addition, it allows the creation of second-degree (quadratic) models, and nonlinear interactions between variables can be determined. Especially in experimental and observational studies, ANOVA (analysis of variance) is preferred to determine the effect levels of the variables on response variables at different variation intervals [22].

Using waste materials in the cement and concrete industry is crucial for reducing both disposal costs and the need for large storage areas. Waste glass powder (WGP), a byproduct of the glass industry, requires significant storage space, making its utilization in construction materials an important area of research. This study aims to evaluate the effects of WGP and glass fiber on mortars' workability and mechanical properties. By analyzing flow value, flexural strength, compressive strength, and splitting tensile strength, the research provides valuable insights into the feasibility of incorporating WGP in fiber-reinforced mortars. Additionally, statistical analysis was conducted to assess the observed effects' significance and the predictive models' reliability.

2 Material and method

2.1 Material

CEM I 42.5 R cement, standard sand (conforming to TS EN 196-1 [23]), distilled water, glass fiber (GF, length, 3 mm), and 300 µm under-sieve waste glass powder (WGP) were used in specimen production. Distilled water with standard content was used to minimize the variability in the experimental results depending on the content of the mixture water. The chemical composition of cement and WGP is given in Table 1. Moreover, the elements in the WGP content were determined by SEM-EDX and shown in Table 2. As expected, Si is the highest element by weight in the WGP. The specific gravity and specific surface value of cement are 3.12 and 4129 cm^2/g, respectively. WGP's particle structure and granulometry curve were determined using SEM imaging and sieve analysis. The granulometry curve and SEM images are shown in Figure 1 and Figure 2, respectively. Moreover, the constituent materials for each run point are given in Table 3.

Table 1. Chemical composition of cement and WGP

Composition (%)	CEM I 42.5 R	WGP
CaO	64.24	8.55
SiO_2	17.73	73.10
Al_2O_3	4.15	1.03
Fe_2O_3	2.98	1.43
MgO	0.90	3.87
SO_3	3.26	0.27
Na_2O	0.35	8.51
K_2O	0.69	0.02
Cl^-	0.02	0.01
H_2O	-	1
Loss of ignition	4.00	2.37
Free lime	1.82	-
Insoluble residue	0.37	-

Table 2. The elements in the WGP

Elements	O	Na	Mg	Al	Si	K	Ca	Fe
wt %	46.34	11.22	3.27	1.015	34.51	0.15	3.165	0.325

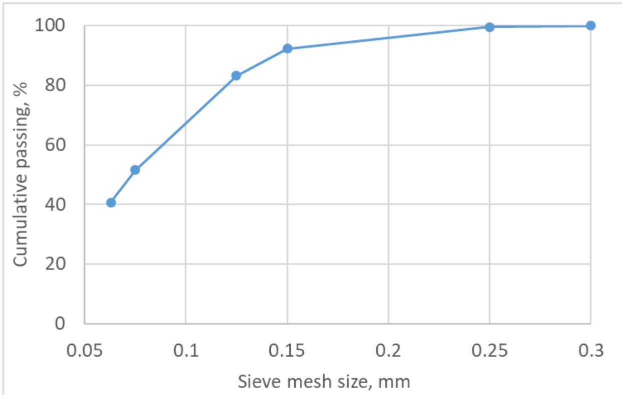

Figure 1. Grading curve for WGP

WGP can trigger pozzolanic reactions [24]. The 75 µm grain size is the threshold value for the pozzolanic reactivity of WGP [25,26]. When the WGP grading curve (Figure 1) is analyzed, it is seen that 60% of the WGP used is coarser than 63 µm. This indicates that the pozzolanic effect of WGP will be low. In general, WGP is known to have an angular shape and sharp edges [27,28]. When Figure 2 (SEM images) is examined, it is seen that the WGPs used in the study also have an angular form and sharp edges. WGP particles have higher aspect ratios and a smoother texture than Portland cement particles [24,29,30].

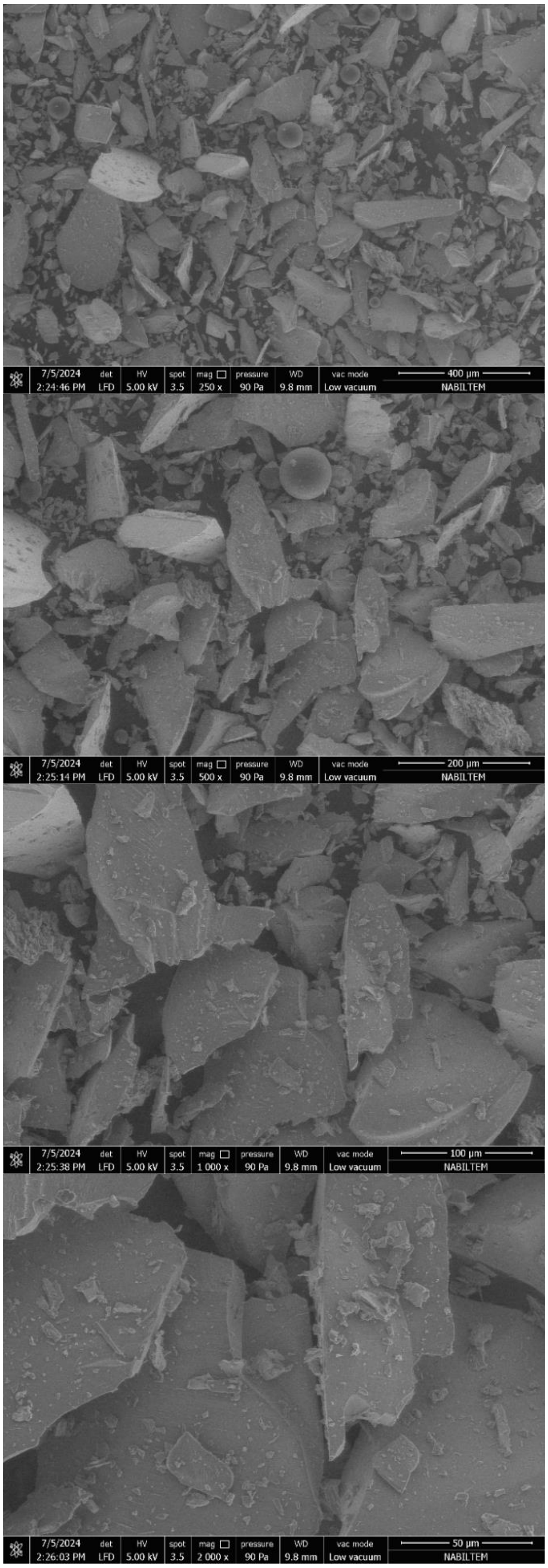

Figure 2. SEM images for WGP (400, 200, 100, and 50 µm)

Table 3. Constituent materials for run points

Run	Space type	Cement g	Standard sand g	Distilled water g	Glass powder g	Glass fiber g
1, 3, 4, 6, 13	Center	1248.8	4050	675	101.3	18.23
2	Axial	1147.5	4050	675	202.5	18.23
5	Axial	1248.8	4050	675	101.3	0
7	Factorial	1350	4050	675	0	0
8	Factorial	1350	4050	675	0	36.45
9	Axial	1248.8	4050	675	101.3	36.45
10	Factorial	1147.5	4050	675	202.5	36.45
11	Factorial	1147.5	4050	675	202.5	0
12	Axial	1350	4050	675	0	18.23

2.2 Method

In the experimental study, glass fiber (GF) ratio (by weight of mix, 0%, 0.3%, and 0.6%), waste glass powder (WGP) substitution ratio (by weight of cement, 0%, 7.5%, and 15%) were selected as effect variables. The run points were determined using a face-centered composite design. The central composite design is named differently depending on the distance of the axial test points from the center point (α) [22]. In the face-centered composite design, it is 1. This means that for two effect variables, the axial points are placed at the centers of the surfaces. For two effect variables, the geometric view of the face-centered composite design is shown in Figure 3. The face-centered composite design enhances applicability, ensuring that experimental points remain within cubic boundaries [22]. In the experimental study, 5, 4, and 4 test points were selected for the center, axial, and factorial regions (as shown in Figure 3), respectively, and 13 run points were determined. The coded values of the variation intervals of the effect variables are given in Table 4.

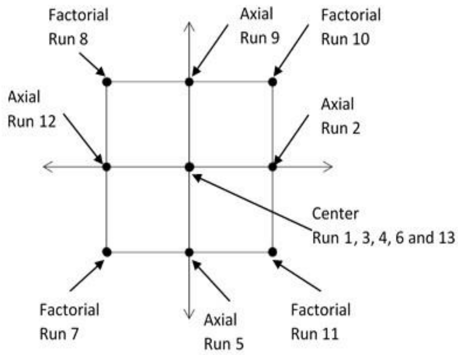

Figure 3. Geometric view of the face-centered composite design for two effect variables

Table 4. Variation intervals of effect variables and coded values

Effect variables	Unit	Type	Min.*	Max.*	Coded values Low	Coded values High
A: WGP ratio	%	Num.*	0.00	15.00	-1 ↔ 0.00	+1 ↔ 15.00
B: GF ratio	%	Num.*	0.00	0.60	-1 ↔ 0.00	+1 ↔ 0.60

Num.: Numerical, Min.: Minimum, Max.: Maximum

The mortar specimens were prepared according to TS EN 196-1 [23]. They were initially subjected to 24-hour sealing curing, followed by immersion in lime-saturated water at

20±1 °C until the testing date. To determine the flexural and compressive strength, 39 specimens (40×40×160 mm) were produced, with three specimens for each run point. Additionally, 13 specimens (100×100 mm) were prepared for splitting tensile strength, with one specimen for each run point.

Flow value (mm), flexural strength (MPa), splitting tensile strength (MPa), and compressive strength (MPa) were selected as response variables. The flow-table, flexural, compression, and splitting tensile tests were performed according to TS EN 1015-3 [31], TS EN 196-1 [23], TS EN 196-1 [23], and TS EN 12390-6 [32] standards, respectively.

In the flow-table test, fresh mortar was placed into the cone in two stages, with each stage compacted by tamping 10 times using a rod. After 15 drops over 60 seconds, the diameters of the spread mortar were measured. The average diameter (flow value) was then calculated using measurements along the x- and y-axis directions.

Mortar samples were loaded at three points for flexural strength, with their lateral faces positioned perpendicular to the loading surface and supporting pins. The span length was 100 mm. Each divided sample was fractured by placing it between head blocks measuring 40×40 mm for compressive strength.

The splitting tensile test was carried out by applying a compressive load perpendicular to the axis of 100×100 mm specimens. The specimen split in the middle due to the tensile stresses that occurred when the load was applied.

The effect levels of the variables on the response were determined by ANOVA [22]. The Box-Cook method [33] was used to determine whether a transformation should be applied to the results to determine the effect levels accurately. In addition, the suitability of the obtained models was evaluated using fit statistics [34]. Statistical calculations within the scope of the study were performed using Design Expert [34].

3 Results and discussion

The test results (flow value, flexural strength, compressive strength, and splitting tensile strength) performed on the specimens produced for 13 run points obtained from the face-centered composite design are given in Table 5.

Table 5 shows that the flow values vary in the 10-16 cm range. The flow value decreases as the waste glass powder and glass fiber ratio increases. The flexural strength, splitting tensile strength, and compression strength values vary in the 6.26-7.57 MPa, 2.36-3.74 MPa, and 27.37-42.05 MPa ranges, respectively.

The design summary for the response variables is given in Table 6. The Box-Cook method was used to determine whether a converter would be required on the results to determine the effect levels correctly. The study determined that the power transducer should be applied only to compressive strength results. The most suitable exponent was obtained as -2.51 in this power transformation and applied to the compressive strength results. The design summary shows that only the model obtained for the spreading table value is quadratic, and the other response variables are linear.

The ANOVA results for the responses are given in Table 7. The p-value <0.1 indicates that the term added to the model has a significant effect level. Therefore, it is seen that all terms used in the models have a significant effect level (Table 6). In addition, the p-value of the response variables' models is <0.0001, which shows that the models are significant.

The models obtained in terms of coded values for flow value, flexural strength, compressive strength, and splitting tensile strength are given in Equation 1, Equation 2, Equation 3, and Equation 4, respectively. The models are given according to the coded values to allow the relative effects to be determined by comparing the coefficients.

Table 5. Run points and experimental results

		Effect variables		Response variables			
Run	Space type	A: WGP ratio %	B: GF ratio %	Flow value cm	Flexural strength MPa	Compressive strength MPa	Splitting tensile strength MPa
1	Center	7.5	0.3	13.00	7.00	30.83	3.13
2	Axial	15.0	0.3	11.75	6.62	29.09	2.79
3	Center	7.5	0.3	13.00	6.98	32.57	2.88
4	Center	7.5	0.3	13.00	7.08	33.25	2.92
5	Axial	7.5	0.0	15.40	7.27	39.99	3.74
6	Center	7.5	0.3	13.00	7.10	33.02	3.02
7	Factorial	0.0	0.0	16.25	7.57	42.05	3.58
8	Factorial	0.0	0.6	10.50	7.42	33.19	3.15
9	Axial	7.5	0.6	11.00	6.77	28.34	2.66
10	Factorial	15.0	0.6	10.00	6.26	27.37	2.36
11	Factorial	15.0	0.0	13.75	6.58	33.08	2.92
12	Axial	0.0	0.3	13.00	7.53	40.42	3.33
13	Center	7.5	0.3	13.00	7.04	30.68	2.98

Table 6. Design summary for response variables

Responses	Units	Obs.*	Analysis	Min.*	Max.*	Mean	Transform	Model
Flow value	cm	13	Polynomial	10	16.25	12.82	None	Quadratic
Flexural strength	MPa	13	Polynomial	6.26	7.57	7.02	None	Linear
Compressive strength	MPa	13	Polynomial	27.37	42.05	33.37	Power	Linear
Splitting tensile strength	MPa	13	Polynomial	2.36	3.74	3.04	None	Linear

Obs.: Observations, Min.: Minimum, Max.: Maximum

Table 7. ANOVA for response variables

	Flow value		Flexural strength		Compressive strength		Splitting tensile strength	
Source	**p-value**	**Significance**	**p-value**	**Significance**	**p-value**	**Significance**	**p-value**	**Significance**
Model	< 0.0001	significant	< 0.0001	significant	< 0.0001	significant	< 0.0001	significant
A-Glass powder ratio	< 0.0001	significant	< 0.0001	significant	< 0.0001	significant	0.0004	significant
B-Glass fiber ratio	< 0.0001	significant	0.0009	significant	< 0.0001	significant	0.0003	significant
AB	< 0.0001	significant	-	-	-	-	-	-
A^2	< 0.0001	significant	-	-	-	-	-	-
B^2	0.0058	significant	-	-	-	-	-	-

$$Flow\ value = 12.99 - 0.7083 \cdot \mathrm{A} - 2.32 \cdot \mathrm{B} + 0.50 \cdot \mathrm{AB} - 0.6009 \cdot A^2 + 0.2241 \cdot B^2 \quad (1)$$

$$Flexural\ strength = 7.02 - 0.5082 \cdot \mathrm{A} - 0.1622 \cdot \mathrm{B} \quad (2)$$

$$Compressive\ strength^{-2.51} = 0.0002 + 4.7179 \cdot 10^{-5} \cdot \mathrm{A} + 4.8751 \cdot 10^{-5} \cdot \mathrm{B} \quad (3)$$

$$Splitting\ tensile\ strength = 3.04 - 0.3309 \cdot A - 0.3461 \cdot B \quad (4)$$

The fit statistics of the models obtained for the response variables are given in Table 8. The highest R^2 value (0.9828) was obtained for the flow value. The R^2 values for flexural, compressive, and splitting tensile strengths were 0.9113, 0.8374, and 0.7248, respectively. Adjusted R^2 and estimated R^2 values were also determined. It is seen that the estimated R^2 values for all response variables are in reasonable agreement with the adjusted R^2 values (i.e., their difference is less than 0.2 [34]).

Table 8. Fit statistics

Responses	**R^2**	**Adjusted R^2**	**Predicted R^2**
Flow value	0.9983	0.9971	0.9828
Flexural strength	0.9586	0.9504	0.9113
Compressive strength	0.9069	0.8882	0.8374
Splitting tensile strength	0.8526	0.8232	0.7248

The variation between the predicted values and the observations (actual) is shown in Figure 4. The best overlap between the measured and predicted values is seen in the flow value variable, where R^2 is the highest. The predictability of the flexural strength is higher than the splitting tensile strength because the use of glass fiber affects the indirect tensile strength at different levels. In particular, it is known that indirect tensile strengths are much more sensitive to glass fiber distribution.

The interaction plots of the response variables depending on waste glass powder and glass fiber are shown in Figure 5. The decrease in the flow value is primarily attributed to adding glass fiber (GF) to the mixture, which increases internal friction and reduces workability. When the WGP ratio is 0% and 15%, adding GF decreases the flow value by approximately 6 cm and 4 cm, respectively. However, at a GF ratio of 0% and 0.6%, WGP addition results in a smaller reduction of approximately 2 cm and 1 cm, respectively. Interestingly, when the GF ratio is 0.6%, incorporating WGP at a rate of 7.5% slightly enhances the flow value, suggesting a potential balancing effect between these components.

The change in the GF ratio leads to only a 0.5 MPa decrease in flexural strength across all WGP ratios, indicating that fiber reinforcement maintains overall structural integrity despite slight reductions. However, as the WGP ratio increases, a more noticeable decrease of approximately 1 MPa in flexural strength is observed at 0% and 0.6% GF ratios. This reduction suggests that while WGP contributes to sustainability by incorporating waste materials, its higher proportions may compromise flexural performance, necessitating an optimal balance for practical applications.

Similarly, the interaction plot of the compressive strength shows that increasing the GF ratio decreases the compressive strength across all WGP ratios. This decrease is significant, with approximately 10 MPa and 5 MPa reductions for GF ratios of 0% and 0.6%, respectively. Such a decline highlights the trade-off between fiber reinforcement and compressive capacity, which must be carefully considered in load-bearing structural applications. In addition, the obtained model indicates that the 95% confidence widens at lower WGP and GF ratios, suggesting greater variability in mechanical performance under these conditions.

Regarding splitting tensile strength, the change in the GF ratio results in a minor decrease of 0.5 MPa at all WGP ratios. However, increasing the WGP ratio further reduces splitting tensile strength by approximately 0.7 MPa at 0% and 0.6% GF ratios, reinforcing the trend of declining tensile performance with higher WGP content. When GF is 0%, increasing the WGP ratio from 0% to 7.5% leads to a 4.5% improvement in splitting tensile strength. This indicates that WGP, at controlled levels, may offer some benefits in tensile performance. Moreover, as expected, the splitting tensile strength was lower than the flexural strength, which aligns with conventional structural behavior.

These results underscore the complex interplay between GF and WGP in influencing mechanical properties. While GF enhances flexural performance to some extent, it compromises compressive and splitting tensile strengths. Likewise, WGP, when used strategically, can contribute to sustainability without severely compromising structural integrity. Therefore, optimizing the balance between these materials is crucial for developing durable and sustainable construction materials.

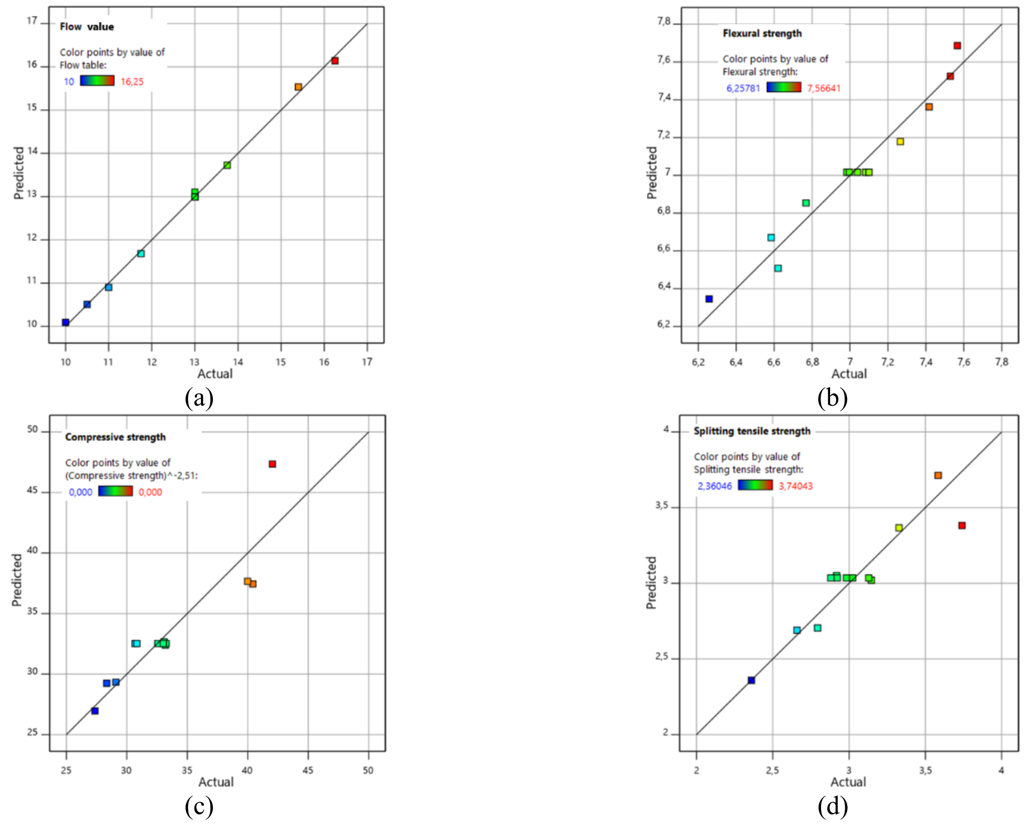

Figure 4. Predicted and actual values for (a) flow value, (b) flexural strength, (c) compressive strength and (d) splitting tensile strength

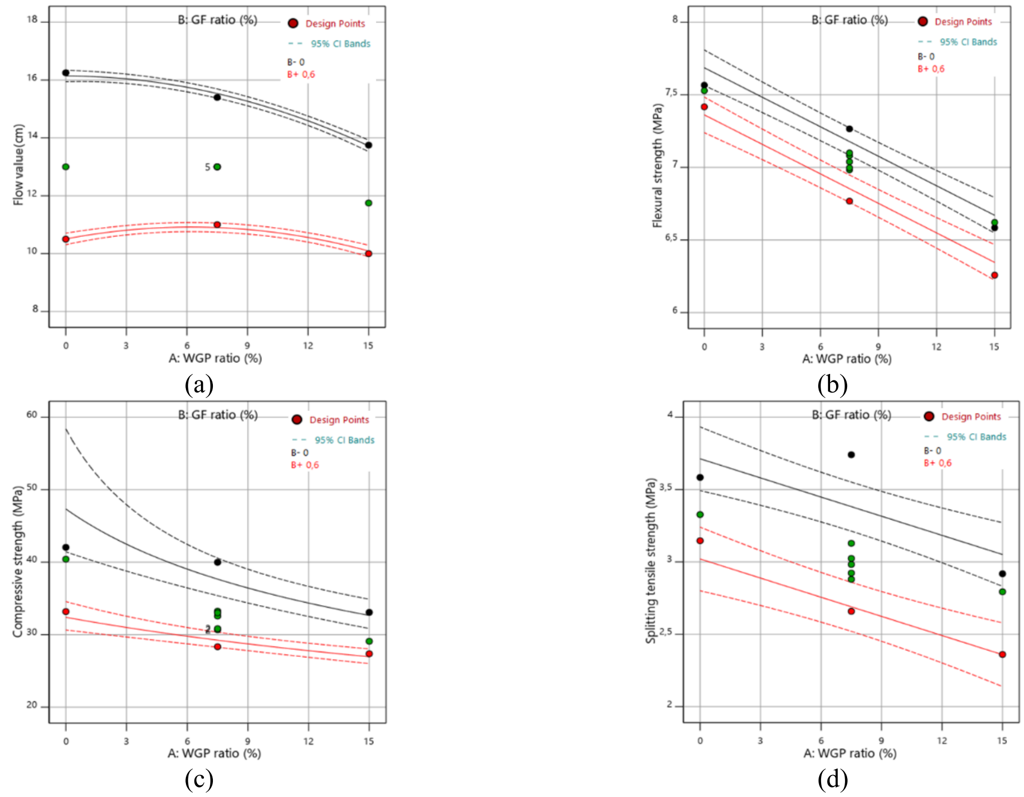

Figure 5. Interaction plots for (a) flow value, (b) flexural strength, (c) compressive strength and (d) splitting tensile strength

4 Conclusion

In the study, the effects of glass fiber (0%, 0.3%, and 0.6%) and waste glass powder (0%, 7.5%, and 15%) substitution on the mechanical properties (flow value, flexural strength, compressive strength, and splitting tensile strength) of the mortars were investigated. The following results were obtained.

- The addition of glass fiber reduces the flow value. With the addition of GF (0.6%) at 0%, 7.5%, and 15% WGP ratios, the flow value decreases by 35.4%, 28.6%, and 27.3%, respectively. Adding WGP reduces the negative effect of glass fiber on the flow values. Using WGP in mortars with 0% GF causes a decrease of 15.4% in the flow value. However, the use of WGP in mortars with 0.6% GF does not cause a change in the flow value.
- While adding glass fiber a bit reduces the flexural strength, adding WGP reduces it much more.
- GF addition causes a decrease in compressive strength at all WGP ratios.
- Adding glass fiber and waste glass powder generally reduces splitting tensile strength. However, when 7.5% waste glass powder is added without any glass fiber (0% GF), the splitting tensile strength increases by 4.5%.
- The predictability of the flow value, flexural strength, and compressive strength is high depending on the glass fiber and waste glass powder (R^2 values are 0.9983, 0.9586, and 0.9069, respectively).
- The predictability of the splitting tensile strength is lower than other mechanical properties (R^2 = 0.8526). It can be said that this situation is due to the variability of the glass fiber distribution in the mortar specimens.

Generally, adding glass fiber to mortars negatively affects their mechanical properties. However, the adverse effects of glass fiber can be reduced by adding a certain amount of WGP to the mixture (approximately 7.5%). In future studies, it is essential to conduct studies that consider other variables affecting the properties of glass fiber mortars, especially the distribution of fibers in the sample regarding the usability of waste glass powder in glass fiber mortars.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): %17

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