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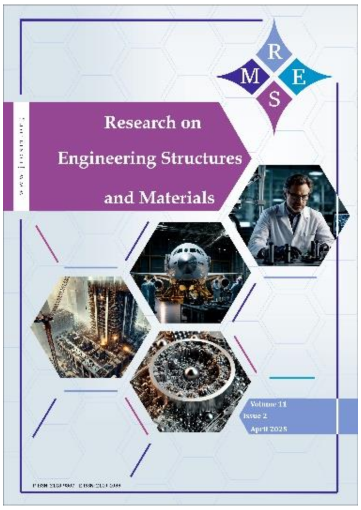

Modelling the performance of superplasticizers in a hybrid concrete system with steel slag and waste glass

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Online Publication Date: 30 November 2025

URL: http://www.jresm.org/archive/resm2025-1254ic1013rs.html
DOI: http://dx.doi.org/10.17515/resm2025-1254ic1013rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Azeez A T, Hassan M S, Atiyah A A. Modelling the performance of superplasticizers in a hybrid concrete system with steel slag and waste glass. *Res. Eng. Struct. Mater.*, 2026; 12(2): 905-916.

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Research Article

Modelling the performance of superplasticizers in a hybrid concrete system with steel slag and waste glass

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Article Info

Article History:

Received 13 Oct 2025
Accepted 26 Nov 2026

Keywords:

Concrete;
Regression;
Superplasticizers;
Steel slag;
Waste glass

Abstract

Superplasticizers (SP) are chemical admixtures that represent a significant innovation in the concrete industry due to their positive effects on workability and mechanical properties. The influence of SP on hybrid concrete with steel slag (SS) replacing coarse aggregates (up to 100%) and waste glass (WG) replacing cement (up to 30%) by weight remains ambiguous. The research gap addresses the motivation of this paper to thoroughly analyze the SP's performance within a hybrid system. Such research objectives strongly support global efforts toward sustainability and environmental preservation. The properties of the developed concrete upon SP inclusion can be precisely monitored by fitting the independent factors (SS, WG, and w/b) to the target responses. The mathematical models were developed using Minitab 21 software. For fresh concrete, w/b was the most influential factor in determining the SP/b dosages needed to keep the slump within the range of 185 mm ± 25 mm. Meanwhile, SS and WG counteracted each other, reducing their impact on workability. However, the responses measured included the compressive strength at 28 and 91 days of water curing, as well as splitting tensile strength and thermal conductivity after 91 days of curing. In all cases, SP enhanced the desired properties of concrete. With the addition of 1.2% SP (by weight of binder i.e. cement and WG) the compressive strength increased from 40 MPa to over 80 MPa. The thermal conductivity rose by 0.1 W/m·K with an SP dosage of 0.1%. The mechanical and thermal properties of concrete responded linearly to SP dosages.

1. Introduction

SP are liquid polymers alternatively known as water-reducing agents. The name reflects their capability to reduce the water content of concrete while maintaining high flowability [1]. SP are the icon of high-strength and durable concrete in the modern construction industry. Additionally, they play a prominent role in reducing the cost of building by minimizing the cement content [2]. As a result, ecological benefits also brought on the stage by reducing the CO2 footprint because a ton of cement is responsible of emission an equal amount of pollutant gases into the air [3]. Using of SP with steel slag (SS) and waste glass (WG) further benefits the green environment because of replacing waste materials with cement or aggregates. Both approaches effectively reduce resource depletion and confirm sustainable and eco-efficient concrete production [4,5].

The performance of SP was improved through the following generations, by employing advanced chemical techniques. They are classified into three generations according to their chemistry and efficiency. The first generation, which is less effective, is extracted from wood pulp such as lignin

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DOI: http://dx.doi.org/10.17515/resm2025-1254ic1013rs

and sugar. The second generation is petroleum by-products and has a greater ability to reduce water and increase workability compared with the first generation. Sulfonated naphthalene and melamine chemically treated with formaldehyde are listed under this group. The third generation, which is the most effective, is of polycarboxylates type. These offer higher workability even at low doses and water content [6]. Researchers appreciated their influences on fresh and hardened concrete from workability to mechanical properties. Moreover, SP could also benefit the ecological system when they effectively compromise the drawbacks in the properties of concrete because of using recycled materials instead of standard natural ingredients. Patowary and Siddique reported the ability to replace natural gravel with 50% recycled aggregates without a significant scarifying in the mechanical properties only if SP was used [7]. Moreover, mathematical models that accurately describe the SP behavior in concrete were developed [1]. Their positive effects were attributed to a three-dimensional network of bonds that mutually bind concrete ingredients [8]. Other researchers extended their scopes by formulating SP in laboratories for applying into specifically predefined functions. These were water-reducing, sustained-released, and early strength polycarboxylic acids SP. The curing periods of concrete were 1, 7, and 28 days to assess the time effects of SP on compressive strength. Regardless of the SP type, concrete showed improved strength with time owing to compacted microstructure and pores refining [9].

However, care must be taken upon the inclusion of SP because thermal conductivity may increase upon the network evolution, which may negatively influence the energy efficiency of buildings if thermal insulation is considered. Improving the thermal insulation of buildings is a global goal aimed at reducing CO_2 emissions from power production [10]. Moreover, an overdose of SP may cause segregation and bleeding in concrete at a constant water content, therefore controlling the dosages is critical to obtaining homogeneous mixtures [11].

It is evident that the literature has explored the impact of SP on the properties of various concretes, except for those where SS and WG were combined. Additionally, disposing of waste materials in landscapes is a growing global concern, and recycling them is essential from an environmental perspective. This paper aims to fill the research gap and support the global strategy of promoting green living. Notably, the authors in their previous research attempted to develop green concrete using waste materials such as SS and WG. They developed models describing the influence of SS, WG, and w/b on the mechanical properties, thermal conductivity, and microstructure evolution of concrete [12–14]. However, these studies did not include SP in their modeling and lacked an in-depth discussion of its role in the properties of the developed concrete. Therefore, further extension is necessary to incorporate this perspective and build upon previous scientific work by developing new models that correlate the fresh and hardened concrete properties with added SP dosages. Including SP in the modeling process, unlike previous efforts, clearly highlights the originality of this paper.

2. Experimental Work

2.1 Materials

Ordinary Portland cement (OPC) type I (42.5) with properties satisfying ASTM C150 was used to bind the materials [15]. The initial and final setting time were 130 min and 205 min, respectively, whereas the fineness was 290 m^2/kg according to Blain method The Hend steel company in Erbil/Kurdistan region of Iraq supplied steel slag, which was stored in outdoor conditions and periodically sprayed with water to prevent harmful volume expansion [16]. Particle size was the criteria for aggregate replacements, where SS retained on sieves 19 mm and 12.5mm exclusively replaced for coarse aggregates of corresponding size. The particle size distributions of the materials are shown in Fig. 1, where both fine and coarse aggregates confirmed ASTM C33 [17,18].

The by-products of window processing plants in Erbil were gathered and further processed to replace cement in concrete. A Los Angeles machine type Control/Italy was used to grind the glass where each batch was loaded with 5kg of ground glass (passing sieve 1.18mm) and steel balls, see Fig. 2. A comminutor of type RRH-1000A was used for grinding. Then the Los Angeles was rotated 12000 cycles and the output powder was sieved to a size less than 150μm to enhance the pozzolanic activity [19]. The materials were chemically analyzed for the oxide contents by an XRF machine and the compositions are shown in Table 1.

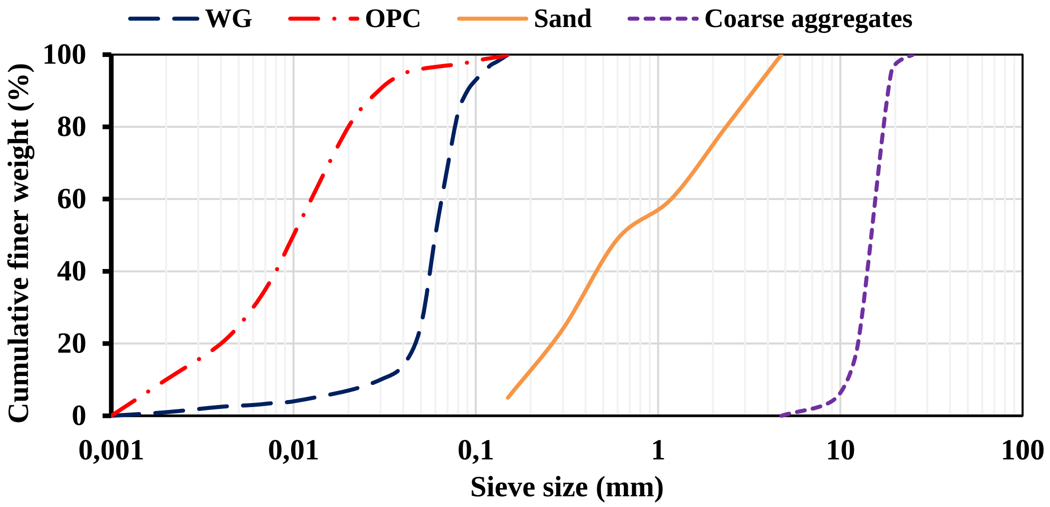


Fig. 1. Particle size distributions of materials

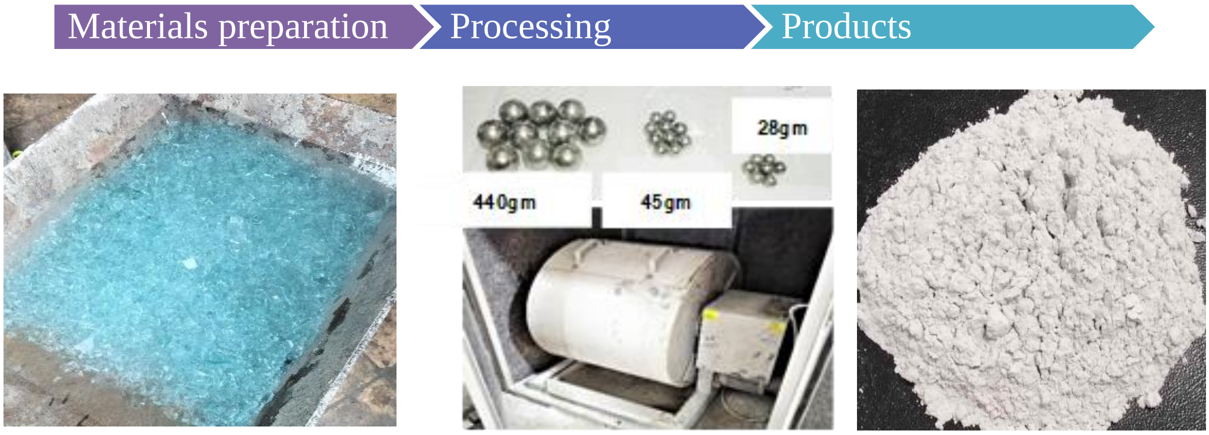


Fig. 2. Preparation of cementitious powder from WG

Table 1. Chemical composition analysis

Composition	SiO_2	CaO	Al_2O_3	MgO	P_2O_5	Na_2O	K_2O	Fe_2O_3	SO_3
OPC (%)	22.05	64.12	4.885	4.100	0.041	0.190	0.600	2.32	0.581
WG (%)	73.277	10.50	1.713	1.146	1.542	7.73	0.100	1.078	1.926
SS (%)	10.7	26.34	2.4	0.408	0.230	0.023	1.03	39.26	2.5

Engineers greatly desire high-fluidity concrete to facilitate smooth pumping on-site. Consequently, Polycarboxylate-based SP were utilized to maintain the concrete workability within the target range ($185 \mp 25\ mm$) at a constant w/b. The admixture has minimum chloride content which makes it a perfect option for reinforced concrete. Furthermore, it prominently enhances the early and later age strength and benefits placing and leveling concrete on site without a risk of bleeding and segregation. The SP was identified as high range water reducer and compatible with high strength concrete. It should be stored on the shelves within 5 – 35°C with firmly tightened package. It has a brownish color along with the following properties: PH = 7%, density = 1.12 kg/L, alkaline < 5%, and total chlorine value <0.1%. According to the properties, the admixture was of type F as per ASTM C494 standards [20]. The specific gravities were 2.55, 2.675, 2.73, 3.36 for WG, sand, coarse aggregates, and SS, respectively. The finesse modulus of sand according to ASTM C33 was

2.82. The absorption rate of coarse aggregates according to ASTM C127 was 0.91% [21]. Whilst it was 1.87% for sand according to ASTM C128 [22].

2.2 Concrete Mix Design

Concrete mix design as per ACI 211.1 code was utilized to proportion the materials to achieve a 45 MPa compressive strength [23]. Mixing 425 kg binder (OPC and WG), 750 kg sand, and 1020 kg coarse aggregates (natural +SS) effectively achieved the target strength after 28 days of moist curing. The percentages of the SS and WG substitutions and w/b were determined using the responsive surface method with Minitab 21 [24,25]. The critical points of the design space, named axial, end, and center points, controlled the combination of materials in the concrete mixtures as shown in Tables 2 and 3 [12,14]. Fine and coarse aggregates were dry-mixed thoroughly with SS for 2 minutes before the OPC and WG blend incorporation. Then a solution of water and SP was introduced into the blender where wet mixing lasted 4 minutes.

Table 2. The actual values of factors

Parameter	Axial	End	Center	End	Axial
SS (%)	0	22	50	78	100
WG powder (%)	0	7	15	23	30
w/b	0.3	0.34	0.4	0.46	0.5

Table 3. Results of the mixtures design by Minitab 21

Mixtures	SS, %	WG, %	w/b	Mixtures	SS, %	WG, %	w/b
M0	0	0	0.4	M10	78	7	0.34
M1	22	23	0.46	M11	50	15	0.4
M2	50	15	0.4	M12	100	15	0.4
M3	50	15	0.4	M13	50	30	0.4
M4	22	7	0.46	M14	0	15	0.4
M5	78	23	0.46	M15	50	15	0.5
M6	78	7	0.46	M16	50	0	0.4
M7	22	23	0.34	M17	50	15	0.4
M8	22	7	0.34	M18	50	15	0.3
M9	78	23	0.34	-	-	-	-

2.3 Sample Preparation and Testing

Slump test as per ASTM C143 standards characterized the mixtures for consistency [26]. The dosage of SP/b tightly controlled the workability, which was consistently maintained within the target range of $185 \mp 25\ mm$.Mixtures removed from the blender were placed in the cubic and cylindrical molds and compacted on vibrator tables. After demolding of the samples, they were maintained under water until 28 and 91 days for curing. The whole process was under the control of ASTM C192 standards. A compressive strength test confirming ASTM C39 was conducted on 100 mm cubic samples aged 28 days and 91 days based on three samples per test [27,28]. Three cylinders, per mixture, with dimensions 100 x 200 mm were investigated under indirect tensile stress after 91 days of water curing, see Fig. 3. The investigation of the cylinders confirmed ASTM C496 standards [29]. A 100mm cube per mixture was tested for thermal conductivity according to ASTM C1113 [30]. Data was captured from three faces to obtain a representative average value for the sample.

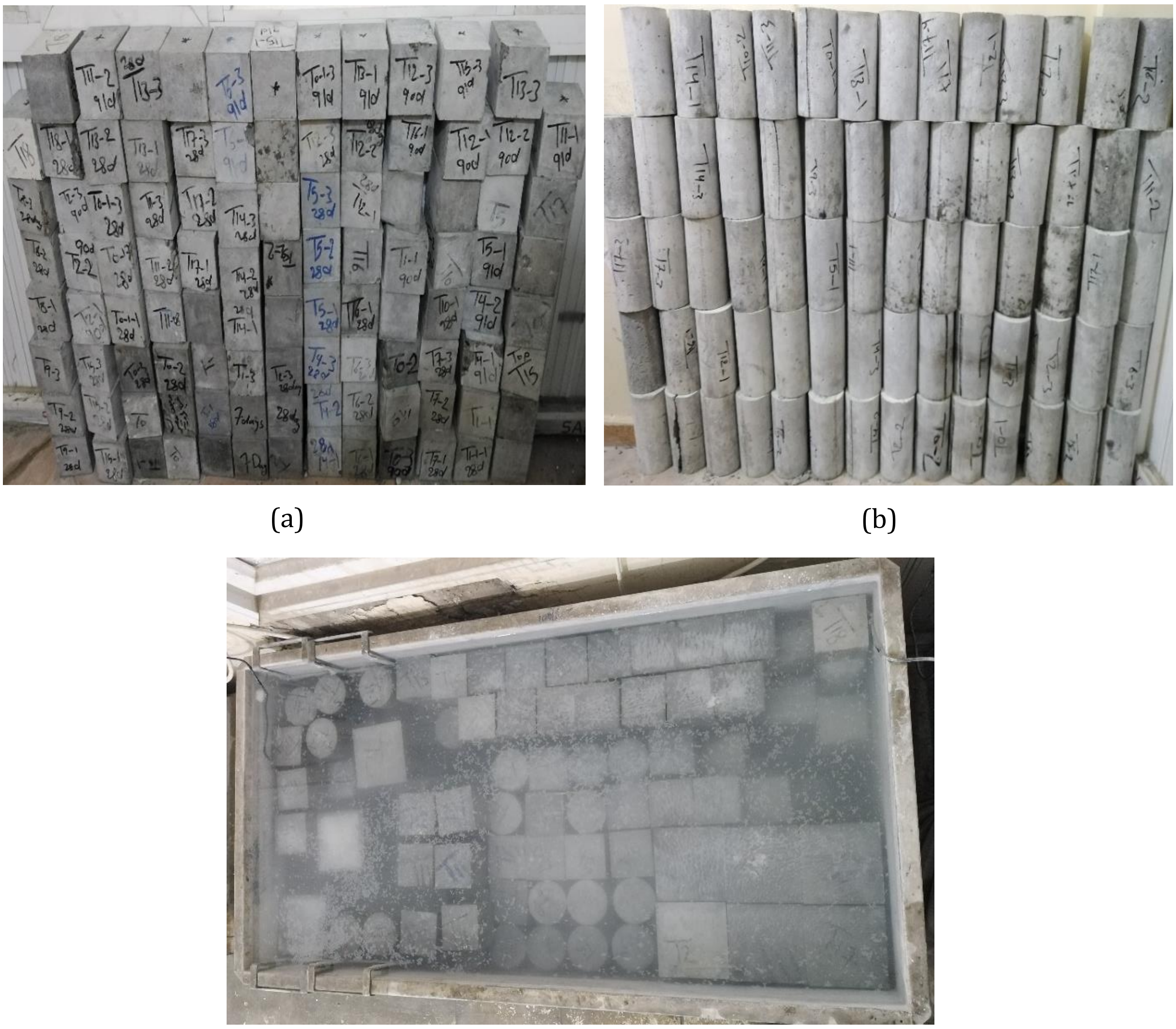

(a) (b) (c)

Fig. 3. Sample preparation (a) cubic samples (b) cylindrical samples (c) water curing

3. Results and Discussion

3.1 Effect of Superplasticizers on Fresh Concrete

Table 4 shows the results of regression and corresponding statistical analysis for the SP/b dosages needed to maintain the slump within the target range ($185 \pm 25\ mm$). The controlling factor in determining the SP/b was w/b, higher w/b needed lower SP/b to achieve the target slump and versa vice. Consequently, the w/b ratio was the dominant factor, while both SS and WG demonstrated negligible effects. The flat surface at a constant w/b value (Fig. 4a) strongly supports this assumption. Additionally, Figs. 4b and 4c further confirmed this conclusion, as the surfaces are steeply inclined with respect to the w/b axis, in contrast to those of SS and WG. Recalling that p-values below 5% are considered statistically significant in curve fitting, the high F-test p-values for SS and WG (p=0.480) provide a statistical explanation for their marginal influence compared with the w/b ratio, which had a zero p-value. However, regardless of the factors' impacts, SP/b responded linearly to all factors in every case. SS and WG may have counteracted each other, thereby diminishing their combined influences on the required SP doses. It was observed that the addition of WG, unlike SS, increased the slump. The hydrophobicity of WG might have increased the retained water which positively increased the slump. In contrast, the porosity of SS consistently absorbs water and creates an irregular matrix where both reduce the flowability of concrete, for details see [14]. The linear model successfully indexed more than 95% of the data manifested by high R-value see Table 4.

Table 4. Results of regression and statistical analysis for admixture doses.

Responses	Models	R-value (%)	Regression p-value	Lack of fit p-value
SP/b	2.649 + 0.000447 SS - 0.00149WG - 5.375 w/b	95.61%	0.000	*

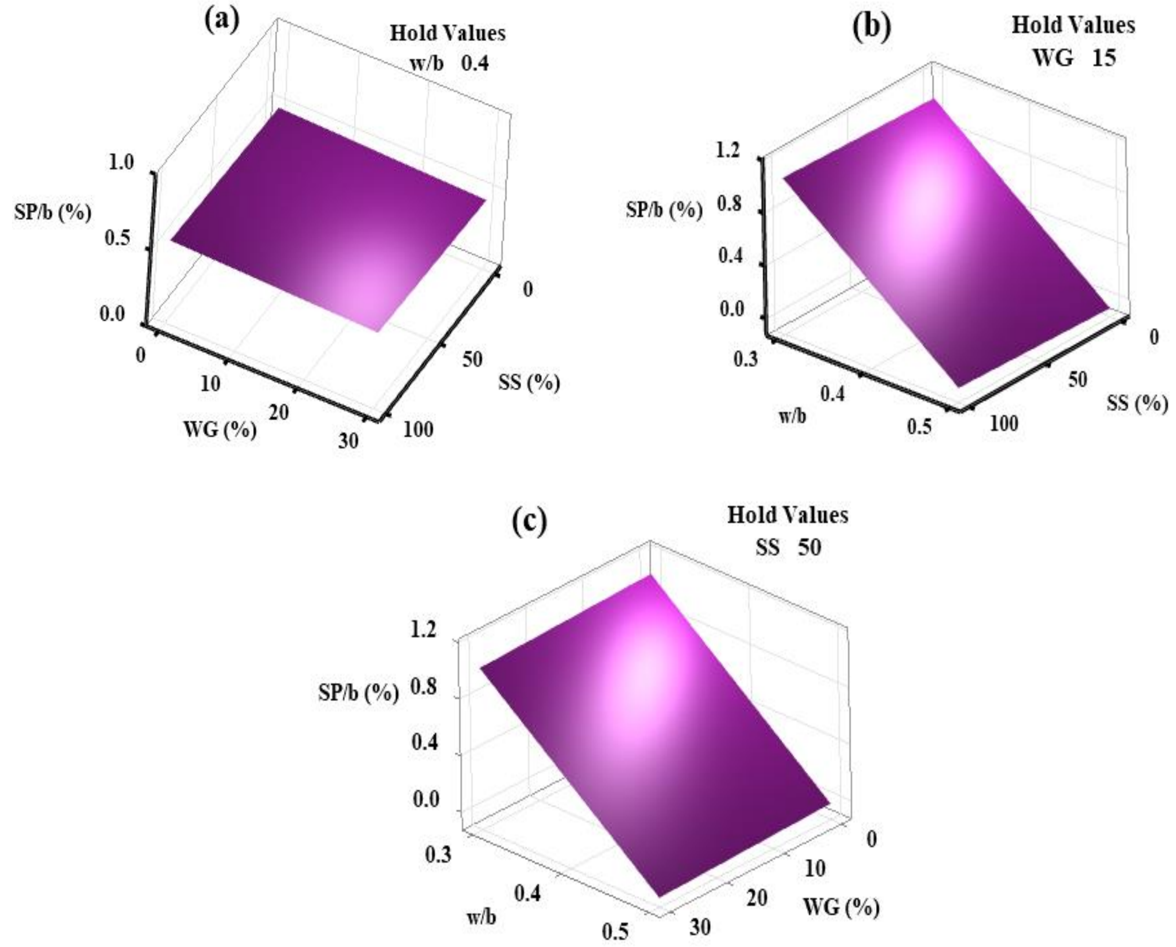


Fig. 4. Correlation between SP/b and affecting factors (a) SS and WG (b) SS and w/b (c) WG and w/b

3.2 Effect of the Superplasticizers on The Mechanical Properties of Concrete

The results of the regression of the compressive strength (C) and the splitting tensile strength (T) of concrete are shown in Table 5. The numbers next to the abbreviations indicate the curing time, which was 28 and 91 days. In all cases, SP/b linearly influenced the responses regardless of curing time. The p-values of the regression and lack of fit completely support their corresponding hypothesis.

Table 5. Results of regressions and statistical analysis

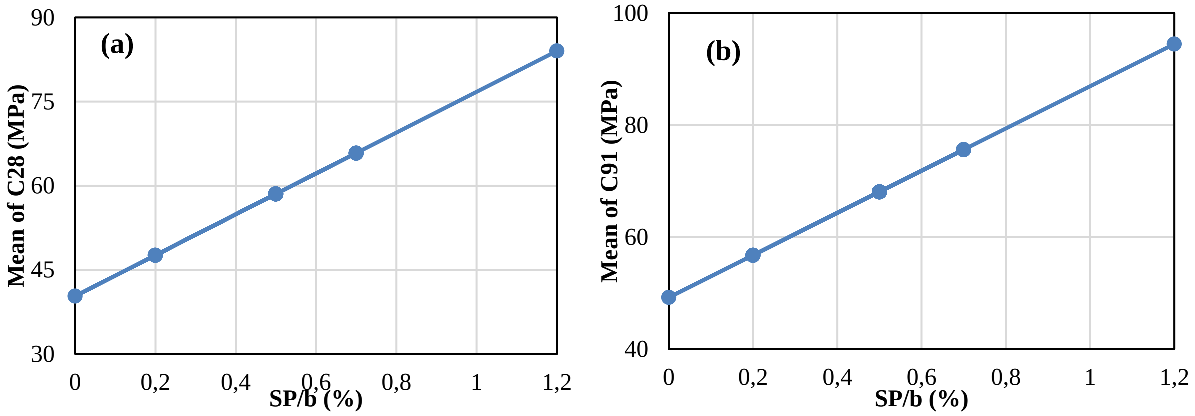
Responses	Models	R-value (%)	R-adj (%)	Regression p-value	Lack of fit p-value
C28 (MPa)	40.32 + 36.41 SP/b	66.11	67.18	0.000	0.107
C91 (MPa)	49.2 + 37.71 SP/b	66.82	64.74	0.000	0.163
T91 (MPa)	3.026 + 1.135 SP/b	61.14	58.71	0.000	0.832
k91(W/ m. K)	0.6969+0.4126 SP/b	70.32	68.47	0.000	0.832

Table 6. The differences between the observed and predicted values for C28, C91, T91

Mixture	SP/b (By weight %)	Predictive values			Δ (MPa)		
		C28	C91	T91	C28	C91	T91
M0	0.2	58.525	68.055	3.253	7.948	2.398	0.003
M1	0.2	47.602	56.742	3.253	6.302	10.142	0.413
M2	0.5	58.525	68.055	3.5935	2.355	0.735	0.0235
M3	0.5	58.525	68.055	3.5935	1.075	0.775	0.0135
M4	0.2	47.602	56.742	3.253	5.188	6.658	0.027
M5	0.2	47.602	56.742	3.253	1.258	1.448	0.197
M6	0.2	47.602	56.742	3.253	10.048	9.198	0.187
M7	0.7	65.807	75.597	3.8205	3.127	0.273	0.0205
M8	0.7	65.807	75.597	3.8205	7.133	5.083	0.3495
M9	0.7	65.807	75.597	3.8205	12.283	17.933	0.5295
M10	0.7	65.807	75.597	3.8205	13.943	12.683	0.4995
M11	0.5	58.525	68.055	3.5935	4.705	3.485	0.1335
M12	0.5	58.525	68.055	3.5935	2.955	2.925	0.0565
M13	0.5	58.525	68.055	3.5935	10.425	8.525	0.2335
M14	0.5	58.525	68.055	3.5935	13.175	13.515	0.2635
M15	0	40.32	49.2	3.026	4.32	0.74	0.086
M16	0.5	58.525	68.055	3.5935	3.925	2.545	0.0765
M17	0.5	58.525	68.055	3.5935	4.235	3.125	0.0635
M18	1.2	84.012	94.452	4.388	1.202	7.312	0.468

Table 6 shows the absolute difference (Δ) between the predictive and the real observed values, which are cited in [14]. Fig. 5a shows that C28 increased from 40 MPa to more than 80 MPa upon incorporation of 1.2% SP/b. The improvement trend was almost similar for C91 indicating no long-term influence of superplasticizers, see Fig. 5b. Wieland et al (2023) also reported a similar trend in their research and attributed it to the sorption of SP into the cement phase at the early age of hydration [31]. Furthermore, their addition also caused a significant improvement in the T91 where it increased by 46.67% from 3 MPa to 4.4 MPa see Fig. 5c. Not to mention, the inferior mechanical properties of M15 (SP/b =0%) compared with the other mixtures are strong evidence for the SP's vitality. Its C28, C91, and T91 were 40.32 MPa, 49.2MPa, and 3.026MPa, respectively. However, these values substantially increased for the other mixtures upon SP incorporation see Table 6.

The improvement influence of SP is well established and mainly attributed to their role in reducing the water content and enhancing the hydration reactions [8]. The prediction power of the suggested models was evaluated against those proposed by Muhammed et al. [1,12] using the following error and efficiency measurements:



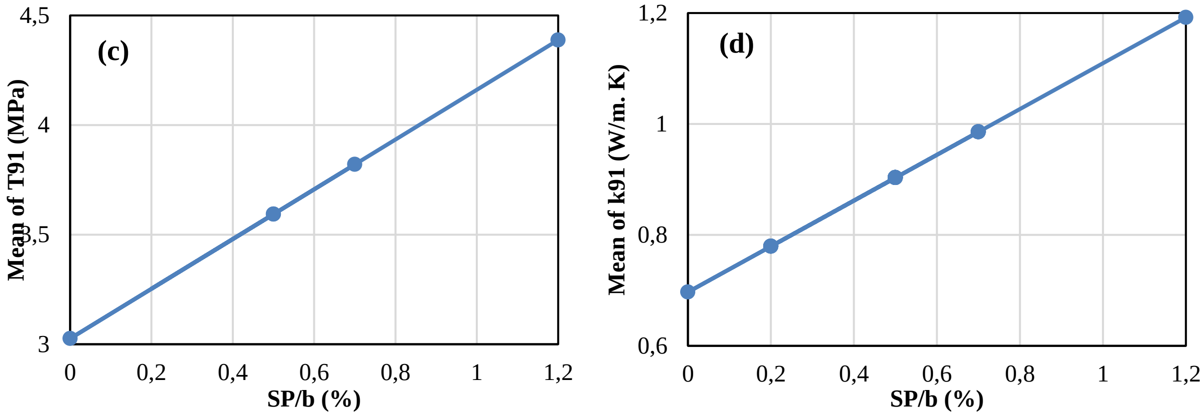


Fig. 5. The effect of SP/b on a) 28 days compressive strength b) 91 days compressive strength c) 91 days splitting tensile strength d) 91 days thermal conductivity

$$IAE \;= \sum_{I=1}^{n} \left(\frac{\sqrt{(Oi-Pi)^2}}{\sum Oi}\right) * 100 \tag{1}$$

$$MAE \;= \frac{1}{n}\sum_{i=1}^{n} |Pi-Oi| \tag{2}$$

$$RMSE \;= \sqrt{\frac{1}{n}\sum_{i=1}^{n} (Oi-Pi)^2} \tag{3}$$

$$EF \;= 1-\frac{1}{n}\sum_{i=1}^{n} \frac{|Pi-Oi|}{Oi} \tag{4}$$

where IAE is integrated absolute error, MAE is mean absolute error, RMSE root mean square error, and EF is the normal efficiency. The variables Pi and Oi refer to the predictive and the real observed values, respectively, and n is the number of observations. They used the nonlinear regression method (NLR) and model tress (M5P) to fit the predictors to the compressive strength see the model parameters in [1]. The newly developed models showed the highest efficiency for prediction at the lowest error measured by all associated statistical methods see Table 7. Figs. 6a and 6b show that NLR overestimated the compressive strength in response to the SP/b of the current study. However, its predictivity is still better compared with M5P, which extremely deviated from the current model. Not to mentioned, the outputs of this research contradicted the conclusion stated by Muhammed et al. [1,12] where models predictivity improved in favor of M5P against NLR.

Table 7. Results of the analysis of the models' prediction power.

Type	Source	Errors			Efficiency
		IAE	MAE	RMSE	EF
C28	Current model	9.98	5.82	7.09	0.89
	NLR (SP62)	20.07	11.70	13.30	0.77
	M5P (SP62)LM1	49.06	28.61	31.86	0.53
C91	Current model	9.03	6.10	7.84	0.91
	NLR (SP62)	17.26	10.07	11.79	0.83
	M5P (SP62)	28.81	19.46	23.48	0.73

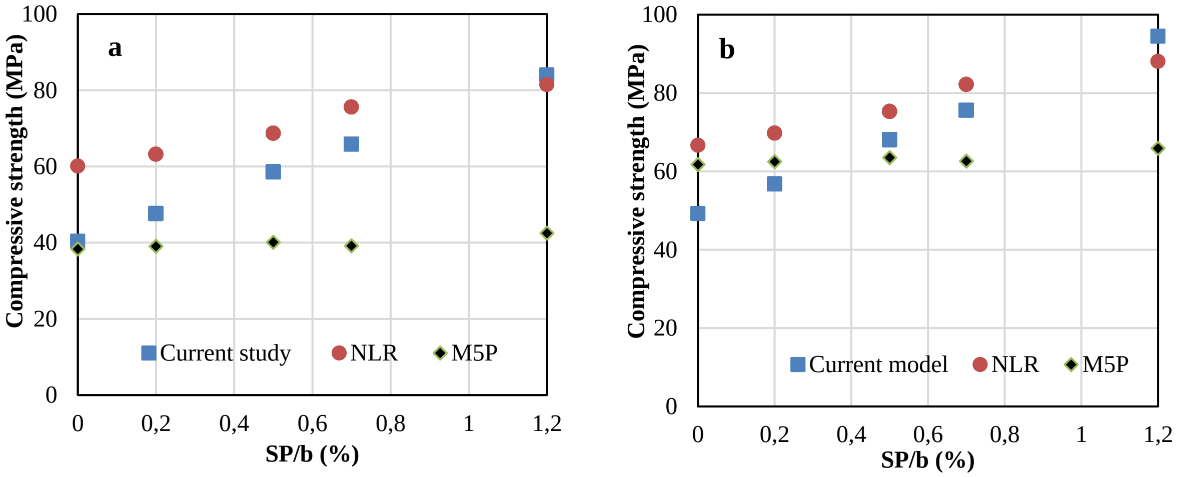


Fig. 6. Predictivity of the models for compressive strength a) 28 days curing b) 91 days curing

3.3 Effect of the Superplasticizers on The Thermal Conductivity Of Concrete

The response of the thermal conductivity of concrete (k91) to SP/b was shown in Table 5. The backward elimination method was used to remove all statistically insignificant terms at a 95% confidence level. The statistical filtration maintained the linear terms only to express the effect of SP/b on the thermal conductivity of concrete. The R-value and R-adj were 70.32% and 68.47%, respectively. The marginal difference between them indicates the vitality of the terms included in model. Additionally, the adequacy of the linear model in relating the SP/ to the conductivity was confirmed by a high p-value (>5%) of the lack of fit.

Fig. 5d shows that increasing SP/b by 0.1% improves the thermal conductivity of concrete by 0.1 W/m.K. The conductivity increased by 71.4% upon the addition of 1.2% SP. Not to mention, SP are liquid molecules with a high affinity to cement and effectively perform in the hydration process. As a result, a three-dimensional network of high bonding strength will be formed with minimum porosity content [10]. The improved cement matrix positively influences the thermal conductivity similarly to the mechanical properties discussed previously. However, effective approaches are required to mitigate the drawback of the superplasticizers influence on the thermal insulation of concrete. For example, SS and WG positively served in this direction owing to their physical structures. SS is porous whereas WG is amorphous and both characteristic features improved the thermal insulation of concrete, for detail see [12]

3.4. Microstructure Analysis

Microstructural analysis is crucial for justifying the observed macroscopic properties. Samples M11 and M15 were studied to examine microstructural development because their contents help identify the effects of admixtures. These samples had different SP/b and w/b ratios, while other factors remained constant. It is noted that SP/b was 0.5% and 0%, respectively, while w/b was 0.40 and 0.50 for M11 and M15. SEM images showed the positive effect of increased SP/b on producing a uniform and homogeneous paste matrix, see figure 6. Porosities characterized M15's structure (Fig. 7a) because water was the only lubricating agent used without any admixture. It is well established that evaporation of excess water is the primary source of porosity, and reducing water content effectively addresses this issue. Fig. 7b provides clear evidence supporting this, where a more compact matrix is observed due to a 10% reduction in water after adding 0.5% SP/b. The admixtures bring cement particles into close contact and prevent flocculation, significantly enhancing the hydration reaction. Overall, the improved mechanical and thermal properties of concrete with increased SP/b are evident, as previously discussed.

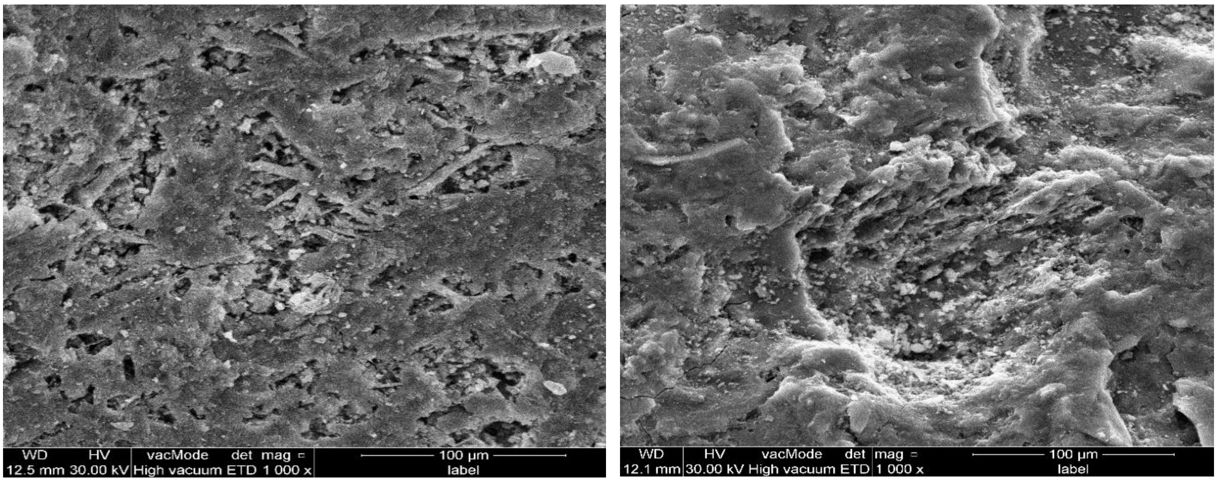


Fig. 7. SEM images (a) M15 (b) M11

4. Conclusions

This study aims to evaluate the mechanical and thermal performance of concrete in response to SP inclusion. Mathematical models were formulated using the response surface method with Minitab 21 to accurately assess the influence of w/b in combination with SS and WG on the doses of SP. The objective was producing concrete with slump of$185 \pm 25mm$ by monitoring the SP/b ratio. Statistical filtration was applied to remove unnecessary terms, thereby enhancing the validity of the fitted models. The following conclusions were drawn:

- Results showed that w/b critically determined the doses of SP necessary to maintain the fresh concrete highly workable. Increasing w/b consistently reduced the needs for SP/b to the extent that the target slump was obtained without the addition of SP at w/b ratio of 0.5.
- No influence was observed for SS and WG in determining the SP/b doses; conversely, the w/b ratio was the dominant factor. The opposing effects of SS and WG likely canceled each other out in the fresh concrete, providing a physical explanation for their negligible impacts in the developed models.
- The mechanical properties of concrete notably improved by SP because of water reduction. The addition of 1.2% SP by weight of binders (cement and WG) increased C28 from 40MPa to more than 80MPa.
- The improvement rate of C91 with SP was highly comparable to that of C28, effectively eliminating time factor from the effects of SP.
- The thermal conductivity of concrete increased by 71.4% with the inclusion of 1.2% SP, which negatively affects the insulation performance of buildings. Therefore, mitigation strategies are necessary to preserve the desired thermal insulation properties of concrete. For example, incorporating insulating materials like SS and WG effectively addresses this issue. In all cases, sp/b linearly correlated with the mechanical and thermal properties of concrete.
- Controlling the dosages of SP is technically essential for modern concrete technology. Developing models that accurately regulate the rate of SP additions to concrete is crucial to avoid undesired performance drawbacks.

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