J Sustain Const Mater Technol, Vol. 9, Issue. 1, pp. 60–71, March 2024

Journal of Sustainable Construction Materials and Technologies
Web page info: https://jscmt.yildiz.edu.tr
DOI: 10.47481/jscmt.1338751

Journal of Sustainable Construction
Materials and Technologies

Research Article

Rheology of superabsorbent polymer-modified and basalt fiber-reinforced cement paste with silica fume: Response surface methodology

Hasan DİLBAS[*]

Department of Civil Engineering, Van Yüzüncü Yıl University Faculty of Engineering, Van, Türkiye

ARTICLE INFO

Article history
Received: 07 August 2023
Revised: 25 September 2023
Accepted: 17 October 2023

Key words:
Basalt fiber, response surface methodology, rheology, silica fume, superabsorbent polymer

ABSTRACT

A composite's rheology can be changed by adding superabsorbent polymer (SAP) and basalt fibers and using silica fume. This study aimed to investigate the effects of these components on the viscosity and shear stress parameters of the paste. The proportions of the components were varied, with SAP content ranging from 0.01% to 0.03%, basalt fiber from 0% to 0.50%, silica fume (micro silica) at 15%, and water content from 0.40 to 0.50. Response surface methodology was used to optimize the mixture proportions, and the rheological properties of the resulting pastes were characterized using a rheometer. Results showed that the addition of SAP and basalt fiber had a significant impact on the rheological properties of the paste, with increasing amounts of both resulting in increased viscosity and shear stress. Overall, this study highlights the potential of SAP and basalt fiber in advances of the rheology of cement paste and provides insight into the optimal proportions of these components for achieving desired rheological properties. The findings of this study could be useful in developing high-performance concrete with enhanced rheological properties, which could have a wide range of applications in the construction industry. In addition, 0.50% BF, 0.01% SAP, and 0.445 water-to-cement were found as optimum proportions regarding the rheology of the cement paste.

Cite this article as: Dilbas, H. (2024). Rheology of superabsorbent polymer-modified and basalt fiber-reinforced cement paste with silica fume: Response surface methodology. *J Sustain Const Mater Technol*, 9(1), 60–71.

1. INTRODUCTION

Rheology studies the deformation and flow of materials under applied forces. It is essential to understand the rheological properties of cement pastes, significantly when they are modified with additives such as a superabsorbent polymer (SAP) and nano-silica (NS), because they affect the workability, pumpability, and performance of the cementitious materials. SAP is a type of hydrogel that can absorb and retain large amounts of water, up to several hundred times its weight. It has been used as an internal curing agent in cement pastes to mitigate autogenous shrinkage, a deformation caused by self-desiccation of the pores due to hydration progress. SAP can release water into the capillaries, thus maintaining a high relative humidity and reducing capillary tension. SAP can also improve cement pastes' durability and mechanical properties by reducing cracking and enhancing pore structure [1]. NS is a nanomaterial with a high specific surface area and reactivity. It has been used as a supplementary cementitious material (SCM) in cement pastes to improve the compressive strength, hydration rate, and microstructure. NS can fill the pores, reduce the porosity of cement pastes, participate in the pozzolanic reaction, and form additional calcium silicate hydrate (CSH) [2]. The rheological properties of cement pastes modified with SAP and NS depend on several factors, such as the dosage, parti-

---

***Corresponding author.**
*E-mail address: hasandilbas@yyu.edu.tr

Published by Yıldız Technical University Press, İstanbul, Türkiye

cle size, dispersion, and interaction of the additives, as well as the water-to-cement ratio (w/c), temperature, and time. Several studies have investigated the effects of SAP and NS on the rheology of cement pastes using rotational rheometry, which can measure the viscosity and yield stress of the materials by applying a shear stress or strain [3]. The viscosity is a measure of the resistance to flow, while the yield stress is a measure of the minimum stress required to initiate flow. Both parameters are influenced by the amount and type of additives in cement pastes. Generally, increasing the dosage of SAP or NS increases the viscosity and yield stress of cement pastes because they consume more water and increase the solid content [4]. However, some studies have reported that low dosages of SAP or NS can reduce cement pastes' viscosity and yield stress because they act as lubricants or dispersants [5]. The particle size and distribution of SAP and NS also affect the rheology of cement pastes. Smaller particles increase viscosity and yield stress more than larger particles because they have a higher surface area and adsorption capacity [6]. The dispersion of SAP and NS in cement pastes is also important for achieving a homogeneous mixture and avoiding agglomeration or segregation [7]. The interaction between SAP and NS in cement pastes is another factor that influences their rheological properties. Some studies have suggested that SAP can reduce NS's negative effects on cement pastes' rheology by providing internal curing water and preventing excessive water consumption by NS [8]. However, other studies have indicated that SAP can interfere with the dispersion and hydration of NS in cement pastes by competing for water or forming a coating layer around NS particles [9]. Therefore, the optimal dosage and ratio of SAP and NS in cement pastes must be determined based on their rheological requirements.

Due to hydration and swelling processes, the rheological properties of cement pastes modified with SAP and NS vary with time. Hydration causes an increase in viscosity and yield stress over time because it consumes water and forms CSH gel [10]. Swelling causes a decrease in viscosity and yield stress over time because it releases water and reduces capillary tension [11]. The rate and extent of hydration and swelling depend on the w/c ratio, temperature, type and dosage of additives, and curing conditions [12]. Basalt fiber-reinforced cement paste (BFRC) is a composite material that consists of a cement paste matrix and basalt fibers dispersed randomly or aligned in a certain direction. Basalt fibers are natural fibers derived from volcanic rocks that have high tensile strength, modulus of elasticity, thermal stability, and chemical resistance [13]. BFRC has been used for various applications such as structural repair, fire protection, thermal insulation, and noise reduction [14]. The rheological properties of BFRC are influenced by several factors, such as the dosage, length, diameter, aspect ratio, surface treatment, and orientation of basalt fibers, as well as the water-to-cement ratio (w/c), admixtures, and curing conditions of the cement paste matrix [13–15]. The rheological properties of BFRC are important for its workability, pumpability, flowability, and stability during mixing, placing, and hardening. Adding basalt fibers to cement paste generally increases its viscosity and yield stress, decreasing its slump and flow [13–15]. However, a higher w/c ratio can also reduce the mechanical properties and durability of BFRC. Therefore, an optimum w/c ratio should be selected to balance the rheological and mechanical performance of BFRC. Admixtures such as superplasticizers or air-entraining agents can enhance the workability and stability of BFRC by reducing the water demand, increasing the fluidity, decreasing the segregation, and improving the air entrainment of the mixture [13–15]. Superplasticizers can also enhance the dispersion and alignment of basalt fibers by reducing their agglomeration and flocculation [14]. Air-entraining agents can create air bubbles that act as lubricants and spacers among basalt fibers and cement paste matrix, which reduce the frictional forces and increase the deformability of BFRC [15].

The surface treatment of basalt fibers can affect their adhesion and compatibility with the cement paste matrix, affecting their dispersion and rheological properties. The surface treatment can be physical (such as heat treatment or plasma treatment) or chemical (such as silane coupling agents or alkali treatment) [13, 14]. The surface treatment can modify basalt fibers' surface morphology, roughness, hydrophilicity/hydrophobicity, polarity, charge density, functional groups, and bond strength. The surface treatment can improve the wetting and bonding of basalt fibers with cement paste matrix, and this leads to a reduction in their pull-out resistance and an increase in their load transfer efficiency. The surface treatment can also reduce basalt fibers' water absorption and alkali reactivity, improving their durability in an alkaline environment. The surface treatment can also affect the dispersion and orientation of basalt fibers by changing their surface energy and electrostatic forces.

The mechanical properties of BFRC can be affected by the w/c ratio, admixtures, and curing conditions of the cement paste matrix [13–15]. The w/c ratio influences the porosity and hydration degree of the cement paste matrix, affecting its strength and durability. A lower w/c ratio can increase the compressive strength, tensile strength, flexural strength, modulus of elasticity, and fracture toughness of BFRC [13–15]. Superplasticizers can reduce the water demand and increase the hydration degree and strength of BFRC. Air-entraining agents can increase the air content and reduce the density and strength of BFRC [15]. However, air-entraining agents can also improve the durability and crack resistance of BFRC by creating air voids that act as stress relievers and crack arresters [15]. The surface treatment of basalt fibers can affect their mechanical properties by changing their adhesion and compatibility with the cement paste matrix [13, 14]. The surface treatment can also reduce the pull-out and slippage of basalt fibers, which improves their fracture toughness and crack resistance of BFRC [13, 14].

In conclusion, rheology is a valuable tool for characterizing the flow behavior of cement pastes modified with SAP and NS. These additives can affect cement pastes' viscosity

Figure 1. View of silica fume, super absorbent polymer, and basalt fiber (from left to right, respectively).

Table 1. Physical properties of the materials used in the study

Material	Specific gravity	Fineness (cm^2/g)	Blaine's surface area (cm^2/g)	Chemical properties
OPC	3.15	3,200	402	SiO_2: 21.1%, Al_2O_3: 4.8%, Fe_2O_3: 3.2%, CaO: 63.1%
Silica fume	2.2	20,000	28,800	SiO_2: 90–97%, Al_2O_3: 1–2%, Fe_2O_3: 0.5–2%, CaO: 0.5–2%
SAP	1.2	N/A	N/A	Na: 6.5%, K: 1.5%, Cl: 0.7%, SO_4: 1.2%
Basalt fiber	2.7	N/A	N/A	SiO_2: 46.1%, Al_2O_3: 10.4%, Fe_2O_3: 7.8%, CaO: 9.3%
Water	1.0	N/A	N/A	H_2O:100%

and yield stress differently depending on their dosage, size, dispersion, interaction, time, etc. Therefore, optimizing their use based on their desired effects on both fresh and hardened properties of cementitious materials is essential. Basalt fiber-reinforced cement paste (BFRC) is a composite material with superior rheological and mechanical properties compared to plain cement paste. The rheological and mechanical properties of BFRC are influenced by several factors related to the basalt fibers and the cement paste matrix. These factors should be considered carefully to optimize the performance and application of BFRC.

Response Surface Methodology (RSM) is a statistical tool that can investigate the relationship between multiple variables and their impact on a response, such as the rheological properties of cement paste [5]. RSM involves using mathematical models to describe the relationship between the input variables and the response variables, and the models are used to optimize the input variables to achieve the desired response. RSM is a useful tool for investigating complex systems with multiple variables, and it can help to identify the optimum conditions for achieving the desired response. The proportions of SAP, basalt fiber, silica fume, and water in cement paste can be optimized using RSM. The proportions of these components can be varied within a specific range, and the rheological properties of the paste can be measured using standard methods such as the slump test, the flow table test, and the rheometer test. The results of these tests can be used to develop mathematical models to describe the relationship between the input variables and the rheological properties of the paste. The models can be used to identify the optimum proportions of the components for achieving the desired rheological properties of the paste.

Table 2. Mix proportions of the cement paste

Component	Mix proportions (by weight)
OPC	1
Silica fume	0.15
SAP	0.01–0.03
Basalt fiber	0–0.50
Water	0.40–0.50

In this study, the impact of SAPs, basalt fibers, silica fume (micro silica), and water on the rheological properties of cement paste was investigated using response surface methodology (RSM) based on central composite design (CCD). The rheological properties of the cement paste, including viscosity and shear stress parameters, were analyzed using a rheometer.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in the study include ordinary Portland cement CEM I 42.5R (OPC), silica fume, superabsorbent polymer (SAP), basalt fiber, and water (Fig. 1). OPC was obtained from a local supplier. Elkem Materials Inc., USA, provided silica fume. SAP was purchased from BASF Corporation, USA. Basalt fiber was obtained from Mafic USA, USA. The physical properties of the materials used in the study are presented in Table 1. SAP had a particle size distribution between 0.5 and 2 mm. The median is 1.1 mm. Basalt fiber had a 9–13 μm diameter and 2 mm length.

Table 3. Testing procedure

Shear rate, rpm	100*	100	50	25	10	5	1	0.10	0.05	0.01
Time, second	75	15	15	15	15	15	15	15	15	15

*Pre-shearing.

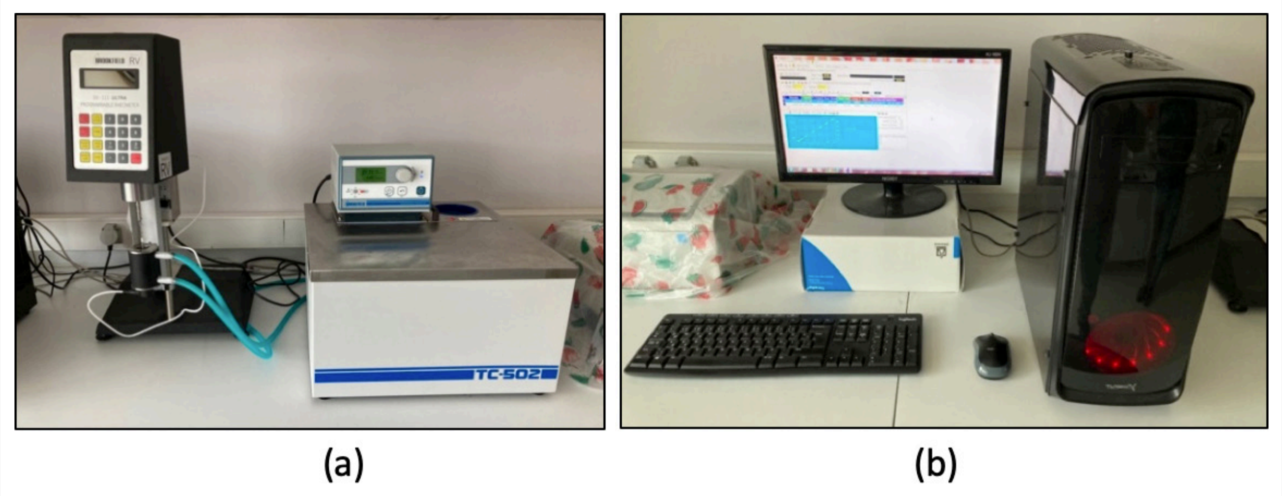


Figure 2. Rheology test setup **(a)** and data curation in computer with software **(b)**.

2.2. Methods

2.2.1. Preparation of Cement Paste

The cement paste was prepared according to ASTM C305-14. The OPC was mixed with silica fume, SAP, basalt fiber, and water in a mixer for 5 minutes at 1400 rpm. The mixture was then poured into a mold and placed in a curing chamber at 25°C and 95% relative humidity for 28 days. The mix proportions used in the study are presented in Table 2.

2.2.2. Rheological Testing

The rheological properties of the cement paste, including viscosity and shear stress parameters, were analyzed using a rheometer (Brookfield RV) (Fig. 2). The test was conducted according to ASTM C1437-15. The sample was placed in a cylindrical container with a diameter of 25 mm and a height of 20 mm. The rheometer had a concentric cylinder measuring system with a SC4-29 spindle. The test was conducted at a shear rate of 0.01–100 s^{-1} at 25°C (Table 3).

2.2.3. Response Surface Methodology

Response Surface Methodology (RSM) is a statistical technique used to optimize and improve the response of a system to various inputs or factors. RSM involves designing experiments to study the effects of different input variables on the output response and then using mathematical models to analyze the data and optimize the response. RSM has been widely used in various fields, such as engineering, chemistry, and agriculture, to optimize and improve the performance of complex systems.

In cement-based composites, RSM has been used to optimize the properties of the composites by studying the effects of various input factors such as cement type, aggregate type, water-cement ratio, and curing conditions. RSM has been used to study the impact of these factors on various properties such as compressive strength, flexural strength, and durability of the composites. RSM is an effective tool for optimizing the properties of cement-based composites as it can help identify the most significant factors affecting the properties and provide optimal conditions for achieving the desired properties.

RSM has been used in several studies to optimize the properties of cement-based composites [16, 17]. For example, RSM was used to optimize high-strength concrete's compressive strength and water absorption by studying the effects of different factors such as water-cement ratio, superplasticizer dosage, and curing temperature. Another study used RSM to optimize the flexural strength of cement-based composites by studying the effects of factors such as fiber type, fiber volume fraction, and curing conditions. In both studies, RSM was found to be an effective tool for optimizing the properties of cement-based composites and providing optimal conditions for achieving the desired properties.

RSM is a powerful statistical technique that can optimize cement-based composites' properties by studying the effects of various input factors on the response.

Central Composite Design (CCD) is a commonly used experimental design in RSM. CCD involves designing a set of experiments that allows for evaluating the curvature and interactions of the input variables. It includes a set of factorial, axial, and center points, allowing for the quadratic response surface model estimation. CCD is an efficient and cost-effective way to optimize the response of a system by studying the effects of various input variables on the output response. CCD is a widely used experimental design method in engineering and applied sciences for modeling and optimizing the response of a system or process under study.

Table 4. Range and levels of the variables used in the study

Variable	Level -1	Level 0	Level 1
X1 (SAP content, %)	0.01	0.02	0.03
X2 (Basalt fiber content, %)	0	0.25	0.50
X3 (Water-to-cement ratio)	0.40	0.45	0.50

Table 5. Rheological properties of the cement paste

Run#	X1	X2	X3	Viscosity (Pa·s)	Yield stress (Pa)	Shear stress (Pa)
1	0.01	0.50	0.50	0.0035	0.033	0.13
2	0.01	0.50	0.40	0.0032	0.031	0.12
3	0.01	0	0.40	0.0030	0.031	0.12
4	0.01	0.25	0.45	0.0034	0.032	0.13
5	0.01	0	0.50	0.0026	0.028	0.11
6	0.02	0.25	0.45	0.0030	0.031	0.12
7	0.02	0.25	0.50	0.0035	0.034	0.14
8	0.02	0.25	0.45	0.0033	0.033	0.13
9	0.02	0.50	0.45	0.0031	0.033	0.13
10	0.02	0.25	0.45	0.0033	0.033	0.13
11	0.02	0	0.45	0.0030	0.031	0.12
12	0.02	0.25	0.45	0.0032	0.033	0.13
13	0.02	0.25	0.45	0.0029	0.032	0.13
14	0.02	0.25	0.40	0.0031	0.033	0.13
15	0.02	0.25	0.45	0.0033	0.033	0.13
16	0.03	0	0.40	0.0028	0.030	0.12
17	0.03	0.25	0.45	0.0033	0.033	0.13
18	0.03	0.50	0.50	0.0034	0.032	0.13
19	0.03	0	0.50	0.0036	0.034	0.14
20	0.03	0.50	0.40	0.0031	0.032	0.13

The design involves creating a set of experimental runs that vary in levels of the input variables to obtain a quadratic response surface that can be used to model the system's behavior and predict optimal input settings. CCD is beneficial in cases where the relationship between input variables and response is complex and can be used to identify optimal input settings for a desired output response [18].

CCD has been applied in various fields, including materials science [19], chemical engineering [18], and environmental science [20, 21], among others. The method has been used for optimizing a range of parameters, including mechanical properties [19], chemical reactions [18], and process parameters [20]. CCD has also been combined with other techniques, such as artificial neural networks and fuzzy logic, for improved optimization and modeling [22, 23].

One of the advantages of CCD is that it allows for the estimation of the input variables' primary effects, quadratic effects, and interaction effects, which can help identify essential factors and their relative contributions to the response. Furthermore, the design is efficient regarding the number of experimental runs required, with a minimum number of runs needed to estimate the response surface [21]. Despite its usefulness, CCD has some limitations, including the assumption of linearity of the response surface and the need for a sufficient number of runs to achieve accurate results [22].

In conclusion, CCD is a powerful experimental design method that can be used to model and optimize the response of a system or process. Its application in various fields has demonstrated its effectiveness in identifying optimal input settings for a desired output response. However, it is essential to carefully consider the limitations and assumptions of the method to obtain accurate results.

The CCD was used to investigate the components' impact on the cement paste's rheological properties. The CCD is a statistical experimental design method used to optimize

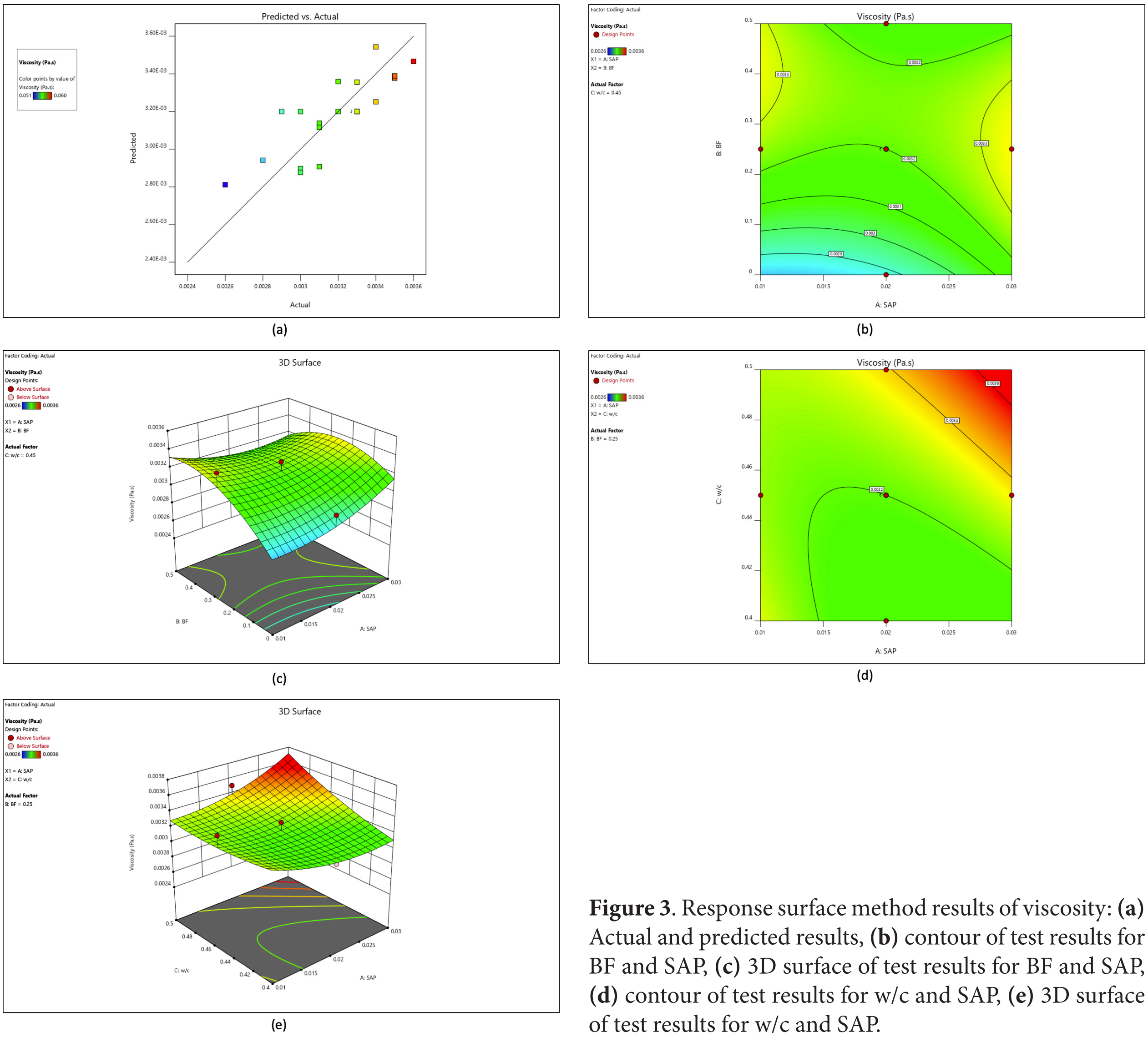


Figure 3. Response surface method results of viscosity: **(a)** Actual and predicted results, **(b)** contour of test results for BF and SAP, **(c)** 3D surface of test results for BF and SAP, **(d)** contour of test results for w/c and SAP, **(e)** 3D surface of test results for w/c and SAP.

a system's response by varying the input parameters. The CCD is a type of second-order design used to model the response surface of the system as a quadratic equation. The CCD requires fewer experimental runs than a complete factorial design and provides a better understanding of the relationship between the input and output variables.

The experimental design for the CCD involved three independent variables, namely SAP content (X1), basalt fiber content (X2), and water-to-cement ratio (X3). The range and levels of the variables used in the study are presented in Table 4.

In this paper, all experimental designs and analyses were examined with the help of the Design Expert software. The experimental design involved 20 runs, including one axial point, one factorial point, and six center points. The experimental runs were randomized to minimize the effect of extraneous variables. The experimental data were analyzed using the response surface methodology, and the quadratic model was developed to predict the rheological properties of the cement paste.

3. RESULTS AND DISCUSSION

The rheological properties of the cement paste, including viscosity and shear stress parameters, were analyzed using a rheometer. The results of the rheological testing are presented in Table 5. The components' impact on the cement paste's rheological properties is discussed below.

The viscosity of the cement paste increased with increasing SAP content and basalt fiber content and decreased with increasing water-to-cement ratio (Fig. 3). The quadratic model developed to predict the viscosity of the cement paste is presented in Equation 1 with R=0.8146.

$$(\text{Viscosity})^{0.5}=0.0565 + 0.0005X_1 + 0.0012X_2 + 0.0012X_3 + 0.0009X_1^2 - 0.0017X_2^2 + 0.0005X_3^2 - 0.0011X_1X_2 + 0.0014X_1X_3 + 0.0002X_2X^3 \quad (1)$$

Where X1, X2, and X3 are SAP content, basalt fiber content, and water-to-cement ratio, respectively.

The yield stress of the cement paste increased with increasing SAP content and basalt fiber ratio and decreased with increasing water-to-cement range (Fig. 4). The qua-

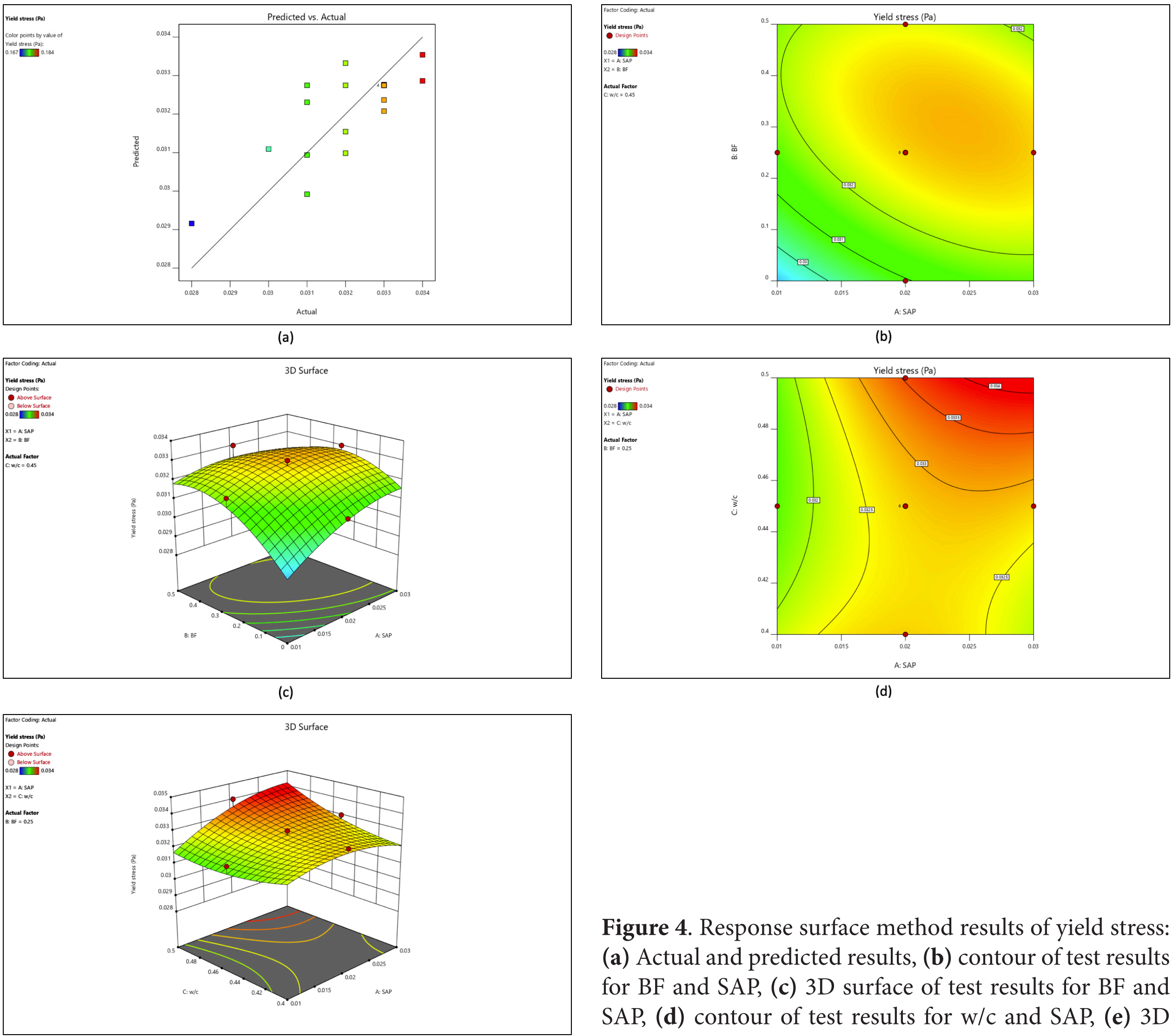


Figure 4. Response surface method results of yield stress: **(a)** Actual and predicted results, **(b)** contour of test results for BF and SAP, **(c)** 3D surface of test results for BF and SAP, **(d)** contour of test results for w/c and SAP, **(e)** 3D surface of test results for w/c and SAP.

dratic model developed to predict the yield stress of the cement paste is presented in Equation 2 with R=0.7899.

$$(\text{Yield Stress})^{0.5}=0.1809 + 0.0017X_1 + 0.0020X_2 + 0.0011X_3 - 0.0017X_1^2 - 0.0031X_2^2 + 0.0011X_3^2 - 0.0018X_1X_2 + 0.0018X_1X_3 + 0.0004X_2X_3 \quad (2)$$

Where X1, X2, and X3 are SAP content, basalt fiber content, and water-to-cement ratio, respectively.

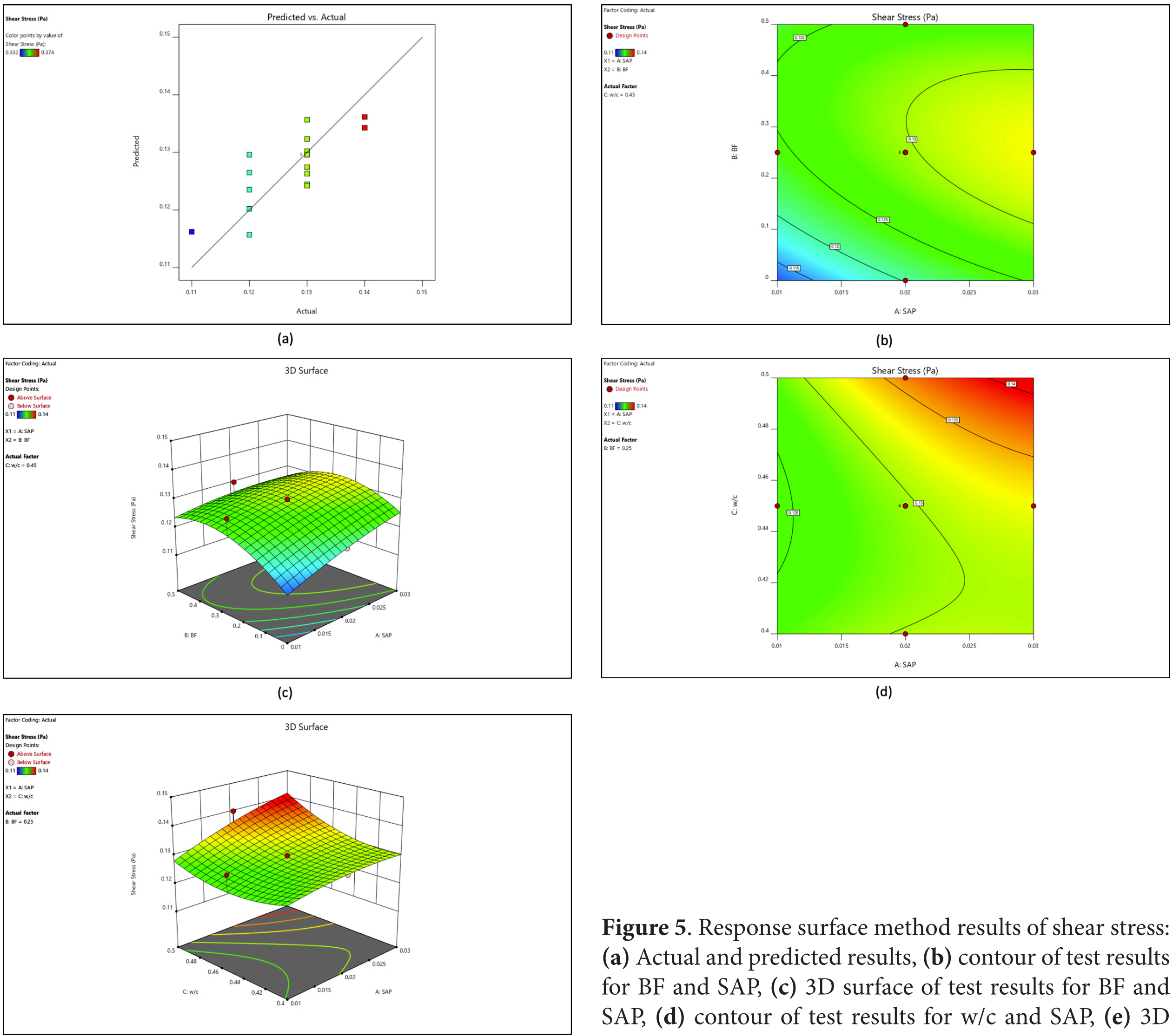
The shear stress of the cement paste increased with increasing SAP content and basalt fiber ratio and decreased with increasing water-to-cement range (Fig. 5). The quadratic model developed to predict the shear stress of the cement paste is presented in Equation 3 with R=0.7855.

$$(\text{Shear Stress})^{0.5}=0.3599 + 0.0057X_1 + 0.0044X_2 + 0.0041X_3 - 0.0019X_1^2 - 0.0090X_2^2 + 0.0049X_3^2 - 0.0035X_1X_2 + 0.0035X_1X_3 + 0.0001X_2X_3 \quad (3)$$

Where X1, X2, and X3 are SAP content, basalt fiber content, and water-to-cement ratio, respectively.

The study found that the viscosity of the paste increases with an increase in SAP content and basalt fiber content while decreasing with an increase in the water-to-cement ratio. In contrast, the shear stress increases with an increase in SAP content and a decrease in water-to-cement ratio while decreasing with an increase in basalt fiber content. The study also developed quadratic models to predict the viscosity and shear stress of the paste. The models considered the interaction between SAP and basalt fiber content and showed that the exchange positively affects yield and shear stresses. The comments are supported by Table 4, which presents the rheological properties of the paste for different runs, including viscosity, yield stress, and shear stress.

Using the Response Surface Methodology (RSM) with Central Composite Design (CCD) in the study is an appropriate statistical technique to optimize the experimental design and analyze the effects of independent variables on the response variables. CCD is a widely used practical design approach that helps to explore the complex relationships between variables by modeling second-order polynomial equations. The study utilized CCD to design and conduct experiments by varying the proportions of paste components within a specified range. The study re-



(a)

(b)

(c)

(d)

(e)

Figure 5. Response surface method results of shear stress: **(a)** Actual and predicted results, **(b)** contour of test results for BF and SAP, **(c)** 3D surface of test results for BF and SAP, **(d)** contour of test results for w/c and SAP, **(e)** 3D surface of test results for w/c and SAP.

sults could be useful in designing cementitious materials with improved rheological properties for various applications. Table 5 provides data on the effect of SAP content, basalt fiber content, and water-to-cement ratio on the cementitious composites' viscosity, yield stress, and shear stress. The data from the table can be analyzed using various statistical techniques to gain insights into the inter-relationships between the variables.

The statistical analysis of the data reveals that the water-to-cement ratio significantly affects the viscosity of the cementitious composites. According to the results of Runs, the composites with a higher water-to-cement ratio have a lower viscosity. This observation is consistent with the findings of previous studies that have shown that an increase in the water-to-cement ratio leads to a decrease in the viscosity of the cement paste [6]. On the other hand, the yield stress of the composites is influenced by the SAP and basalt fiber content. As seen from the data in Runs, the composites with a higher SAP content and basalt fiber content exhibit a higher yield stress. This result is in line with the previous studies that have demonstrated the reinforcing effect of SAP and basalt fiber on the mechanical properties of cementitious composites [6, 14]. The data in Table 5 also suggest that the shear stress of the composites is affected by the interaction between the SAP content, basalt fiber content, and water-to-cement ratio. For instance, the composites in Runs, which have the same SAP and basalt fiber content but different water-to-cement ratios, show different shear stress values. This finding is consistent with the research highlighting the complex interplay between multiple variables in determining the rheological properties of cementitious composites [6, 7, 9, 24].

In conclusion, the data in Table 5 and Figures 3–5 demonstrate the significant influence of SAP content, basalt fiber content, and water-to-cement ratio on the rheological properties of cementitious composites. The findings highlight the importance of carefully selecting the material components and optimizing their proportions to achieve the desired rheological behavior of the composites. The optimization of the test results is given in the next section.

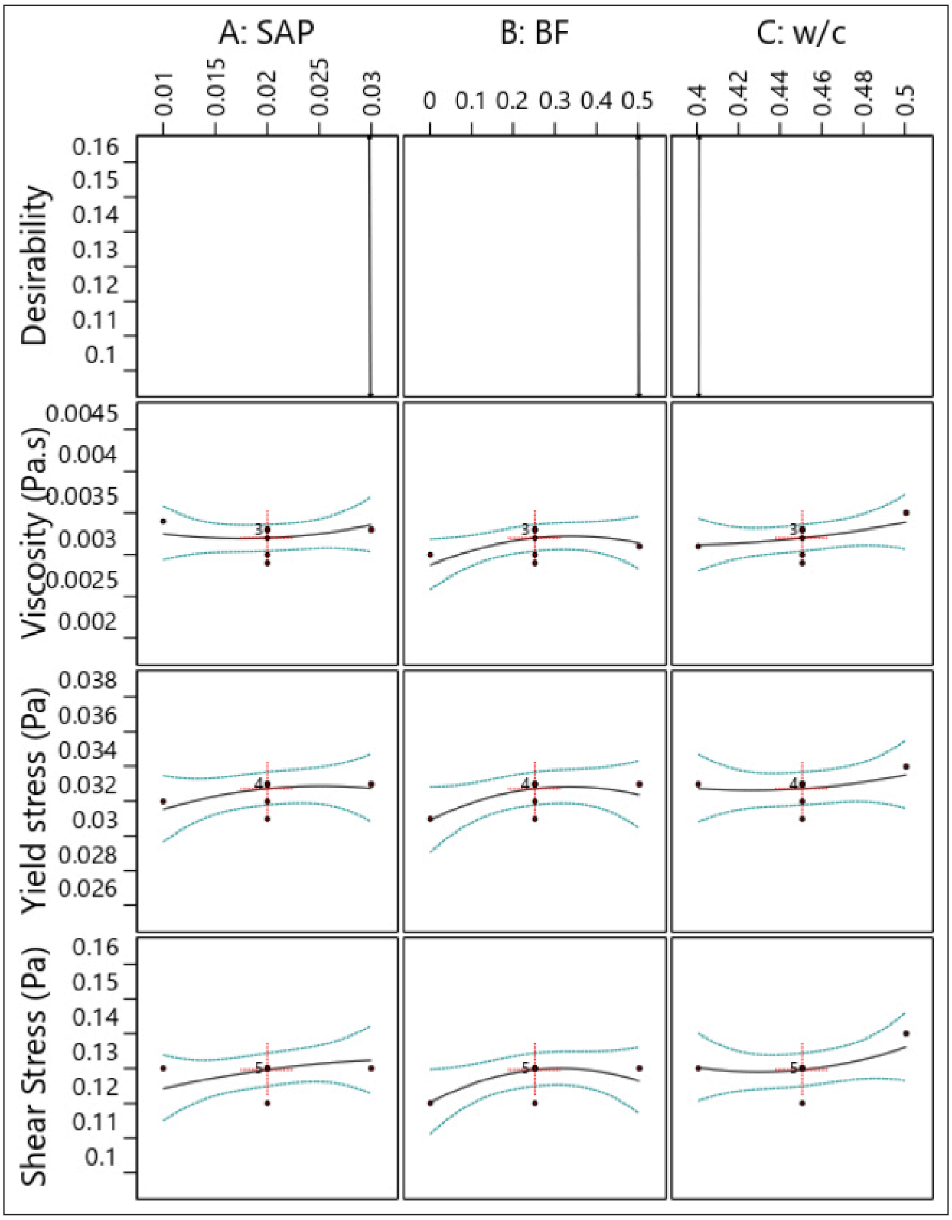
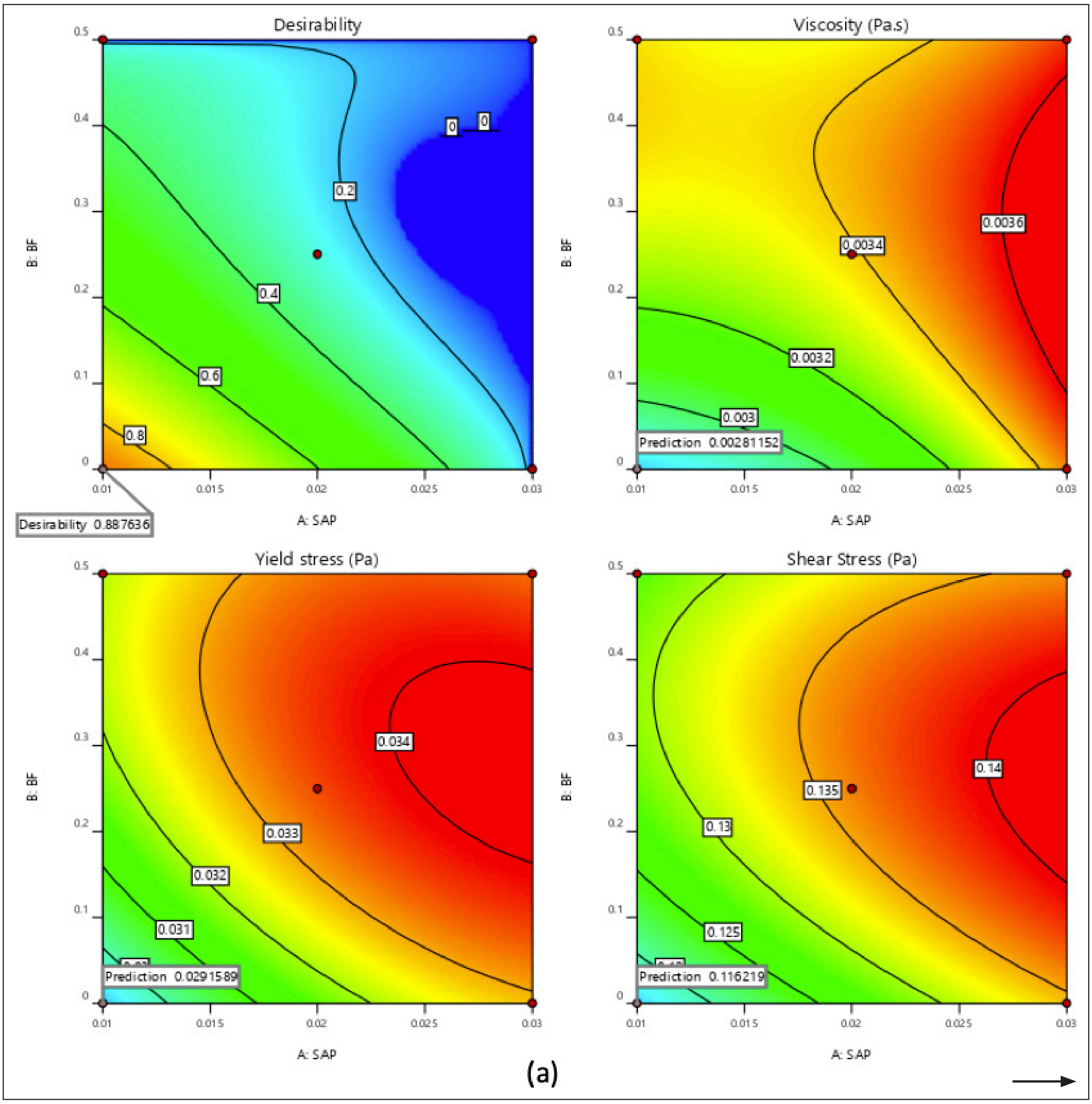


Figure 6. All factors impact on the test results.

Cement-based fresh paste has colloidal properties, and flow properties are essential during placement in the mold. Being in a fluid consistency like water is the most essential feature that is generally desired. For this reason, it is necessary to have a viscosity close to water, a low yield stress for it to flow, and a low shear stress between the particles. Considering the mentioned situations, the obtained test results have been optimized. Accordingly, the viscosity, yield stress, and shear stress are required to be minimum in the optimization. In addition, it is thought that the minimum SAP content, minimum basalt fiber content, and maximum water/cement content of the materials used will contribute positively to the results. Finally, the results shown in the figures below were obtained (Fig. 6, 7).

According to Figure 6, the relationship between the components and rheological parameters was given. The change in the rheology due to the use of SAP, BF, and w/c were observed. It was understood from Figure 6 that the increasing SAP and BF content in the mixture increased the yield and shear stress. Although the mixtures' components changed the mixtures' rheology, the mixtures' expected optimum behavior was evaluated below, as stated/argued in Figure 7.

In this comprehensive study, the viscosity, yield, and shear stress are required to be minimum in the optimization. In addition, it is thought that the minimum SAP content, minimum basalt fiber content, and maximum water/cement content of the materials used will contribute positively to the results. This leads to a high desirability of 0.887636, suitable up to 1.00. At this point, the proportions of components were BF=0%, SAP=0.01%, w/c=0.50, and the predicted rheological properties were approximately viscosity=0.0028 Pa.s, yield stress=0.029 Pa, and shear stress=0.116 Pa (Fig. 7). However, if the desirability level was set to 0.80 and the high is suitable up to 1.00, the proportions of components were BF=0.50%, SAP=0.01%, w/c=0.445, and the predict-



ed rheological properties were viscosity between 0.0028–0.0030 Pa.s, yield stress between 0.029–0.030 Pa, and shear stress between 0.114–0.115 Pa (Fig. 7).

4. CONCLUSIONS

In conclusion, the rheology of superabsorbent polymer-modified and basalt fiber-reinforced cement paste with silica fume was investigated using response surface methodology. The study demonstrated that adding superabsorbent polymer and basalt fibers significantly changed the rheological properties of the cement paste. The response surface methodology effectively optimized the mix design parameters to achieve the desired rheological properties. Some of the key findings of the study are commented on below.

Rheological properties: Adding superabsorbent polymer changed the cement paste's workability, yield stress, and plastic viscosity. The increase of water-to-cement proportion in the mixture increased workability, decreasing viscosity, yield/shear stress, super absorbent polymer, and basalt fiber's impact was the opposite of this. Basalt fibers enhanced the shear-thinning behavior of the cement paste, leading to a more stable and pumpable mixture.

Mixture design based on rheology: The optimum mix design parameters for achieving desired rheological properties were identified using the response surface methodology. Accordingly, the proportions of components such as BF=0.05%, SAP=0.01%, and w/c=0.445 can be offered for achieving desired rheological properties (low viscosity, yield stress, and shear stress).

The study highlights the potential of superabsorbent polymer and basalt fibers as effective additives for improv-

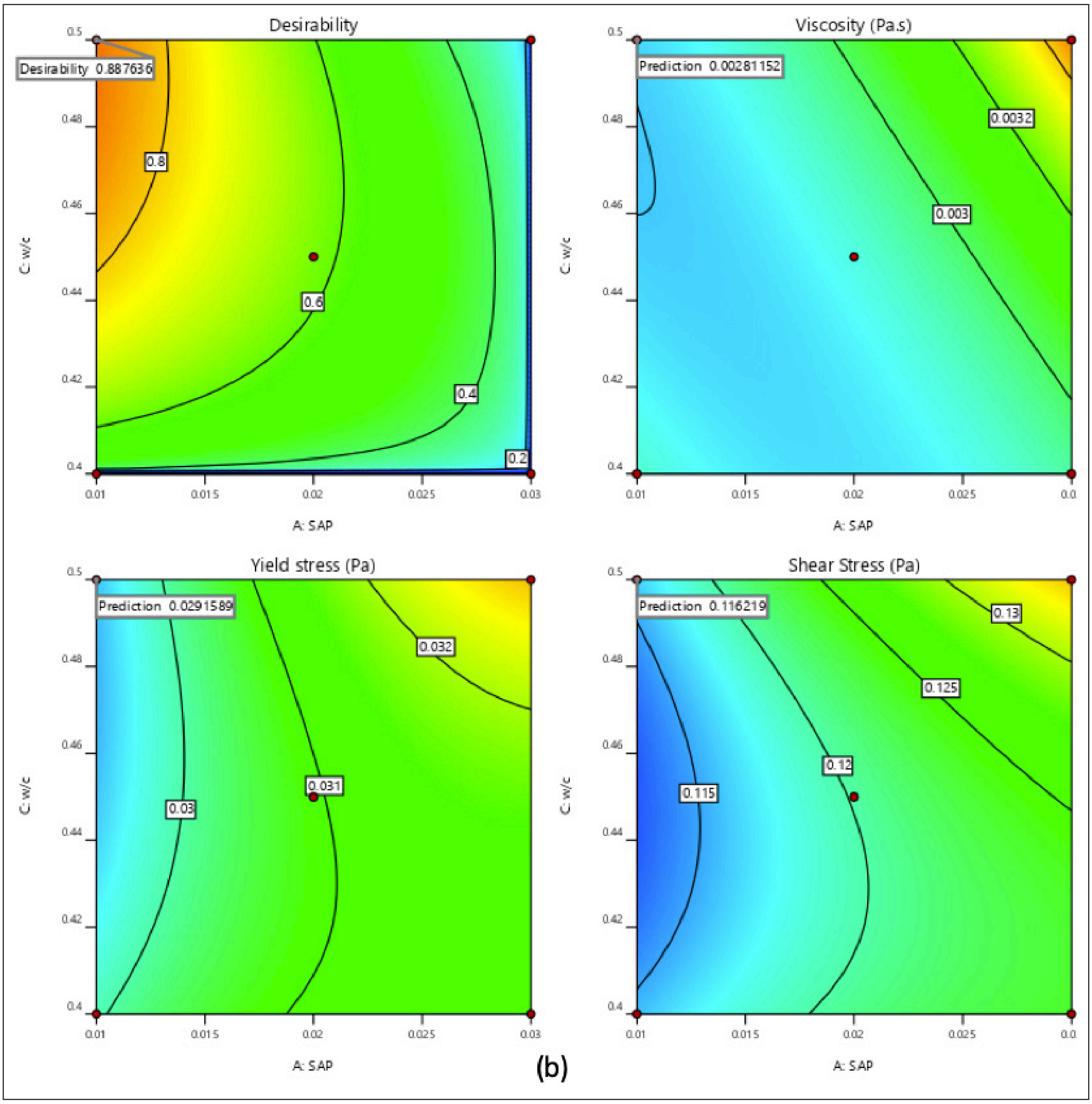


Figure 7. Desirability results: **(a)** rheological properties-BF-SAP, **(b)** rheological properties-SAP-w/c.

ing the rheological properties of cementitious materials. Further research is needed to explore the use of these materials in other cement-based applications, such as concrete and mortar. Additionally, the study focused on the effects of individual mix design parameters on the rheological behavior of the cement paste. Future research could investigate the interactions between multiple mixed design parameters and their combined impact on the material's rheological properties. This would provide a more comprehensive understanding of the factors influencing the rheology of cement-based materials and enable the development of more advanced mix designs that meet specific application requirements. Overall, the study demonstrates the potential of response surface methodology as a valuable tool in optimizing the mix design of cementitious materials for desired rheological behavior.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

REFERENCES

[1] Ma, X., Liu, J., Wu, Z. & Shi, C. (2017) Effects of SAP on the properties and pore structure of high-performance cement-based materials. *Constr Build Mat* 131, 476–484. [CrossRef]

[2] Björnström, J., Martinelli, A., Matic, A., Börjesson, L., & Panas, I. (2004) Accelerating effects of colloidal nano-silica for beneficial calcium–silicate–hydrate formation in cement. *Chem Phys Lett*, 392(1), 242–248. [CrossRef]

[3] Jensen, O. M. & Hansen, P. F. (2001). Water-entrained cement-based materials: I. Principles and theoretical background. *Cem Concr Res*, 31(4), 647–654. [CrossRef]

[4] Kong, D. Y., Du, X., Wei, S., Zhang, H., Yang, Y., & Shah, S. P. (2012). Influence of nano-silica agglomeration on microstructure and properties of the hardened cement-based materials. *Constr Build Mater*, 37, 707–715. [CrossRef]

[5] Lura, P., Jensen, O. M., & van Breugel, K. (2003). Autogenous shrinkage in high-performance cement paste: An evaluation of basic mechanisms. *Cem Concr Res*, 33(2), 223–232. [CrossRef]

[6] Mechtcherine, V., & Reinhardt, H. W. (2012). *Application of superabsorbent polymers (SAP) in concrete construction*. State-of-the-Art Report Prepared by Technical Committee 225-SAP. Springer. [CrossRef]

[7] Mechtcherin, V., Secrieru, E., & Schröfl, C. (2015). Effect of superabsorbent polymers (SAPs) on rheological properties of fresh cement-based mortars – Development of yield stress and plastic viscosity over time. *Cem Concr Res*, 67, 52–65. [CrossRef]

[8] Agostinho, L. B., Alexandre D. C. P., Silva, E. F., & Filho, R. D. T. (2021). Rheological study of Portland cement pastes modified with superabsorbent polymer and nanosilica. *J Build Eng*, 34, 102024. [CrossRef]

[9] Manzano, M. A. R., Fraga, Y. S. B., da Silva, E. F., de Oliveira, R. B., Caicedo Hormaza, B., & Toledo Filho, R. D. (2021). Internal curing water effect of superabsorbent polymer on microstructure of high-performance fine-grained concrete. *ACI Mater J*, 118(5), 125–135. [CrossRef]

[10] Roussel, N. (2006). A thixotropy model for fresh fluid concretes: Theory, validation and applications. *Cem Concr Res*, 36(10), 1797–1806. [CrossRef]

[11] Snoeck, D., Pel, L., & De Belie, N. (2018). Superabsorbent polymers to mitigate plastic drying shrinkage in a cement paste as studied by NMR. *Cem Concr Compos*, 93, 54–62.

[12] Zhang, M.H., & Islam, J. (2012). Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag. *Constr Build Mater*, 29, 573–580. [CrossRef]

[13] Bheel, N. (2021). Basalt fibre-reinforced concrete: Review of fresh and mechanical properties. *J Build Rehab*, 6(1), 12. [CrossRef]

[14] Hanafi, M., Aydin, E., & Ekinci, A. (2020). Engineering properties of basalt fiber-reinforced bottom ash cement paste composites. *Mater*, 13(8), 1952. [CrossRef]

[15] Zhou, X., Zeng, Y., Chen, P., Jiao, Z., & Zheng, W. (2021). Mechanical properties of basalt and polypropylene fiber-reinforced alkali-activated slag concrete. *Constr Build Mater*, 269, 121284. [CrossRef]

[16] Sridhar, J., Jegatheeswaran, D., & Gobinath, R. (2022). A DOE (Response Surface Methodology) Approach to predict the strength properties of concrete incorporated with jute and bamboo fibres and silica fumes. *Adv Civ Eng*, 2022, 1150837. [CrossRef]

[17] Luan, C., Zhou, M., Zhou, T., Wang, J., Yuan, L., Zhang, K., Ren, Z., Liu, Y., & Zhou, Z. (2022). Optimizing the design proportion of high-performance concrete via using response surface method. *Iranian J Sci Technol Trans Civ Eng*, 46, 2907–2921. [CrossRef]

[18] Soldatkina, L., & Yanar, M. (2023). Optimization of adsorption parameters for removal of cationic dyes on lignocellulosic agricultural waste modified by citric acid: Central composite design. *Chem Eng*, 7(1), 6. [CrossRef]

[19] Ali, M., Kumar, A., Yvaz, A., & Salah, B. (2023). Central composite design application in the optimization of the effect of pumice stone on lightweight concrete properties using RSM. *Case Stud Constr Mater*, 18, e01958. [CrossRef]

[20] Taşdemir, T., & Taşdemir, A. (2023). Optimization of floc-flotation process in the removal of suspended particles from wastewater in a Jameson cell using central composite design. *J Water Process Eng*, 52, 103552. [CrossRef]

[21] Montes Dorantes, P. N., & Mendez, G. M. (2023). *Non-iterative Wagner-Hagras general type-2 Mamdani singleton fuzzy logic system optimized by central composite design in quality assurance by image processing*. Recent Trends on Type-2 Fuzzy Logic Systems: Theory, Methodology and Applications. Springer. [CrossRef]

[22] Khan, M. Z., Yousuf, R. I., Shoaib, M. H., Ahmed, F. R., Saleem, M. T., Siddiqui, F., & Rizvi, S. A. (2023). A hybrid framework of artificial intelligence-based neural network model (ANN) and central composite design (CCD) in quality by design formulation development of orodispersible moxifloxacin tablets: Physicochemical evaluation, compaction analysis, and its in-silico PBPK modeling. *J Drug Deliv Sci Technol*, 82, 104323. [CrossRef]

[23] Hafez, H. M., Barghash, S. S., Soliman, M. M., Soltan, M. K., Elrahman, M. A., & Katamesh, N. S. (2023). Central composite design driven optimization of sustainable stability indicating HPLC method for the determination of Tigecycline and greenness assessment. *F1000Research*, 12, 341. [CrossRef]

[24] Dilbas, H. (2023). Effect of cement type and water-to-cement ratio on fresh properties of superabsorbent polymer-modified cement paste. *Mater*, 16(7), 2614. [CrossRef]