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# Rheological Optimization of Steel Fiber-reinforced Self-compacting Concrete (SFSCC) Incorporating Calcareous Tuff Powder (CTP)

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ABSTRACT

The purpose of this study is to formulate a steel fiber-reinforced self-compacting concrete (SFSCC) with optimal rheological properties, using calcareous tuff powder (CTP) as an addition and partial substitution for cement. The design of experiments (DOE) method was used to analyze the effect of fiber dosage, paste volume, and gravel-to-sand ratio on the SFSCC. A concrete rheometer was used to quantify the intrinsic rheological parameters. The rheological results of the SFSCC containing calcareous tuff powder indicate that both paste volume and fiber dosage significantly affect flow capacity, while plastic viscosity is exclusively governed by paste volume. The measured rheological parameters indicated that the steel fiber-reinforced self-compacting concrete incorporating calcareous tuff powder is a high yield stress self-compacting concrete (HYSCC), with yield stress values ranging from 62 Pa to 335 Pa and plastic viscosity values between 12 and 31 Pa.s. Rheological optimization through the DOE method allowed the identification of optimal composition factors, ensuring a targeted self-compacting behavior. The self-compacting behavior of the SFSCC observed in the rheometer was confirmed and validated at full scale, with slump flow values up to 72 cm and flow time ($T_{500}$) between 3.0 seconds and 4.3 seconds.

***Keywords:*** Rheology, self-compacting concrete, Design of experiments method, Calcareous tuff powder, Steel fibers.

## INTRODUCTION

Self-compacting concretes (SCCs) are considered innovative construction materials that enable faster and more efficient placement of concrete structures. They are defined by their ability to flow into place without vibration, owing to their high fluidity and internal cohesion. However, the use of Portland cement in SCC production results in significant $CO_2$ emissions, thereby contributing to climate change. For this reason, many researchers have investigated the use of supplementary cementitious materials as partial replacements for cement in order to reduce the $CO_2$ emissions associated with concrete production (Huang, 2017). The most commonly used supplementary materials include limestone fillers, marble and granite powders, fly ash, volcanic pumice powder, ground granulated blast furnace slag, and silica fume. These materials increase the fine content in SCC mixtures and enhance both their rheological and mechanical properties (Sadek, 2016).

The production of self-compacting concrete requires a relatively high fines' content, which leads to a limited deformation range, particularly under tensile stresses. For this reason, the incorporation of fibers into SCC has been proposed to improve its ductility, as well as its flexural and tensile strengths (Saba, 2021). However, a preliminary mix design must be developed to optimize the formulation of fiber-reinforced SCC. This optimization can be achieved either by enhancing workability through the control of the paste or mortar fraction (Okamura, 2003; Saak, 2001), or by optimizing the aggregate skeleton (Su, 2001). In general, the incorporation of fine materials enables better aggregate distribution and enhances the cohesion of the mix (Khayat, 2000).

In this context, the use of limestone tuff as a supplementary cementitious material in the production of fiber-reinforced SCC is considered a suitable solution for countries such as Algeria, where this material is readily available. Its use as a partial replacement for Portland cement would help reduce the cost of SCC, lower the demand for filler materials, and limit $CO_2$ emissions.

A literature review highlights the limited number of studies focusing on the partial replacement of cement with limestone tuff to optimize the properties of self-compacting concrete, particularly when reinforced with steel fibers.

In direct relation to the use of limestone tuff as a fine substitute material, Hadj Aissa (2020) demonstrated that this addition enhances the flowability and stability of self-compacting concrete. The maximum 28-day compressive strength was obtained for an SCC mix containing 10% tuff powder. Beyond this level, a decrease in compressive strength was observed, reaching up to 40% for a replacement rate of 30%. The absorbent nature of tuff powder was identified, affecting both admixture and water demand. Micro-structural analysis revealed that a dense structure was achieved through the incorporation of tuff, which in turn influenced the rheological and mechanical properties of SCC.

Furthermore, Cherrak (2013) reported results on the use of limestone tuff as a partial replacement for sand in conventional concrete, with substitution rates ranging from 5% to 35%. The best performance was obtained with a 25% replacement level, leading to a 33% increase in compressive strength. The physical properties of the resulting concrete were influenced by the absorbent nature of the tuff, which proved to be a determining factor. However, increasing the tuff content may reduce resistance to chemical attack.

In addition, more recent studies have confirmed the potential of tuff in various cementitious formulations. For instance, Abutaqa (2024) demonstrated that replacing 10% of cement with volcanic tuff improved compressive strength (+5.6%) and flexural strength (+35.6%), while reducing water permeability by 57%. Edris (2021) confirmed that a 10% tuff replacement led to micro-structural densification and significant performance gains, whereas a 15% substitution resulted in a slump loss estimated at 66.7%. Finally, Naadia (2025) optimized the mechanical behavior of a steel fiber-reinforced SCC incorporating tuff powder using a three-variable experimental design. This study showed that the pozzolanic effect of tuff, combined with fiber dosage, made it possible to simultaneously improve compressive strength (+59%) and ductility index (+687%).

In the general case of fiber-reinforced self-compacting concrete, Saba (2021) confirmed that replacing cement with silica fume, combined with the incorporation of steel fibers, results in a durable, workable, and more economical fiber-reinforced SCC. With a 20% replacement level and a fiber dosage of 0.5%, a satisfactory consistency was achieved. At the same fiber content, compressive strength increased by up to 12.5%. In contrast, tensile and flexural strengths were found to be directly proportional to the fiber content, with gains reaching 48% and 51%, respectively, at 1% fiber dosage. Moreover, Goel (2018) evaluated the combined effect of fly ash and steel fibers in self-compacting concrete. The authors showed that starting from 0.5% fiber content, ductility and flexural strength increased significantly (up to 80%), while the fresh-state properties remained in accordance with EFNARC requirements.

On the other hand, Alabduljabbar (2019) used various cement replacement materials (CRMs) in combination with steel fibers. Workability was improved by some of these CRMs, particularly fly ash, silica fume, and calcined rice husk ash. An improvement of 9% in workability was reported in the case of fly ash. From a mechanical perspective, these materials offered the best performance, with increases of 19% in compressive strength and 13% in flexural strength.

Furthermore, two separate studies by Magbool, both published in 2021, focused on steel fiber-reinforced self-compacting concrete incorporating volcanic pumice powder. In his first article (Magbool 1, 2021), the author investigated the effect of incorporating VPP on the properties of SFSCC. The results showed that steel fibers reduce rheological performance, while the addition of VPP, at a dosage of 30% by cement mass, improves both compressive and flexural strengths. In his second article (Magbool 2, 2021), five types of steel fibers were tested in an SCC mix containing VPP. A reduction in workability was observed (slump flow < 500 mm), along with enhanced tensile and flexural strengths, attributed to improved post-cracking behavior.

In a similar approach, Sree Lakshmi Devi (2022) adopted a partial replacement of cement with three types of fine materials—fly ash, ground granulated blast furnace slag, and micro-silica—for the formulation of a quaternary steel fiber-reinforced SCC (SFQBSCC). Steel fibers were incorporated in proportions ranging from 0 to 1.5%. At 1% fiber content, a 14.7% increase in flexural strength was recorded compared to the reference SCC. With a water-to-binder ratio of 0.4 and 1.5% fiber content, the strength gain reached 30%.

Athiyaman (2020), for his part, incorporated 30% fly ash and 10% silica fume to produce a steel fiber-reinforced SCC. The formulations containing these mineral additions exhibited better fresh-state performance. However, the addition of steel fibers reduced flowability. The hydration process continued beyond 28 days in SCC mixes containing these fine materials.

Finally, Donmez (2023) demonstrated that the use of mineral additions as partial replacements for cement plays a crucial role in improving the workability of hybrid fiber-reinforced self-compacting concrete (HFRSCC), while also contributing to the reduction of $CO_2$ emissions. The use of various powders as binders proved effective in ensuring better workability and a more homogeneous distribution of fibers. Hybrid mixes with ternary binders yielded the best results in terms of compressive strength, whereas binary binder concretes containing fly ash achieved the best tensile and flexural strength performance.

Thus, the main objective of this study is to formulate a steel fiber-reinforced self-compacting concrete incorporating calcareous tuff powder, with optimal rheological properties in the fresh state. The value of this work lies in the utilization of a natural and locally abundant resource such as calcareous tuff. The originality of this research resides in the rheological optimization of an SFRSCC containing a significant amount of tuff as an addition and partial substitute for cement. A suitable rheometer is used to quantify intrinsic rheological parameters. The design of experiments (DOE) method was employed to analyze the effect of formulation parameters on SFRSCC. The variables studied are fiber dosage (%Fib), paste volume (Vp), and the gravel-to-sand ratio (G/S).

## MATERIALS USED

The cement used in all compositions is a blended Portland cement (CPJ CEM II / B - 42.5). Furthermore, calcareous tuff powder was used as an additive and a substitute for cement. The tuff was supplied in a raw and wet form, consisting of graded rock fragments up to 2 cm in size. After drying at 105 °C, it was crushed and then ground to obtain a fine powder. Grinding was performed in two separate sessions to produce two distinct fineness levels, referred to as SSB1 and SSB2. These correspond to two blaine specific surface areas of the tuff powder.

The chemical compositions and the physical properties of the cement and the calcareous tuff powder used are given in Tables 1 and 2, respectively.

**Table 1. Chemical compositions of the cement and the calcareous tuff powder**

| **Elements (%)** | **Cement** | **Tuff Powder** |
|---|---|---|
| $SiO_2$ | 17.38 | 60.55 |
| $Al_2O_3$ | 4.69 | 17.20 |
| $Fe_2O_3$ | 2.72 | 4.85 |
| CaO | 61.53 | 4.61 |
| MgO | 1.55 | 1.79 |
| $K_2O$ | 0.95 | 3.23 |
| $Na_2O$ | 0.2 | 2.40 |
| $SO_3$ | 2.44 | 0.01 |
| $P_2O_5$ | / | 0.16 |
| $TiO_2$ | / | 0.48 |
| CaO free | 1.44 | / |
| Cl | 0.028 | / |
| Ins. | 2.82 | / |
| L.o.I. | 8.54 | 4.73 |

Ins.: Insoluble residue; L.o.I: Loss on ignition.

**Table 2. Physical properties of the cement and the calcareous tuff powder**

| Characteristics | Tuff Powder | Cement |
|---|---|---|
| Bulk specific density (g/cm$^3$) | 0.72 | / |
| Specific weight (g/cm$^3$) | 2.52 | 2.99 |
| Porosity (%) | 40 | / |
| Color | Yellowish | Grey |
| Specific surf. (SSB1/SSB2) (cm$^2$/g) | 3440/5700 | 4026 |
| Standardized consistency $H_2O$ (%) | / | 26.6 |
| Time of initial setting (min) | / | 140 |
| Time of final setting (min) | / | 250 |

Two standard size fractions of coarse aggregates (3/8 mm and 8/15 mm; i.e., aggregates passing through 8-mm and 15-mm sieves, respectively) were used. These sizes are commonly adopted in Algeria. Both aggregates are crushed and have the same mineralogical nature. A natural silica sand from the city of Oued Souf, located in southern Algeria, was used. This region is known for the abundance of its sand resources. The main characteristics of the aggregates employed are provided in Table 3.

**Table 3. Characteristics of aggregates**

| Characteristics | Symbol | Sand | Gravel 3/8mm | Gravel 8/15mm |
|---|---|---|---|---|
| Absolute density (g/cm$^3$) | $P_S$ | 2.65 | 2.70 | 2.70 |
| Apparent density (g/cm$^3$) | $P_p$ | 1.44 | 1.53 | 1.45 |
| Water absorption (%) | $A_s$ | 1 | 1.5 | 0.95 |
| Fineness modulus | $M_f$ | 2.7 | / | / |
| Sand equivalent (%) | ESV | 83 | / | / |
|  | ESP | 81 |  |  |

The superplasticizer used is a high water reducer according to EN 934-2, designed from the polycarboxylates, under the name of Medaflow145.

The fibers used are hooked-ended steel fibers called "Dramix", as shown in Figure (1) and their characteristics are represented in Table 4.

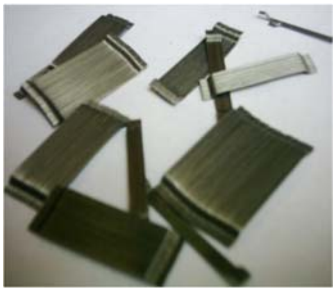

**Figure (1): Steel fibers used**

**Table 4. Standard characteristics of fibers**

| Shape | Hooks |
|---|---|
| Bonding | Bonded |
| Length (mm) | 30 |
| Diameter (mm) | 0.55 |
| Tensile strength (N/mm$^2$) | 1345 |
| Aspect ratio (L/D) | 55 |
| Density (g/cm$^3$) | 7.8 |

## EXPERIMENTAL PROGRAM

The first experimental phase involves optimizing a cement paste incorporating calcareous tuff, while the second focuses on the optimization of steel fiber reinforced self-compacting concrete (SFSCC). To optimize the paste, both the fineness and the amount of calcareous tuff powder were varied. This material was used either as a partial replacement or as an addition, relative to the cement weight. Two levels of tuff powder fineness were considered (as detailed in Table 2), and for each level, four paste mixtures were prepared with a 10% addition of calcareous tuff relative to the cement weight. A control paste (PPT), without cement substitution by CTP, was prepared, along with three pastes (PPT1, PPT2, and PPT3) incorporating 10%, 20%, and 30% cement replacement by CTP, respectively. The admixture dosage was varied from 0.8% to 2% for each fineness level, which resulted in 28 distinct formulations per level. Thus, a total of 56 paste formulations were studied. The 28 formulations corresponding to a given tuff powder fineness are presented in Table 5. The initial cement content was fixed at 400 kg/m³, with a water-to-binder ratio (W/B) of 0.28.

**Table 5. Organization of paste formulations for a given CTP fineness**

| Formulation ID | CTP addition (%) | Cement substitution (%) | Admixture dosage (%) |
|---|---|---|---|
| PPT | 10 | 0 | 0.8 – 2.0 (step of 0.2) |
| PPT1 | 10 | 10 | 0.8 – 2.0 (step of 0.2) |
| PPT2 | 10 | 20 | 0.8 – 2.0 (step of 0.2) |
| PPT3 | 10 | 30 | 0.8 – 2.0 (step of 0.2) |

Several flow tests using a mini-cone, in accordance with standard EN 196-1, were performed to determine the admixture saturation point. The grout spread diameter was measured immediately after mixing (see Figure (2)).

**Figure (2): Paste flow test**

Based on the optimized self-compacting paste, a control self-compacting concrete (SCCT) was formulated using the Japanese method (Okamura, 1994). As shown in Figure 3, this SCCT was subjected to standard rheological tests, including the slump flow test, sieve stability test, and L-box test, in order to validate its performance according to the recommendations of the French Civil Engineering Association (AFGC, 2000).

a- Slump-flow test b-Sieve-stability test c- L-box test

**Figure (3): Fresh tests of SCC**

After validating this self-compacting concrete, steel fibers were incorporated in varying amounts to optimize a steel fiber reinforced self-compacting concrete (SFSCC) with improved rheological performance. To achieve this, the design of experiments (DOE) method was employed. A three-factor experimental design was adopted, and to evaluate the influence of each parameter, a full factorial design ($2^3$) was implemented, resulting in eight mixtures. The selected variables were: paste volume (Vp), varied between 355 l/m³ and 385 l/m³; fiber dosage (%Fib), representing the volume of steel fibers expressed as a percentage of the total concrete volume (1 m$^3$), ranging from 0.2% to 0.5%; and the gravel-to-sand ratio (G/S), varied between 0.85 and 1. Table 6 presents the combinations derived from this three-factor experimental design.

**Table 6. Different combinations deduced from the selected design of experiment**

| **Concrete ID** | **Parameters** | | |
|---|---|---|---|
| | **$V_P$ (L)** | **Fib (%)** | **G/S** |
| SCCT | 385 | 0 | 0.9 |
| SFSCC1 | 355 | 0.2 | 0.85 |
| SFSCC2 | 385 | 0.2 | 0.85 |
| SFSCC3 | 355 | 0.2 | 1 |
| SFSCC4 | 385 | 0.2 | 1 |
| SFSCC5 | 355 | 0.5 | 0.85 |
| SFSCC6 | 385 | 0.5 | 0.85 |
| SFSCC7 | 355 | 0.5 | 1 |
| SFSCC8 | 385 | 0.5 | 1 |

Based on the selected experimental design, eight full-scale compositions of steel fiber-reinforced self-compacting concrete (SFSCC), along with a control self-compacting concrete (SCCT), were formulated and subsequently reproduced at reduced scale for rheological testing using a rheometer (See Figure (4)). These eight SFSCC mixtures, designated SFSCC1 to SFSCC8, together with the control SCCT, are detailed in Table 7.

**Table 7. The compositions of the eight studied SFSCC and the control concrete (SCCT)**

| | **Components (Kg)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **C** | **CTP** | **W** | **SP** | **S** | **G (3/8mm)** | **G (8/15mm)** | **$G_{eq}$ (3/8mm)*** | **Fib** |
| SCCT | 332 | 125 | 219 | 6.4 | 873 | 472 | 314 | 120 | 0 |
| SFSCC1 | 306 | 115 | 202 | 5.9 | 941 | 480 | 320 | 122 | 16 |
| SFSCC2 | 332 | 125 | 219 | 6.4 | 897 | 458 | 305 | 116 | 16 |
| SFSCC3 | 306 | 115 | 202 | 5.9 | 870 | 522 | 348 | 133 | 16 |
| SFSCC4 | 332 | 125 | 219 | 6.4 | 829 | 497 | 332 | 127 | 16 |
| SFSCC5 | 306 | 115 | 202 | 5.9 | 941 | 480 | 320 | 122 | 39 |
| SFSCC6 | 332 | 125 | 219 | 6.4 | 897 | 458 | 305 | 116 | 39 |
| SFSCC7 | 306 | 115 | 202 | 5.9 | 870 | 522 | 348 | 133 | 39 |
| SFSCC8 | 332 | 125 | 219 | 6.4 | 829 | 497 | 332 | 127 | 39 |

* The equivalent amount of the gravel fraction (3/8) to replace that of (8/15) in order to get the reduced concrete.

C: cement, CTP: Calcareous Tuff powder, W: water, SP: superplasticizer, S: sand, G: gravel, Fib: fiber.

All mixtures were subjected to rheological testing using a concrete rheometer to optimize intrinsic rheological parameters; namely, yield stress and plastic viscosity. This optimization was performed on reduced-scale concretes (1.65 liters), in accordance with the model proposed by Naadia (2020).

In these reduced-scale formulations, the entire self-compacting fiber-reinforced concrete was replaced by a reduced version in which the largest aggregate fraction (8/15 mm gravel) was substituted with an equivalent amount of the immediately smaller fraction (3/8 mm gravel), based on specific surface area. This type of equivalence (gravel for gravel) ensures similar shape and texture, thereby minimizing the replacement error.

**Figure (4): Rheometer used (Naadia, 2020)**

## RESULTS AND DISCUSSIONS

### Paste Optimization

In order to optimize the self-compacting paste, the admixture dosage and the cement replacement rate with calcareous tuff powder (CTP) were considered for each tuff powder fineness (SSB1 and SSB2). For each fineness level, the optimized paste formulation corresponds to the composition that yields the maximum spread, as determined through mini-cone tests. The results of the mini-cone tests performed on the various paste formulations for both calcareous tuff powder fineness levels are presented in Figures (5) and (6).

Based on the results presented in Figures (5) and (6), the saturation point of the superplasticizer was identified as the admixture dosage corresponding to the maximum spread diameter, which reflects optimal flowability.

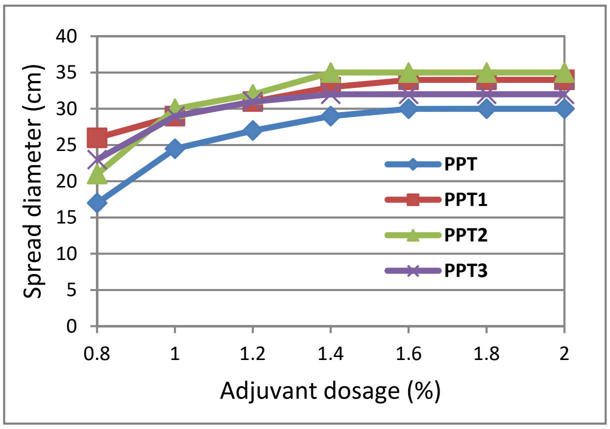

**Figure (5): Evolution of the spread of pastes with powder tuff fineness (SSB1) based on the adjuvant dosage**

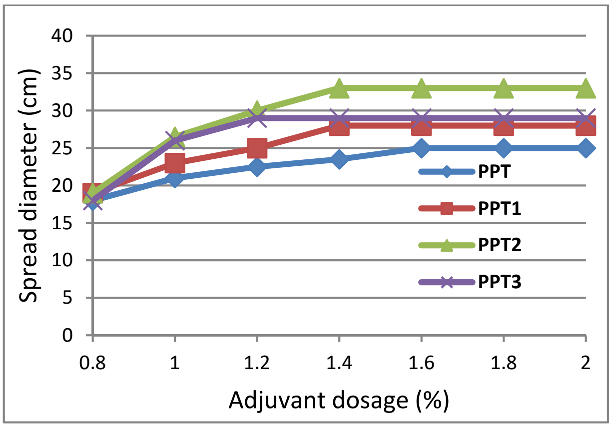

**Figure (6): Evolution of the spread of pastes with powder tuff fineness (SSB2) based on the adjuvant dosage**

For all paste formulations and both tuff powder fineness levels, an increase in superplasticizer dosage leads to an increase in spread, up to a saturation threshold beyond which no further significant improvement is observed. This saturation point varies depending on the paste composition, particularly the cement replacement rate with tuff powder and the fineness of the latter.

Moreover, a decrease in cement content within the paste systematically leads to a reduction in the saturation dosage of the superplasticizer, regardless of the cement replacement rate with calcareous tuff powder. This behavior can be attributed to the mechanism by which the superplasticizer acts, primarily through adsorption onto the surface of cement particles, thereby reducing flocculation upon contact with water. The results also revealed that an increase in the fineness of the calcareous tuff powder leads to a reduction in the spread diameter. This phenomenon is explained by the mineralogical nature of the additive: calcareous tuff possesses pozzolanic activity and reacts with water during hydration. A higher specific surface area increases the water demand of the system, consequently reducing flowability. Therefore, the use of tuff powder can enhance rheological performance only when its fineness remains moderate; i.e., less than or equal to that of the cement, as highlighted in the works of Hadj Aissa (2020) and Cherrak (2013) who noted that tuff powder's absorbent nature affects admixture efficiency and water demand, ultimately influencing the fresh-state performance of concretes.

Based on the rheological optimization, the most effective paste composition (PPT2) corresponds to a formulation in which 20% of the cement is replaced by calcareous tuff powder. This composition achieves optimal flow with a superplasticizer saturation dosage of 1.4%, and the calcareous tuff powder used has a specific surface area (SSB) of 3440 cm²/g. These characteristics confirm the beneficial role of moderately fine calcareous tuff powder in enhancing the fresh-state behavior of the paste while maintaining a reduced demand for chemical admixtures.

### Fresh Test Results of the SCCT

A reference self-compacting concrete (SCCT) was formulated using the optimized self-compacting paste (PPT2) and following the Japanese mix design method. The composition and results of fresh state tests, including slump flow test using the Abrams cone, sieve stability test, and the L-box test, are presented in Table 8, which confirms that the measured performance meets the criteria for self-compacting concrete (SCC) in accordance with AFGC guidelines (AFGC, 2000).

**Table 8. Composition and results of the fresh state test of the SCCT**

| SCCT components in (kg) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Cement** | **Addition** | **Substitution** | **Superplasticizer** | **Water** | **Sand (0/4mm)** | **Gravel (3/8mm)** | **Gravel (8/15mm)** |
| 332 | 42 | 83 | 6.4 | 219 | 873 | 472 | 314 |

| Tests in the fresh state | | | | |
|---|---|---|---|---|
| **Slump flow (cm)** | **Time flow ($T_{500}$) (s)** | **Filling capacity (H1/H2)** | **Laitance weight (%)** | **Bulk density (kg/m$^3$)** |
| 72 | 3.05 | 0.94 | 6.66 | 2406 |

## Optimization of SFSCC Made with Tuff Powder by the Design of Experiments (DOE) Method

### Experimental Data

The results of the rheological tests performed with the concrete rheometer are presented in the form of rheograms. These rheograms represent the variation of torque (M), which resists the rotation of a vane or mobile element, as a function of its rotational speed (V), expressed as [M = f(V)]. Figure (7) presents the rheogram of the SFSCC1 mixture as a representative example. The other mixtures exhibit a similar trend, reflecting Bingham-type behavior, with variations depending on formulation parameters. The differences observed among mixtures mainly concern the yield stress and plastic viscosity, which are reflected by the intercept and slope of the curves, respectively. The fundamental rheological parameters (namely, yield stress ($\tau_0$) and plastic viscosity ($\mu$)) are derived using the calculation method developed by our research team (Naadia, 2020). This method enables the conversion of torque (M) into shear stress ($\tau$) exerted within the self-compacting concrete.

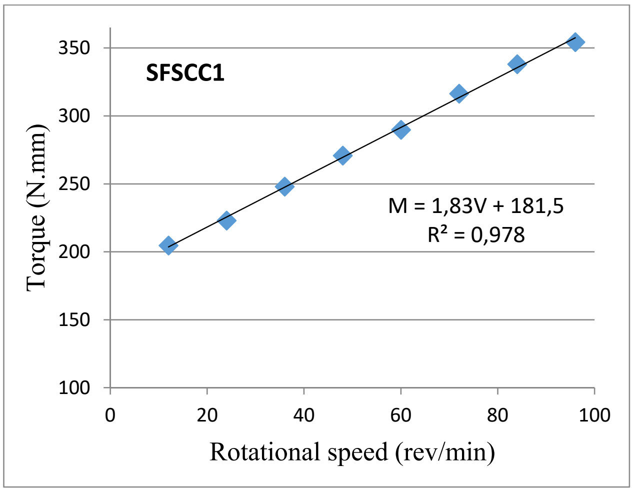

**Figure (7): Experimental torque *versus* rotational speed data fitted by a linear model for the SFSCC1 concrete**

The results of the rheological parameters (yield stress ($\tau_0$), plastic viscosity ($\mu$)) of the eight fiber-reinforced concretes as well as the control concrete (SCCT) are given in Table 9.

According to Figure (8), each formulated concrete is represented by a point corresponding to the pair (yield stress, plastic viscosity) ($\tau_0$, $\mu$) and is compared to the typical rheological domain of self-compacting concretes (SCCs) as defined by Wallevik (2011).

**Table 9. Rheological parameters of the studied concretes**

| | SCCT | SFSCC1 | SFSCC2 | SFSCC3 | SFSCC4 | SFSCC5 | SFSCC6 | SFSCC7 | SFSCC8 |
|---|---|---|---|---|---|---|---|---|---|
| $\tau_0$ (Pa) | 62.02 | 253.95 | 63.5 | 249.37 | 77.32 | 335.55 | 128.04 | 259.15 | 82.06 |
| $\mu$ (Pa.s) | 17.16 | 30.93 | 16.93 | 24.8 | 12.77 | 24.07 | 14.26 | 21.37 | 12.13 |

It is observed that this type of fiber-reinforced SCC incorporating tuff powder exhibits relatively high yield stress values compared to other types of fiber-reinforced SCC, particularly those formulated with marble powder as reported by Gueciouer (2019). This observation is further supported by the fact that all data points for the studied concretes fall either within or beyond the upper bounds of the domain associated with self-compacting concretes exhibiting high yield stress.

According to Figure (8) and in reference to the rheological domain defined by Wallevik (2011), only the compositions SCCT, SFSCC2, SFSCC4, and SFSCC8 fall within the range corresponding to self-compacting concretes (SCCs). The SFSCC6 mixture slightly deviates from this domain due to a marginally higher yield shear stress. To validate this observation, conventional fresh-state tests were conducted on these five SCCs at full scale, including the slump flow test, the L-box test, and the sieve stability test. The results of these tests are presented in Table 10.

The four concretes; namely, SCCT, SFSCC2, SFSCC4, and SFSCC8, all exhibit a slump flow greater than 60 cm, a laitance content below 15%, and a filling capacity exceeding 80%. These results confirm their self-compacting behavior. This was validated even at full scale, in accordance with the AFGC recommendations.

In contrast, the SFSCC6 mixture shows results that slightly deviate from the expected performance of a self-compacting concrete at full scale.

These findings demonstrate that the reduced-scale modeling approach adopted in this study correlates well with full-scale behavior. Moreover, the proposed experimental design proves effective in identifying an optimized range of formulation parameters for producing SCCs with suitable rheological properties.

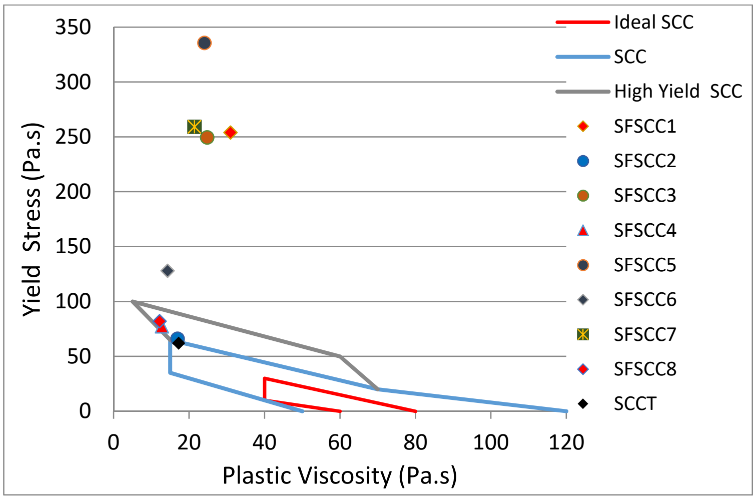

**Figure (8): Rheological parameters of the SFSCC compared to the self-compacting concrete domain defined by Wallevik (2011)**

**Table 10. Results of rheological tests on SFSCC and SCCT at the real scale**

| SCC ID | Slump flow (cm) | Filling capacity (H1/H2) (%) | Laitance weight (%) |
|---|---|---|---|
| SCCT | 72 | 94 | 6.66 |
| SFSCC2 | 71 | 93 | 1.75 |
| SFSCC4 | 67 | 93 | 2.30 |
| SFSCC6 | 58 | 75 | 1.33 |
| SFSCC8 | 65 | 80 | 1.25 |

## Modeling and Analysis of the Results by the Design of Experiments (DOE) Method

The identification of statistically significant factors influencing rheological parameters was carried out using the Design of Experiments (DOE) method. As shown in Figure (9), the Pareto chart indicates that both the fiber dosage (%Fib) and the paste volume (Vp) have a significant effect on the flow capacity, as reflected by the yield shear stress. Among these, fiber dosage emerges as the most influential variable, a trend also observed in previous studies on steel fiber-reinforced SCC incorporating marble powder as a cementitious addition (Guecioeur, 2019). The marked influence of paste volume is attributed to the specific nature of the additive used (calcareous tuff powder) which is known for its high water-absorption capacity, as previously reported by Cherrak (2013). Compared to SFSCC formulated with marble powder (Guecioeur, 2019), SFSCC with calcareous tuff powder exhibits no statistically significant interaction effects between the formulation parameters in achieving flow. In this context, flowability is primarily governed by the paste matrix, while the presence of fibers plays a secondary, mitigating role.

As illustrated in Figure (9), the chart displays the absolute value of the effects and draws a reference line (significance threshold). Any effect that exceeds this line is considered statistically significant. The effect of a factor corresponds to the difference between the overall mean of the results and the mean response when this factor reaches its highest level.

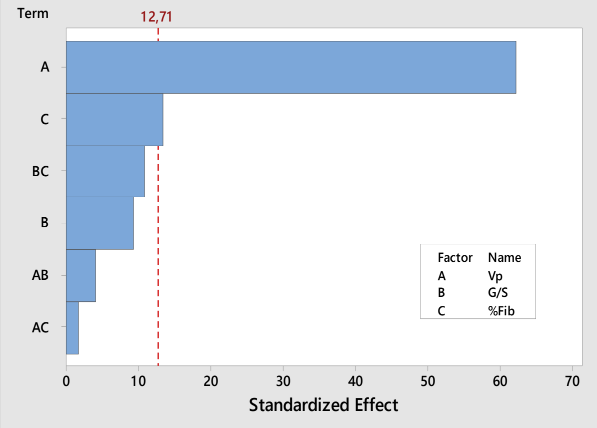

**Figure (9): Pareto chart of the standardized effects of the yield shear stress**

As shown in Figure (10), plastic viscosity (which reflects resistance to segregation) is exclusively and significantly influenced by the paste volume (Vp). This pronounced effect is largely attributed to the nature of the binder, particularly the presence of calcareous tuff powder, known for its high water-absorption capacity.

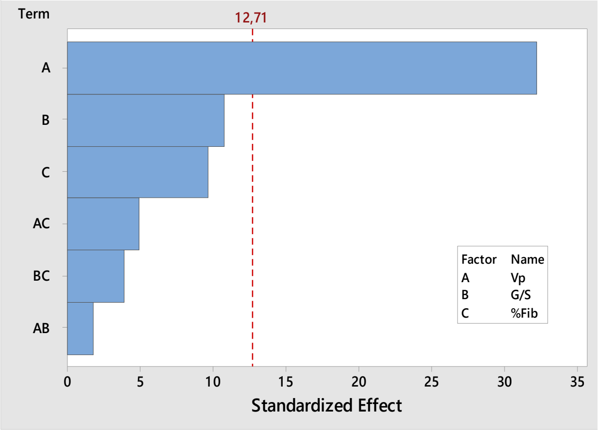

**Figure (10): Pareto chart of the standardized effects of plastic viscosity**

This characteristic increases the overall water demand of the system, thereby raising the viscosity of the concrete. These findings are consistent with the observations of Cherrak (2013), who reported similar behavior in conventional concretes.

In contrast, the influence of other parameters, such as fiber dosage and the sand-to-gravel ratio (G/S), as well as their interactions, is statistically negligible. These results corroborate the conclusions reported by Naadia (2020) and Gueciouer (2019).

Furthermore, a comparison between a self-compacting fiber-reinforced concrete (SFSCC) and a self-compacting concrete without fibers, as reported by Naadia (2020), reveals that fibers primarily affect the yield stress without significantly altering viscosity.

The analysis of yield stress variation with respect to each formulation parameter (Figure (11a)) indicates that increasing both the paste volume and the G/S ratio leads to a reduction in yield stress, thereby enhancing workability. However, increasing the fiber content results in a higher yield stress, which negatively impacts the fresh-state rheological performance.

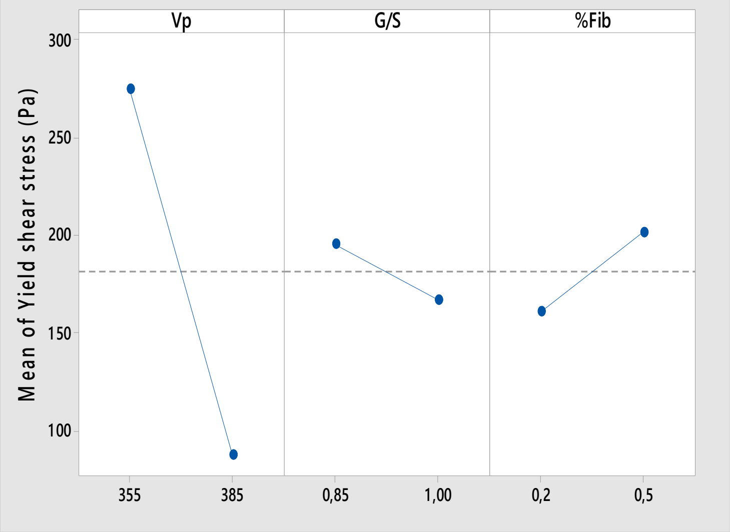

**Figure (11a): Main effects' plot of the composition factors on yield shear stress**

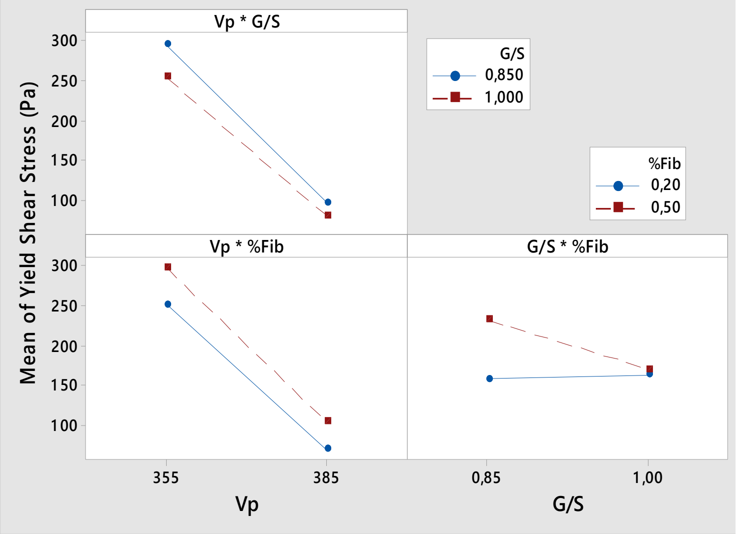

**Figure (11b): Interactions' plot of the composition factors on yield shear stress**

According to Figure (11b), the interactions between the selected composition factors influencing flow behavior are generally negligible. However, a slight interaction between the sand-to-gravel ratio (G/S) and the fiber content (%Fib) is observed, although it remains statistically insignificant.

According to Figure (12a), increasing the three composition factors (paste volume (Vp), sand-to-gravel ratio (G/S), and fiber dosage [%Fib]) results in a progressive decrease in plastic viscosity, thereby increasing the risk of segregation. This behavior is primarily attributed to the abundance of paste, which is further enhanced by the increase in the G/S ratio that reduces the specific surface area of aggregates, and to the disruptive effect of fibers, which introduce voids within the concrete matrix. This latter effect is supported by the observed decrease in the density of SFSCC mixtures (with constant Vp and G/S, but varying %Fib), as fiber dosage increases. However, this disruptive influence remains less significant than that of the paste volume. This tendency is further amplified by the presence of tuff powder in the binder, which increases the water demand and contributes to a higher initial viscosity; once the paste volume becomes excessive, the mixture becomes unstable and more prone to segregation.

A complete absence of the interaction effects among the three composition parameters on plastic viscosity is observed. According to Figure (12b), all interaction curves are almost parallel.

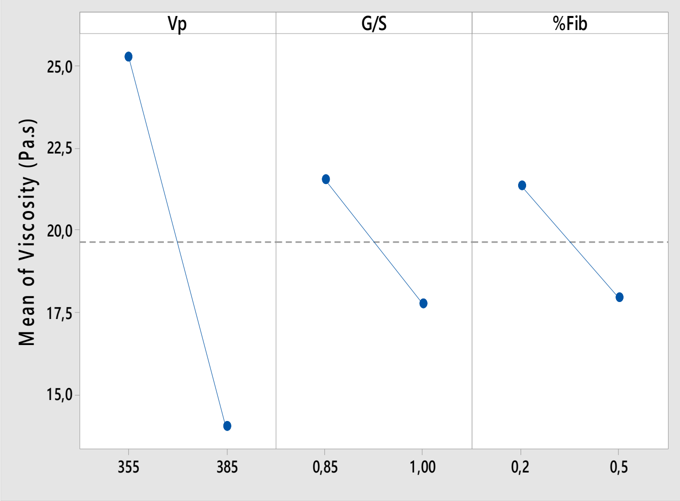

**Figure (12a): Main effects' plot of the composition factors on viscosity**

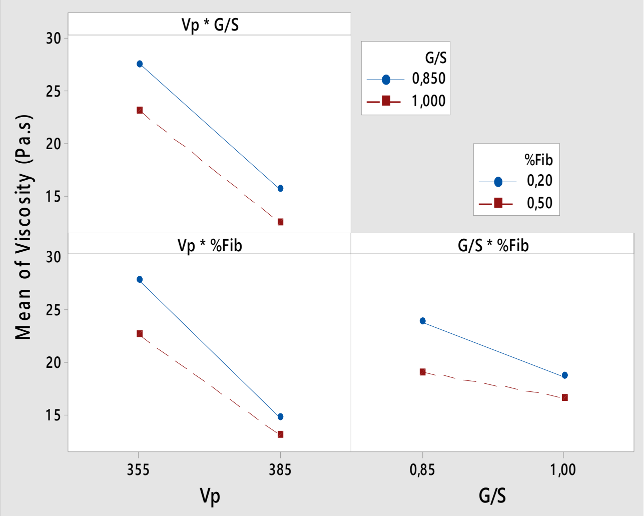

**Figure (12b): Interactions' plot of the composition factors on viscosity**

According to the yield shear stress contour plots shown in Figures (13a) and (13b), in the case of steel fiber-reinforced self-compacting concrete (SFSCC) incorporating calcareous tuff powder, the presence of steel fibers reduces flowability and disrupts the paste distribution mechanism within the granular skeleton.

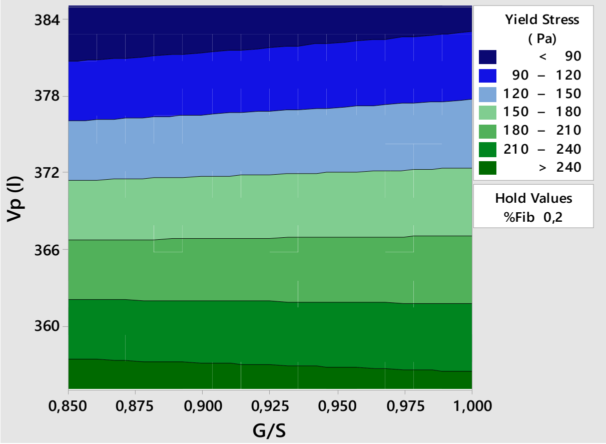

**Figure (13a): Contour plot of yield stress *versus* composition parameters for fiber dosage (0.2%)**

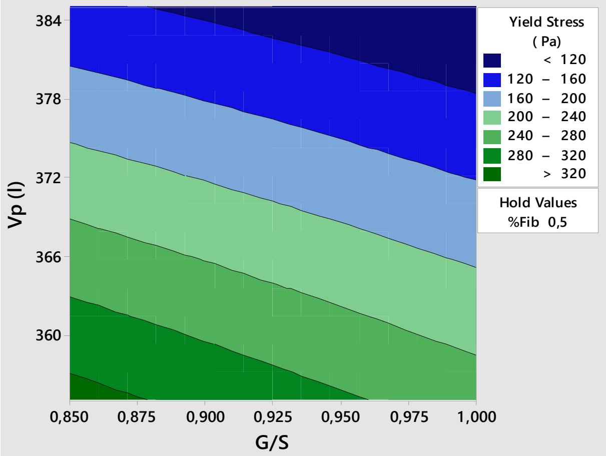

**Figure (13b): Contour plot of yield stress *versus* composition parameters for fiber dosage (0.5%)**

This behavior appears to be particularly pronounced in the case of concretes incorporating tuff powder, due to the high water-absorption capacity of this binder and its structuring effect on the paste. Thus, at low fiber dosages, the flow is governed exclusively by the paste, independently of the granular structure (G/S). The variation in workability, represented by the yield shear stress, can then reach an average of 38% for every 10-liter increase in paste volume.

At high fiber dosages, flow is primarily governed by the excess paste, beyond the amount required to coat the granular skeleton. Aggregates (sand and gravel) must be covered by a minimal paste layer, and any surplus contributes to flowability. As the gravel-to-sand (G/S) ratio increases, the overall specific surface area of the granular phase decreases, resulting in more excess paste and improved flow. The presence of tuff powder in the paste can amplify this effect due to its high water-absorption capacity, which increases the system's water demand and alters the paste-to-aggregate interaction. Therefore, in mixtures with a coarser granular structure (higher G/S), maintaining a constant flow level may require a reduction in paste volume. For instance, at a fiber dosage of 0.5% and a paste volume of 370 liters, flow can improve by 36% when increasing the G/S ratio from 0.85 to 1.00.

In parallel, the increasing incorporation of tuff into the matrix tends to raise the yield stress, reflecting a decrease in the flow capacity of the self-compacting concrete. This behavior results from several physical mechanisms. The calcareous tuff powder particles, with their high specific surface area and notable porosity, absorb a substantial portion of the mixing water. This reduces the amount of free water available for lubricating the granular skeleton and enhances interparticle friction, ultimately increasing the yield stress.

According to the contour plots presented in Figures (14a) and (14b), an increase in paste volume leads to a decrease in plastic viscosity, regardless of the gravel-to-sand ratio (G/S) and fiber dosage (%Fib). Irrespective of the fiber content, viscosity is primarily governed by the amount of excess paste relative to the quantity required to coat the aggregates. To maintain a constant viscosity level, the paste volume must be reduced as the G/S ratio increases.

As the fiber dosage increases, a decrease in viscosity is observed, particularly in granular compositions rich in fine aggregates (i.e., low G/S). For instance, for a paste volume of 370 liters and G/S = 0.85, the viscosity reduction resulting from an increase in fiber dosage from 0.2% to 0.5% can reach 25%. This effect is less pronounced in mixtures with higher coarse aggregate content. For example, at the same paste volume and G/S = 1, the viscosity reduction due to the same fiber increase is limited to 12%. This reduction in plastic viscosity can be attributed to the voids and discontinuities introduced by the presence of fibers, which disrupt the internal cohesion of the paste. At high dosages, fibers may compromise the continuity of the granular skeleton by creating local disorganizations, especially when coating is insufficient. This structural loss of compactness, combined with inter-fiber voids, facilitates the flow of the paste between obstacles, resulting in a decrease in plastic viscosity. This behavior is further amplified by the presence of calcareous tuff powder; whose high water-absorption capacity increases the sensitivity of viscosity to variations in paste volume.

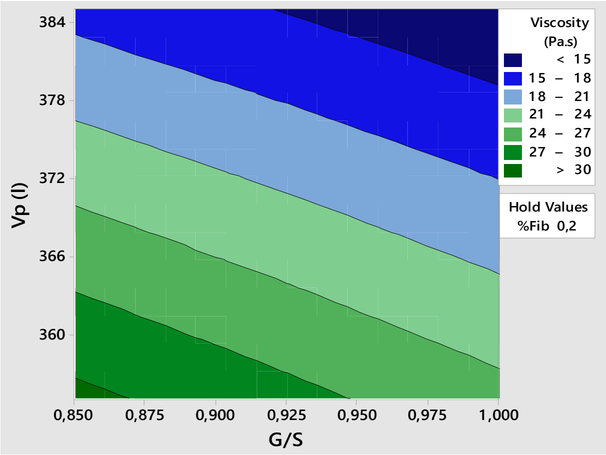

**Figure (14a): Contour plot of viscosity *versus* composition parameters for fiber dosage (0.2 %)**

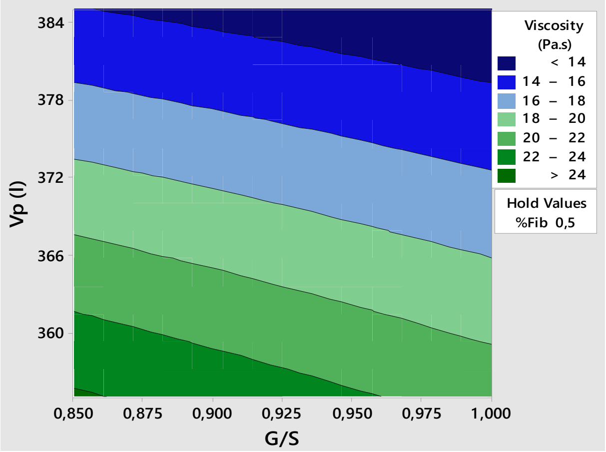

**Figure (14b): Contour plot of viscosity *versus* composition parameters for fiber dosage (0.5%)**

Using statistical software, a mathematical model of the two rheological parameters (yield stress and plastic viscosity) was proposed in the form of Equations (1) and (2).

**Yield shear Stress**: $\tau_0$= 3835 - 10,81 Vp - 1683 G/S + 1943 %Fib + 5,42 Vp*G/S – 1,233 Vp*%Fib - 1463 G/S*%Fib……………..(1) With $R^2$=99.98%

**Plastic viscosity**: $\mu$= 352,4 - 0,772 Vp - 150,9 G/S - 210,9 %Fib + 0,282 Vp*G/S + 0,3878 Vp*%Fib + 60,7 G/S*%Fib ……… …...(2) With $R^2$=99.92%

To optimize the rheological behavior of SFSCC, superimposed contour plots of the two key parameters (yield stress and plastic viscosity) were utilized. As shown in Figure (15), by defining target ranges for these rheological parameters to ensure optimal self-compacting performance, the corresponding composition factors (G/S ratio and paste volume, Vp) can be identified for any given fiber dosage.

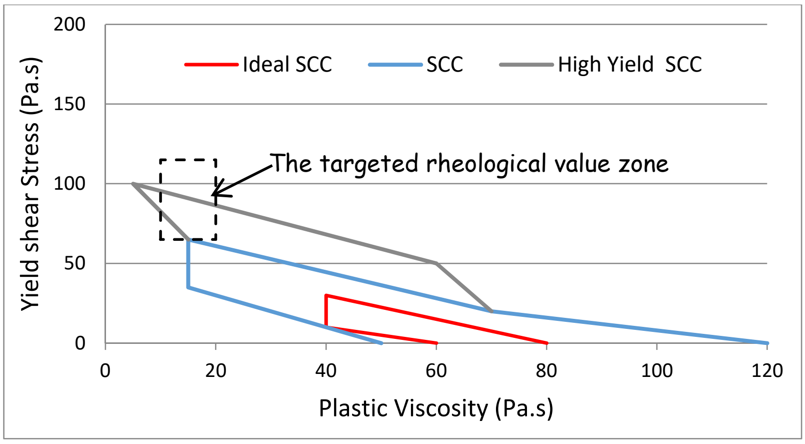

**Figure (15): Optimization of the composition of SFSCC based on tuff to achieve targeted rheological parameters, compared to the area defined by Wallevik (2011)**

According to Figure (16), for a maximum fiber dosage of 0.5%, the required paste volume should not be less than 379 liters for G/S ratio values between 0.9 and 1.

### Validation of Results at Full Scale

Based on the optimal composition zones provided by the reduced model and shown in Figure (16), five self-compacting concretes were selected to test and validate their rheological and mechanical behaviors at full scale. The five chosen self-compacting concretes are: a reference SCC (without fibers) and four steel fiber-reinforced self-compacting concretes (SFSCCT1, SFSCCT2, SFSCCT3, and SFSCCT4), with fiber dosages of 0.2%, 0.3%, 0.4%, and 0.5%, respectively.

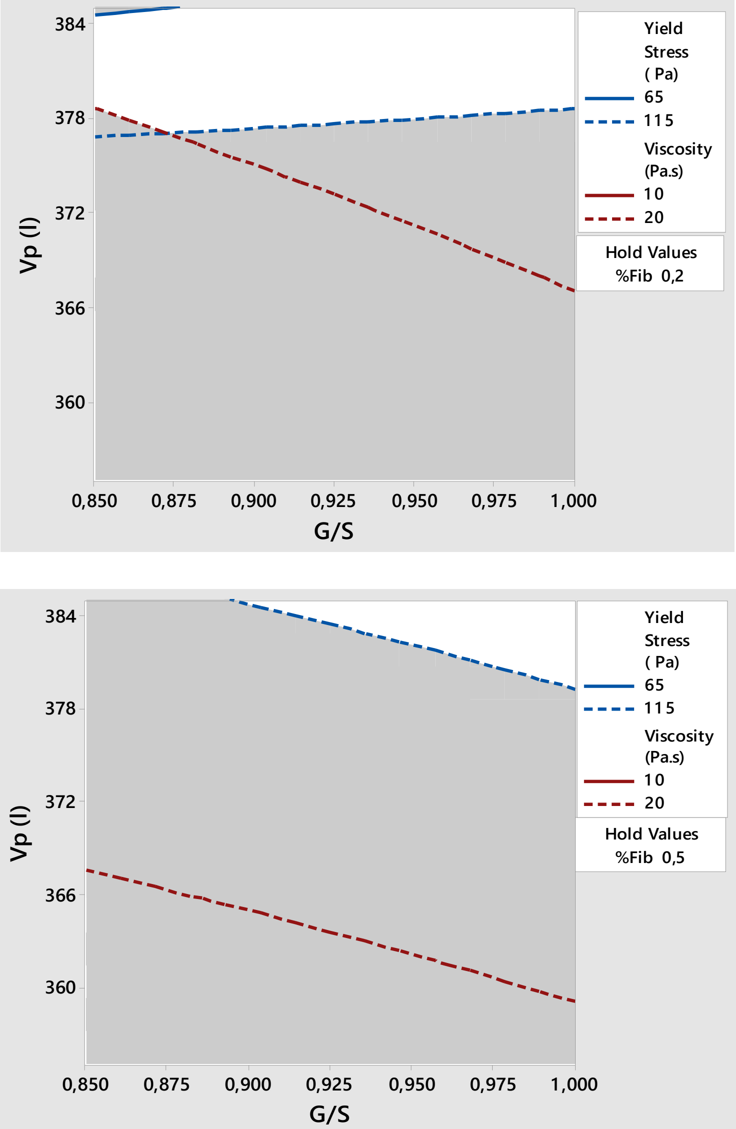

**Figure (16): Optimization curves of the rheological parameters of an SFSCC for fiber dosages (0.2% and 0.5%)**

**Table 11. The rheological results at full scale compared to those provided by the reduced model for the tested SFSCCs**

| | **Slump flow (cm) (full scale)** | **Yield stress (Pa) (by the model)** | **Flow time ($T_{500}$) (s) (full scale)** | **Viscosity (Pa.s) (by the model)** |
|---|---|---|---|---|
| SCCT | 72 | 62.02 | 3.05 | 17.16 |
| SFSCCT1 | 70 | 67.61 | 3.34 | 15.60 |
| SFSCCT2 | 65 | 82.79 | 3.86 | 14.89 |
| SFSCCT3 | 61.5 | 97.98 | 4.08 | 14.20 |
| SFSCCT4 | 60 | 113.17 | 4.31 | 13.49 |

The composition of these five self-compacting concretes corresponds to a paste volume (Vp=385 liters) and a gravel-to-sand ratio (G/S=0.9).

Table 11 displays the results of slump flow and flow time ($T_{500}$) of self-compacting concretes produced at full scale, as well as the values of rheological parameters (shear yield stress and viscosity) of their reduced concretes estimated according to the proposed mathematical models (given by Equations (1) and (2)).

In the case of SFSCC based on calcareous tuff powder, Figures (17) and (18) show an excellent correlation between the rheological parameters estimated by the model at a reduced scale and those at full scale. Indeed, as the fiber dosage increases, the yield shear stress also increases, resulting in SFSCC having a reduced flow capacity. This result is often confirmed by several other researchers, such as Wallevick (2011).

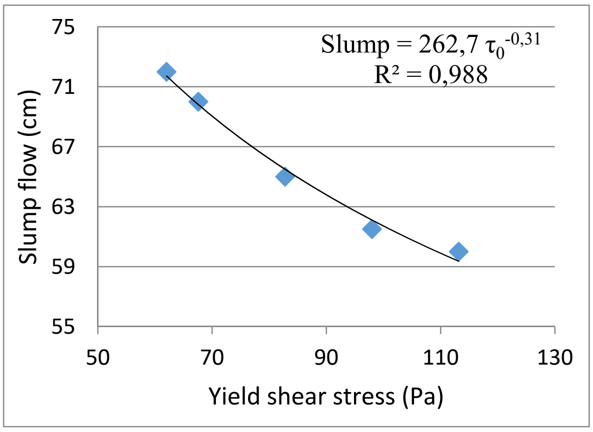

**Figure (17): Correlation between the slump flow and the estimated yield stress**

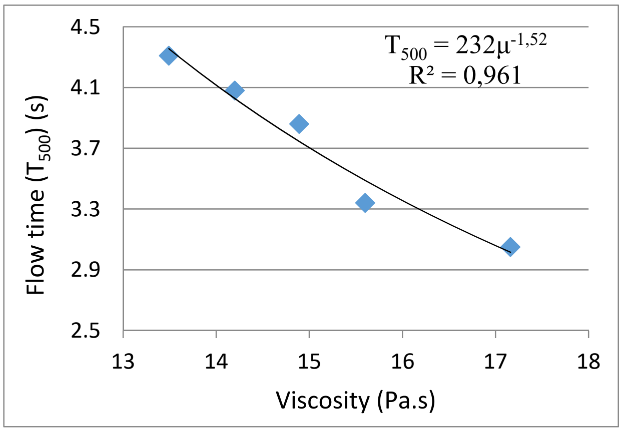

**Figure (18): Correlation between the flow time ($T_{500}$) and the estimated viscosity**

Moreover, with an increase in fiber dosage, viscosity decreases while the flow time ($T_{500}$) increases. This finding is a result of the obstruction caused by the presence of fibers, leading to a flow delay (at time $T_{500}$) and creating intergranular voids that contribute to a decrease in viscosity. This result is confirmed by research conducted on self-compacting fiber-reinforced concretes based on marble (Guecioue, 2019) and also by other researchers (Haddadou, 2014).

Beyond the rheological advantages demonstrated in this study, the formulation of steel fiber-reinforced self-compacting concrete (SFSCC) with calcareous tuff powder also presents a potential economic benefit. Calcareous tuff is a naturally abundant and locally available material in Algeria, making it a low-cost solution for the partial replacement of cement. Its use contributes to reducing the share of the most expensive component in the mix while promoting the valorization of an underexploited mineral resource.

Although the inclusion of steel fibers introduces an additional cost, their dosage remains moderate (between 0.2% and 0.5%), and their mechanical contribution (particularly in terms of ductility) justifies their incorporation within a performance-oriented approach. Compared to conventional SCC composed exclusively of Portland cement and often requiring high dosages of superplasticizers, the proposed formulation allows for a reduction in both cement and admixture demand, while maintaining satisfactory fresh-state properties.

From a quantitative perspective, the partial substitution of cement with calcareous tuff leads to an estimated reduction of 12% to 15% in binder cost, considering only the transport-related expenses of tuff. This cost saving helps partially offset the additional expense associated with the use of steel fibers, while maintaining the target rheological and mechanical performance. The tuff–fiber combination therefore offers a relevant balance between cost, performance, and local material valorization, particularly in contexts where calcareous tuff is abundant and underutilized.

## CONCLUSIONS

Based upon the above discussion, the following conclusions can be drawn:

- The optimization of the paste (comprising 10% addition and 20% substitution of cement with calcareous tuff powder), combined with a superplasticizer saturation dosage of 1.4%, enabled the formulation of a fiber-reinforced self-compacting concrete that satisfies the performance criteria typically recommended for SCC.

- Rheological measurements revealed that the SFSCC incorporating tuff powder developed in this study can be classified as a high-yield stress self-compacting concrete (HYSCC), due to the combined effects of the fiber network and the water demand induced by the porous tuff. The yield stress values ranged from 62 Pa (reference SCC) to 335 Pa for the most fibered mix, while plastic viscosity varied between 12 and 31 Pa.s.
- The analysis conducted using the design of experiments (DOE) method showed that the flow capacity (reflected by the yield stress) of the SFSCC incorporating tuff powder is primarily governed by the paste volume, with a secondary effect from the fiber dosage.
- The rheological optimization of SFSCC using the design of experiments (DOE) method has enabled the identification of optimal composition factors ensuring targeted self-compacting behavior. For instance, at a fiber dosage of 0.5%, the required paste volume should not be lower than 379 liters for a gravel-to-sand (G/S) ratio between 0.9 and 1.0.
- The self-compacting behavior of the optimized SFSCC observed on the rheometer has been confirmed and validated at full scale. Slump flow values ranged from 60 cm to 72 cm depending on the fiber dosage, while flow time ($T_{500}$) increased from 3.05s to 4.31 s. A strong correlation was found between the predicted values from the model and the experimental results obtained at full scale.

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