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Influence of Different Fibre Types on the Rheology of Strain Hardening Cementitious Composites

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Abstract. Strain-hardening cementitious composites (SHCC) have a high tensile strength and display a remarkable strain-hardening behaviour. These unique characteristics make them an interesting choice for improving the strength and durability of new and existing structures. The tensile strain behaviour of SHCC is strongly influenced by its rheological properties as they determine the hardened state behaviour such as fibre-bridging strength and ultimately the degree of multiple cracking. The presence of fibres significantly affects the rheological performance of SHCC.

This study aimed at investigating the relationship between rheological characteristics of SHCC mortar before and after the addition of different fibres. Polyvinyl alcohol (PVA), high modulus polyethylene (HDPE) and glass fibres were added at three different contents in order to assess their effect on the workability of SHCC. Flow tests along with rheological assessment were conducted to evaluate the fresh state behaviour of SHCC. The addition of fibres reduced the flowability of mix, especially at high dosages. A modified fibre influence factor was developed to characterize different types of fibres and was related to the viscosity and yield stress of the mix.

Keywords: Fibres · Strain-hardening cementitious composites · Rheology · Flowability

1 Introduction

Strain-hardening cementitious composites (SHCC) are a special class of material which display an increase in stress beyond the formation of initial cracks under uniaxial tensile loading [1]. This behaviour is usually achieved by the addition of discontinuous fibres which bridge the cracks resulting in a reduced crack width and higher fracture toughness [2]. In recent years extensive research has been carried out to improve the mechanical properties of SHCCs resulting in ultra-high performance SHCC having tensile strengths up to 15 MPa and a strains capacity of up to 8% [3, 4]. These properties make SHCC an excellent choice not only as a construction material but also as repair material for existing structures.

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The addition of fibres comes with undesired effects on the flow and rheology of concrete and should be taken into account when designing SHCC. Short synthetic fibres are mostly used in SHCC to achieve micro-cracking behaviour. The type and content of the fibres, the mixing regime and the binder content greatly influence the rheological properties of the resulting mortar. It is important to analyse rheological properties as they can cause variation in ductility and mechanical properties of SHCC.

Most work in this regard is done on rigid fibres which has shown that increasing the fibre content decreases the workability of the fibre reinforced cementitious matrix [5–7]. The influence of steel fibres is found to increase as the fibre content increases This reduction in workability was observed to become non-linear at increasing fibre content. At the end, these studies successfully demonstrated the correlation between viscosity, yield stress and flow of steel fibre reinforced matrices. However, for plastic and glass fibres these correlations are not established in detail. The objective of this study was to develop correlations for different fibre types at varying fibre contents. This study was carried out using PVA, HDPE and glass fibres at different fibre contents. Flow and rheological correlations were established for all fibre types based on the experimental results.

2 Materials and Methods

2.1 Materials

A suitable control mixture was designed with a target flow spread of 340 mm using Haegermann's flow test and fibre contents tested were 1.0, 1,5 and 2.0 vol.% of the mixture keeping other parameters constant. Ordinary Portland Cement (CEM 1 52.5 N, Holcim, Belgium) was used as binder. Very fine silica sand (M34, Sibelco, Belgium) having an average particle size of 174 μm was used to increase the packing density of the granular skeleton and to obtain a high strength matrix. A polycarboxylate-based superplasticizer (Glenium 51, 35% con, BASF) was used to achieve the desired workability. Three different types of fibres including PVA, HDPE and glass fibres were tested having properties listed in Table 1.

Table 1. Properties of fibres used

Fibre type	Aspect ratio	Diameter (μm)	Length (mm)	Young Modulus (Gpa)
PVA	307	39	12	42.8
HDPE	600	20	12	80
Glass	857	14	12	72

2.2 Mix Formulations and Mixing Regime

A total of 10 formulations were investigated having a w/c ratio of 0.22. The amount of cement, sand and superplasticizer (SP) were kept constant in order to better understand the effect of fibres on the mixture characteristics. The mixture proportions along with constituent dosage per weight relative to the cement are listed in Table 2; the fibre contents are represented as volume fraction of the mixture.

Table 2. Mixture formulations

Mix[a]	Cement	Sand	Water	Fibre volume (%)	SP
C	1	0.5	0.22	–	0.021
PE1	1	0.5	0.22	1.0	0.021
PE1.5	1	0.5	0.22	1.5	0.021
PE2	1	0.5	0.22	2.0	0.021
Glass1	1	0.5	0.22	1.0	0.021
Glass1.5	1	0.5	0.22	1.5	0.021
Glass2	1	0.5	0.22	2.0	0.021
PVA1	1	0.5	0.22	1.0	0.021
PVA1.5	1	0.5	0.22	1.5	0.021
PVA2	1	0.5	0.22	2.0	0.021

[a] Fibre content is represented as volume fraction of mix, while rest of the ingredients are weight proportion of cement

A Hobart mixer was used to prepare the mortar mixes. A total of 6-min wet mixing time was arranged to ensure a homogenous fibre dispersion throughout the matrix. Cement and sand were first dry mixed in the Hobart mixer for 60 s at 145 rpm followed by the addition of water and suerplasticizer (SP). The mixer was then operated at 145 rpm for 180 s followed by the fibre addition and 180 s of fast mixing at 285 rpm. Fibres were added in 4 about equal batches to ensure an equal distribution of fibres.

2.3 Test Methods

2.3.1 Flow Tests

Flow tests of SHCCs mortars (without compacting action) were conducted using Haegermann's cone with a height of 60 mm and diameters of 70 and 100 mm at the top and the bottom of the cone, respectively. The value of SP was adjusted to maximize the flow in the control formulation without any apparent segregation. This SP value was then kept constant for formulations containing fibres.

2.3.2 Rheological Investigation

The rheological parameters were measured using the rotational type MCR 52 Rheometer produced by Anton Paar. This rheometer consists of a fixed rheometer cup having an internal diameter of 70 mm and a 39 mm rotating probe cylinder attached to the motor. SHCC mortars were prepared using the specified mixing regime and were poured in the rheometer cup. Excess material was carefully scraped off using a spatula and the filling level of material was adjusted so that it won't flow out after probe insertion. The cup was then fixed in the machine and the rotating probe was inserted to start the measurement.

The shear rate was increased from 1 1/s to 100 1/s with 100 measuring points in between (2 s point duration). Assuming a plastic Bingham model, the average yield stress value is calculated as the axis intercept of the linear regression line of the measured points while the viscosity is calculated as the slope of the regression line. A test resulted in the shear rate-shear stress curve, further interpolations were then executed to determine the yield values and viscosities of the mixtures.

3 Results and Discussion

3.1 Flowability

3.1.1 Measurements of Flow Spread

Table 3 shows the results of flow spread tests carried out. The addition of different fibres considerably reduced the flow spread of the specimens compared with the control specimen. The increase in fibre content results in a non-proportional decrease in flowability to the point where almost no flow is observed at a fibre content of 2 vol.%. This effect is visually depicted in Fig. 1 for HDPE fibres.

Table 3. Flow spread test results.

Mix	Spread (cm)
C	34.0
PE1	17.3
G1	18.5
PVA1	18.8
PE1.5	12.5
G1.5	11.5
PVA1.5	12.8
PE2	10.7
G2	10.3
PVA2	11.0

The flowability dependent on both type and content of fibres. Glass fibres had a similar effect as the other fibre types at 1 vol.% fibre content, however they had a more pronounced effect on the workability at higher fibre contents. This outcome can be explained by the higher aspect ratio of glass fibres compared with the other fibre types.

3.1.2 Effect of the Fibre Factor

The fibre factor of fibres is calculated by multiplying the volume of the fibres with the respective aspect ratio [V_{f*}L/D] [8]. This factor was applied to assess the flow measurements and the results are displayed in Fig. 2a. It can be seen that the fibre factor

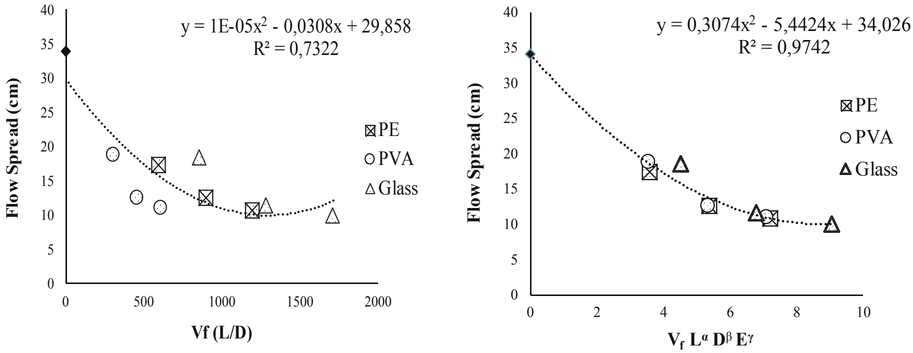
Control PE1 PE1.5 PE2

Fig. 1. Effect of HDPE fibre addition on the flow spread

does not corelate well when considering the different fibre types. This deviating effect can be explained by an entirely different physical and chemical nature of the fibres. As this study also was carried out with glass and plastic fibres, a more comprehensive factor was needed to take into account the different nature of the studied fibres. A generalized fibre influence factor was then developed to accurately predict the tests results obtained with the studied fibres. Considering different fibre materials, the modulus of elasticity was also included as dependent variable [9]. After incorporating all governing parameters, the fibre influence factor is stated as:

$$F = V_f L^{\alpha} D^{\beta} E^{\gamma} \tag{1}$$

Where α, β,γ are influence coefficients. Chu et al. [10] also used a similar type of fibre influence indicator for FRC mixes without E parameter as only steel fibres were studied and E was constant. After performing several regression analyses, the authors found that $\alpha = 1$, $\beta = -0.5$ and $\gamma = -0.5$ results in the best correlation. The best fitting curve is plotted in Fig. 2b. It can be seen that $V_f\, L^{\alpha} D^{\beta}\, E^{\gamma}$ seems to be a more suitable factor than the traditional V_f (L/D) which is overly simplistic in order to take into account different fibre types.



(a) (b)

Fig. 2. a. Traditional fibre factor b. Modified fibre influence factor

Another interesting observation is that the flow spread decreased at increasing fibre dosage. With increase in fibres content the decrease in flow spread is less than proportional which contradicts with other studies carried out on steel fibre types. This trend can be explained by the very stiff consistency of mixes at 2 vol.% fibre dosage as the flow spread is close to 100 mm, which is the base diameter of the flow cone itself.

3.2 Rheological Investigation

The shear stress was measured at increasing shear rate. The effect of different fibre additions is shown in Fig. 3 for different fibre types. It can be seen that because of the addition of the fibres the curves are not completely straight which is often the case with plain mortars or concretes, which are typical Bingham materials. The yield value was obtained as the y-axis intercept of each curve idealised as a straight line and the plastic viscosity was determined by calculating the slope of the linear model.

3.2.1 Relation Between Yield Stress and Flow Spread

In order to study the effect of different shear-rates, the curve was assessed for five maximum shear-rate values of 20, 40, 60, 80 or 100 1/s. These values were plotted against the flow spread as shown in Fig. 4. A considerable increase in the yield stress is noted at increasing shear rate. At a shear rate of 20 1/s an almost linear increase in yield stress is noted at decreasing flow spread, however as the shear rate increased to 100 1/s, a more than proportional rise in yield stress is observed. This can be explained by the higher mechanical energy required during the initial seconds to get the mix flowing at higher shear rates. This leads to a high torque registration, which is translated in a high yield stress.

3.2.2 Relation Between Viscosity and Fibre Influence Factor

The addition of more fibres increases the internal friction among the fibres. In order to characterize the relation between plastic viscosity and fibre content, the viscosity values were calculated from rheological readings and plotted against both fibre factor and the modified fibre influence factor at three different strain-rate ranges as shown in Fig. 5. R^2 values along with equations were plotted for each trendline which depicts a better correlation of viscosity with the modified fibre influence factor. The plastic viscosity increased at increasing fibre factor in both cases. With a maximum shear rate of 20 1/s there is a steep increase in viscosity values at increasing fibre influence factor, however as the strain-rate increases, the viscosity values drop indicating the breakdown of the mixes. A more preferred fibre orientation during testing could be an explanation for the decrease in viscosity, which first increases at increasing fibre dosage and is about constant at a higher fibre influence factor.

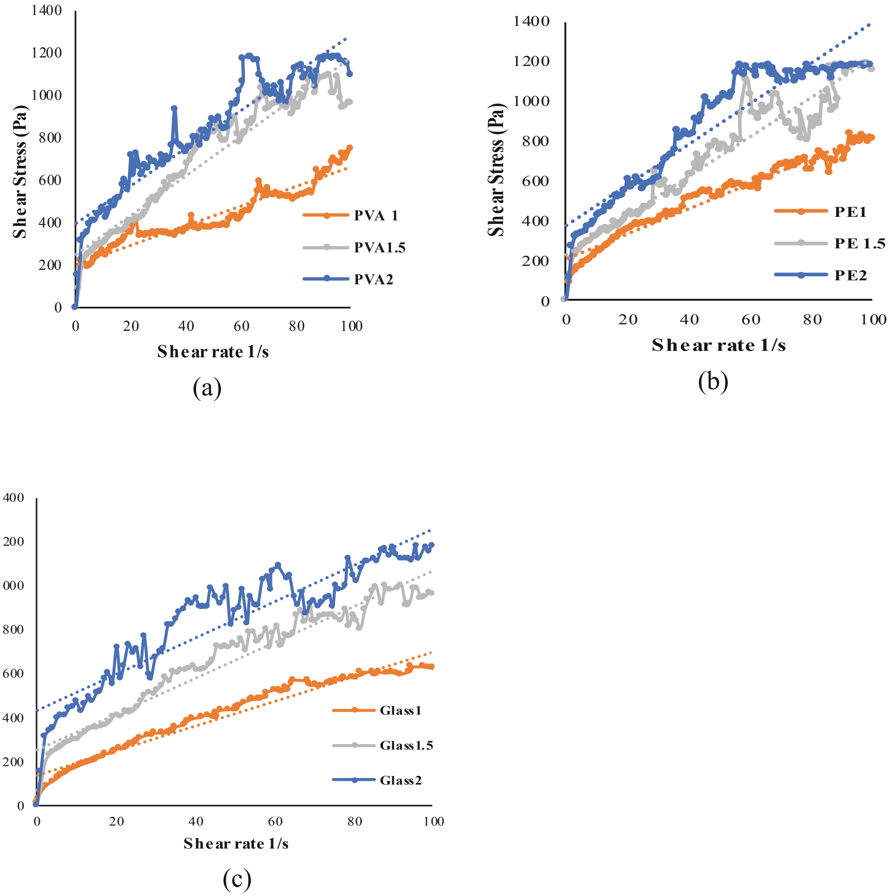


Fig. 3. a. Shear stress-shear rate curves for PVA fibres b. Shear stress-shear rate curves for PE fibres c. Shear stress-shear rate curves for glass fibres

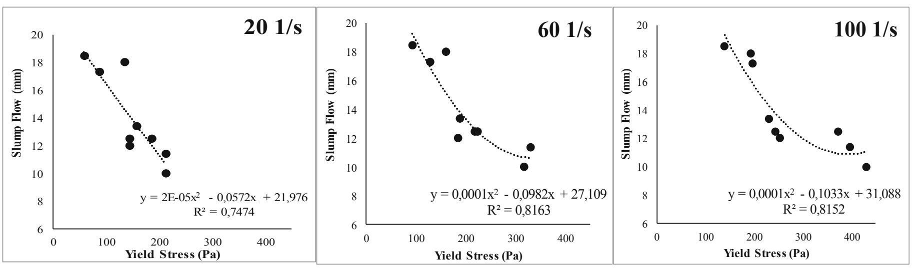
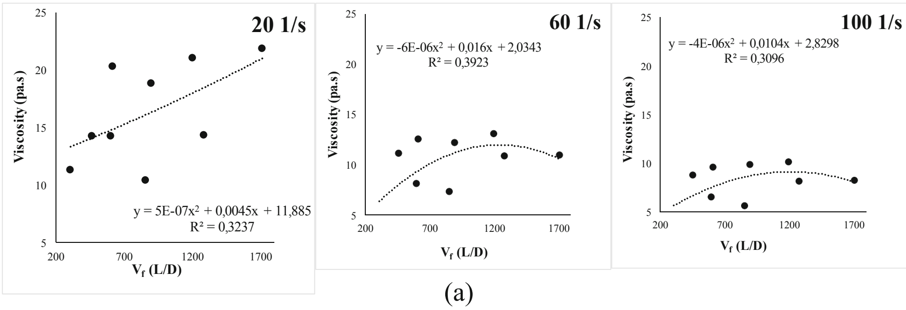
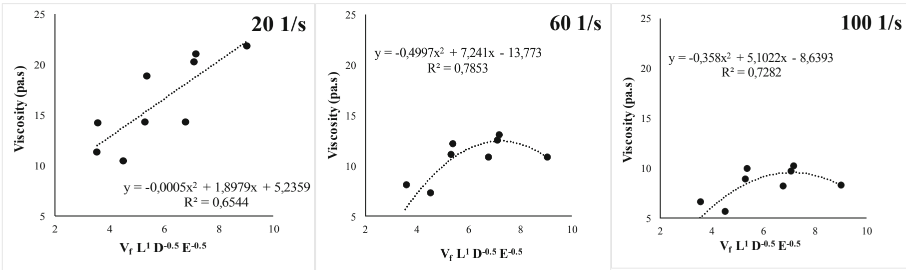


Fig. 4. Relationship between yield value and flow spread at different shear rates



(a)



(b)

Fig. 5. a. Relationship between viscosity and fibre factor b. Relationship between viscosity and modified fibre influence factor

4 Conclusions

This paper discusses the effect of different fibre types and contents on flow and rheological properties of SHCC. An experimental program of 10 SHCC mixes was executed with 3 different fibre types with three contents per fibre type. Based on the experimental results, the following conclusions can be drawn:

- The addition of fibres significantly reduced the flow spread of the mixes. This effect is more pronounced at higher fibre dosages and should be accounted for in the mix design.
- The yield stress exhibits an almost linear relation with flow spread when assessing the flow curves at a lower shear rate of 20 1/s, however the yield stress increases significantly as the shear-rate values increased.
- The effect of fibres on the flowability depends not only on the fibre content but on the type of fibres as well. A modified fibre influence factor was developed to depict fibre behaviour resulted in a better prediction ability compared with the traditional fibre factor.
- The plastic viscosity increased steeply with increase in fibre influence factor at lower shear rates. No significant increase in viscosity was observed at higher strain rates.

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