RHEOLOGICAL BEHAVIOUR OF CEMENT MORTARS REINFORCED WITH ACRYLIC FIBRES

Luiz Antonio Pereira de Oliveira*; José Carlos Monteiro de Carvalho; Miguel Costa Santos Nepomuceno

C-MADE, University of Beira Interior, PORTUGAL.

*: corresponding author. luiz.oliveira@ubi.pt

ABSTRACT

The fibre reinforcement efficacy of mortar is dependent upon many factors, including the properties of the matrix as well as the fibre geometry, size, type, volume and dispersion. Among the plastic fibres typically used in mortars, little or nothing is known about the rheological behaviour of acrylic fibres. Thus, in this study the influence of different acrylic fibres characteristics on the rheological behaviour of cement mortars was investigated. The method selected is based on factorial design of experiments in which the parameters considered are the length, diameter and acrylic fibre content. The test results indicate that Herschel-Bulkley model better simulate the rheological behaviour of acrylic fibres reinforced mortars. It was also observed that the yield stress increases with the reduction of fibre length and diameter and the plastic viscosity increases as the fibre length increases.

Keywords: acrylic fibres; cement mortar; yield stress; plastic viscosity

INTRODUCTION

Synthetic fibres are the result of many studies and advances in materials engineering, arising from research on the chain of oil and its derivatives, as well as the development of textile technology. The use of synthetic fibres in mortar improves its strength with long term stability. Despite the low modulus of elasticity, the addition of these kinds of fibres on mortar inhibits the mortar cracking. The reinforcing ability of a particular fibre is mainly influenced by its properties, fibre volume content in the composite, size, dispersion and interface adhesion between fibre and cement matrix [1, 2, 3]. However, the incorporation of fibres on mortar can hamper the mixing as well the uniformity of dispersion of the mortar components. The fresh state properties of fibres reinforced mortar must be controlled so as to make easy to handle in the fresh state and not adversely affected in hardened state [3]. The literature about the fresh state behavior of mortar containing synthetic fibres, as acrylic fibres, is not abundant. However, it has been shown that the addition of fibres decreases the workability of the cementitious materials [4, 5]. It has been also observed that the acrylic fibres reinforced mortar consistency index obtained by flow table test, decreases with fibres length increasing and increases when the fibre diameter is increased for constant length and fibre volume [6].

The fresh state characteristics of cementitious materials, mainly mortars renders, can also be described using rheological parameters as yield stress and plastic viscosity. These rheological parameters can best evaluate the mortar easiness to be used in the fresh state, including workability, placeability, compactability, finishability, flowability, pumpability and extrudability [3]. In fact, the acrylic fibres used in the textile industry are not so much applied as technical fibres in construction products, but their use in construction products is recently discussed as an important tool for fibres European industry innovation [7]. In this sense, this study focuses the rheological behaviour of cement mortar reinforced with acrylic fibres. The fibres used were transformed from the textile application to technical application by a national Portuguese textile fibre industry. In this research, the effect of length (L), diameter (D) and volume content (Vf) of acrylic fibres on relative yield stress and relative plastic viscosity, were assessed.

MATERIALS

In this experimental study two mortar groups were tested. Group 1 was composed of a more stiff mortar with cement to sand ratio 1.00:2.30 by weight, and water-cement ratio 0.66. The minimum level of fibre percentage was 0.33 % and the maximum 0.85% by volume of mortar. In the group 2, the mortars were prepared with cement to sand ratio 1.00:0.50 by weight, water-cement ratio of 0.35, with 0.2% as minimum fibre volume level and 0.5% as maximum. In the two mortars groups the superplasticizer – cement ratio was 0.005 by weight.

All mortar mixtures investigated in this study were prepared in constant mixing process in order to obtain the same homogeneity and uniformity. To obtain the uniform fibres dispersion, a hand dry-mixing before the wet mechanical mixing was conducted for each mixture. In this dry mixing process, the fibres were mixed with sand and cement before being placed in the mixer. After weighing, the material was gradually introduced in a container. The fibres manually entered into the container were mixed first with the sand by shaken in the vertical and horizontal direction for about 1 min. After the introduction of cement into the container, this is shaken again, for about 1 min. After the dry mixing, the mortar was mixed with water and superplasticizer in a mixer by the procedure according the EN 196-1 [8]. The mixed state was carefully observed, and neither fibre balling nor any abnormalities were observed.

A commercial Portland cement type CEM I 42.5N conforming to European Standards EN 197-1 [9] with a Blaine surface specific area of 400.9 m^2/kg and a density of 3140 kg/m^3 was used for all mixes. For the production of group 1 of mortars, natural sand with a maximum particle size of 4.76 mm, a density of 2450 kg/m^3 and Modulus of Fineness of 2.82 was used. Group 2 mortars used natural sand with maximum particle size of 2 mm and fineness modulus of 1.96. The superplasticizer used in this investigation was a ViscoCrete 3002 HE from Sika (solid content of 26.5 % and specific density of 1060 kg/m^3). The characteristics of acrylic fibres used in this study are given in Table 1. The acrylic fibres were produced by FISIPE - Synthetic Fibres of Portugal.

Table 1 - Chemical and mechanical properties of acrylic fibers

Properties	Diameter [μm]	Length [mm]	Density [Kg/m^3]	Modulus of elasticity [GPa]	Tensile strength [N/mm^2]	Rupture elongation [%]
Acrylics	14.4	4; 6; 12	1170	12.04	690	15 a 20
	27.0			8.78	500	14 a 18
	43.0			8.19	380	13 a 17

METHODS

In this study the mortar rheological parameters was evaluated with a specific rheometer (Viskomat NT) for mortars. This apparatus automatically measures a series of data points of torque (T) and rotational speed (N). The mortar fresh behaviour was approximated using a Bingham model or a Herschell-Bulkley model. If the fresh mortar is assimilated to a Bingham fluid, T and N are related by the straight-line according to Eq. (1). In this equation, g (the intercept) is proportional to yield stress and h (the gradient) is proportional to plastic viscosity of the material [10]. If the fresh mortar is assimilated to a Herschell-Bulkley fluid, T and N are related conform to Eq. (2), where b is a material parameter giving indications on the degree of fluid dilatancy (b>1, the fluid is dilatants and b<1 is attributed to pseudo plastic fluid).

$$T = g + hN \quad (1)$$

$$T = g + hN^b \quad (2)$$

Measurement was performed after 5 min resting from the end of mixing. In this study, two types of speed profiles were used. In the first, named step profile, the rotation speed is adjusted to vary with time, increasing from an initial value of zero to 160 rpm and then decreasing from 160 rpm to zero. At each speed, it waits around 1 min before 20 rpm up or down each time. This allows reaching equilibrium values of torque for each speed and to build equilibrium flow curves for a better determination of plastic viscosity and yield stress-related coefficients (h and g, respectively). The effect of the fibres characteristics on these mortar rheological parameters was evaluated using this step speed profile with a sand/cement ratio of 2.3 (by mass). In the second profile, named ramp, which was adapted from Banfill *et al* [5], the speed was increased from zero to 160 rpm in 60 s, holding this speed for 2 min and then decreasing to zero by 5 min. This profile was used with a sand/cement ratio of 0.5 (by mass).

The statistical modelling approach is ideal for optimizing fibres parameters and achieving desired properties while minimising the number of trials [11, 12]. Using this approach, a mathematical model describing the main effect and two-way interaction of various parameters on a given property can be established. Factorial design approach was used to evaluate the influence of three fibre independent variables (Length L, diameter D, and fibre volume V_f) on mortar relative plastic viscosity and yield stress. The modelled responses are assumed to be linearly dependent on the level of each independent variable. The two-level statistical design of experiments for the three independent variables (k = 3) consists of eight ($2^k = 8$) factorial points where each variable is fixed at two different levels (min and max) within the modelled region. Initial levels of L, D, and V_f were varied from 4 to 12 mm, 14.4 – 43 µm, 0.33 – 0.85% for group 1 mortar and 0.2 – 0.5% for group 2 mortar, respectively. The actual variable ranges are transformed to dimensionless coded values to facilitate calculation and analysis. The codified values are expressed as -1 for minimum values and +1 for the maximum values. The linear model associated with a two-level statistical design the case of three independent variables (L, D, and V_f) is expressed as follows:

$$Y = a_0 + a_1 L + a_2 D + a_3 V_f + a_4 L.D + a_5 L.V_f + a_6 D.V_f + a_7 L.D.V_f + E \quad (3)$$

The third order interaction is usually neglected. The model's coefficients (a) represent the contribution of the independent variables on the response, and E is the random error term representing the effects of uncontrolled variables that are not included in the model, as well as the assumption of linearity. The model's coefficients are determined by multi-linear regression analysis and are assumed to be normally distributed. The error is assumed to be random and normally distributed, so the residual terms, which represent the difference between the observed and predicted values should exhibit similar properties [13]. Analysis of variance (ANOVA) is used to test the significance of regression, and t-tests are performed to identify the non-significant variables and their interaction. The accuracy of the established models is evaluated by comparing the predicted-to-measured modelled responses using typical selected mortar mixtures included in the experimental domain.

RESULTS AND DISCUSSION

Table 2 summarizes the main test results for mortars mixtures used to model the linear effect of three independent variables (L, D and V_f) that affect the relative yield stress and plastic viscosity. Eight points within the experimental domain are considered to mortar groups 1 and 2 to evaluate the accuracy of established model.

Table 2 Test results for mortars used to establish models

Mix	Coded values	Yield stress (N.mm)		Plastic viscosity (N.mm.min)	Consistency (N.mm.min)
		Group 1 1:2.3:0.66	**Group 2 1:0.5:0.35**	**Group 1 1:2.3:0.66**	**Group 2 1:0.5:0.35**
1	- - -	76.252	5.012	0.1774	0.0135
2	+ - -	64.471	17.995	0.3715	0.0915
3	- + -	56.202	4.155	0.1177	0.0071
4	+ + -	78.620	2.854	0.0177	0.0110
5	- - +	176.693	58.404	0.1085	0.00018
6	+ - +	71.484	4.261	0.1231	0.00055
7	- + +	155.664	3.648	0.3646	0.0049
8	+ + +	102.511	4.377	0.1213	0.0299

Model coefficients, correlation coefficients, t-ratio and p-values for each term are given in Table 3 and 4 for relatives yield stress, plastic viscosity and consistency. A negative estimate of a given variable indicates that the response decreases when the value of that variable increases. The majority of derived estimates were obtained with 95% confidence interval. The significance of each modeled variable on a given response is investigated using the analysis of variance. For example, in yield stress response model, presented in Table 4, where the variables interaction was take into account a significant effect on yield stress is shown by the p-values. This fact is also support by the high yield model correlation coefficient (R^2 = 0.99). Thus all variables were kept as significant terms; by other hand the plastic viscosity model shows a non significant effect of fibres variables on this property. This fact was also support by their very low correlation coefficient (R^2 = 0.27).

Table 3. Model regression coefficients (mortar 1.00:2.30)

	Yield stress; R^2 =0.99			Plastic viscosity; R^2 =0.27		
	Coefficient	**t-ratio**	**p-value**	**Coefficient**	**t-ratio**	**p-value**
Intercept	21.04	4.51	0.00030	0.1647	0.41	0.69176
Length (L)	2.25	5.14	0.00008	0.0540	1.41	0.17730
Diameter (D)	-1.81	-14.79	0.00000	-0.0054	-0.50	0.62302
Volume (Vf)	44625.83	41.15	0.00000	-55.1097	-0.58	0.56913
L by D	0.19	19.98	0.00000	-0.0012	-1.46	0.16362
L by Vf	-3515.04	-38,96	0.00000	-6.7274	-0.85	0.40616
D by Vf	94.26	3,73	0.00164	3.8915	1.76	0.09612

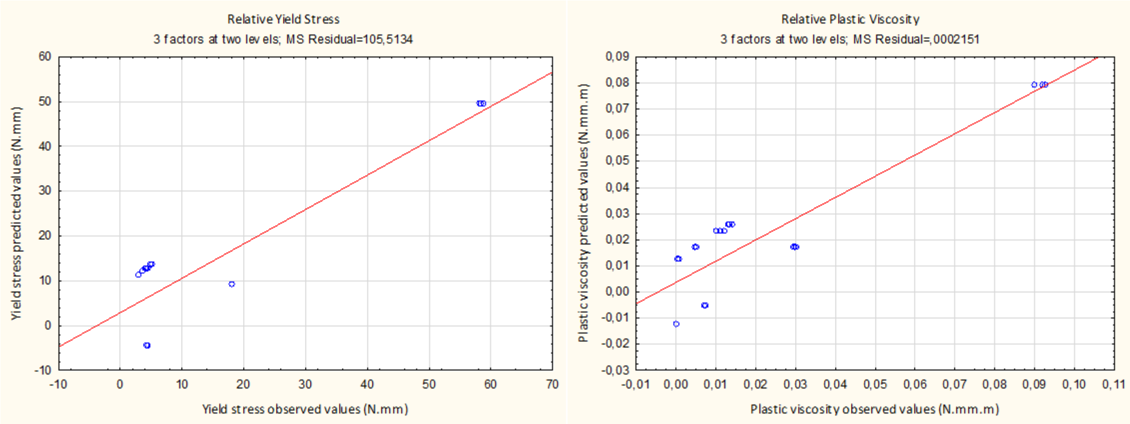
All these analysis were supported with the results obtained for 1.00:2.30 mortars modelled as Bingham fluid with model correlation coefficients R^2 higher than 0.95. Inside this mortar group it was possible to observe that acrylic fibres incorporations were responsible by the mortar stiffness. Despite the indifference of the fibres variables on the relative plastic viscosity, the yield stress was increased significantly by the fibre volume followed by the fibre lengths and theirs interactions.

Table 4. Model regression coefficients with variables interactions (mortar 1.00:0.50)

	Yield stress; R^2 =0.77			Consistency; R^2 =0.82		
	Coefficient	**t-ratio**	**p-value**	**Coefficient**	**t-ratio**	**p-value**
Intercept	-9.36	-0.52734	0.604771	0.0430	1.69641	0.108042
Length (L)	0.77	0.45829	0.652547	0.0105	4.38631	0.000403
Diameter (D)	-0.56	-1.20001	0.246594	-0.0020	-2.98691	0.008283
Volume (Vf)	11943.42	4.92899	0.000127	-10.4353	-3.01635	0.007779
L by D	0.09	2.41975	0.027024	-0.0001	-2.07141	0.053852
L by Vf	-782.41	-3.88077	0.001201	-0.6802	-2.36300	0.030307
D by Vf	-129.92	-2.30374	0.034131	0.4063	5.04578	0.000100

The test results of 1.00:0.50 mortar mixtures are presented in Table 4. The relative yield stress and consistency values were determined from Herschell-Bulkley model support by a R^2 higher than 0.95. In yield stress response model obtained with variables interaction, presented in Table 4, V_f and the interaction between L and D, L and V_f, D and V_f are kept as significant terms. The consistency model shows a significant effect of fibres variables and their interactions on this property. The predicted-to-observed plots, obtained with all the mortar mixtures of relatives yield stress and consistency are shown in Figure 1. The established model can be used to show the influence of any variable in this work (L, D and V_f) on the yield stress and consistency of acrylic fibres reinforced mortars in the modelled region.

Figure 1. Observed value versus predicted value of yield stress and consistency



Isoresponse curves in Fig. 2 shows that for a given value of W/C, SP and a same fibre volume, the yield stress increases with the reduction of fibre length and fibre diameter. This behavior could be explained by the increase of fibre numbers and consequently by the surface area effect on mortar wettability, which considerably increases the mortar stiffness.

Figure 2. Contour surfaces of yield stress as function of fibre variables

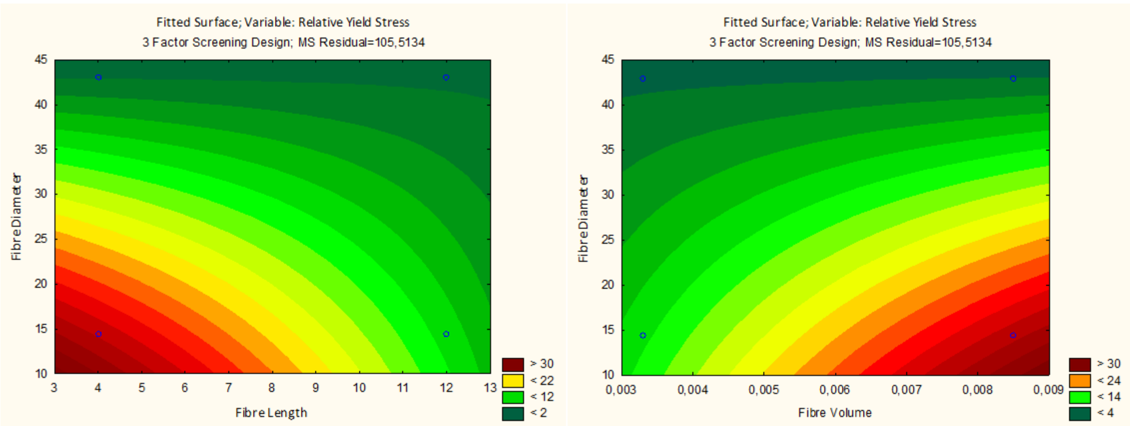


Figure 3. Contour surfaces of plastic viscosity as function of fibre variables

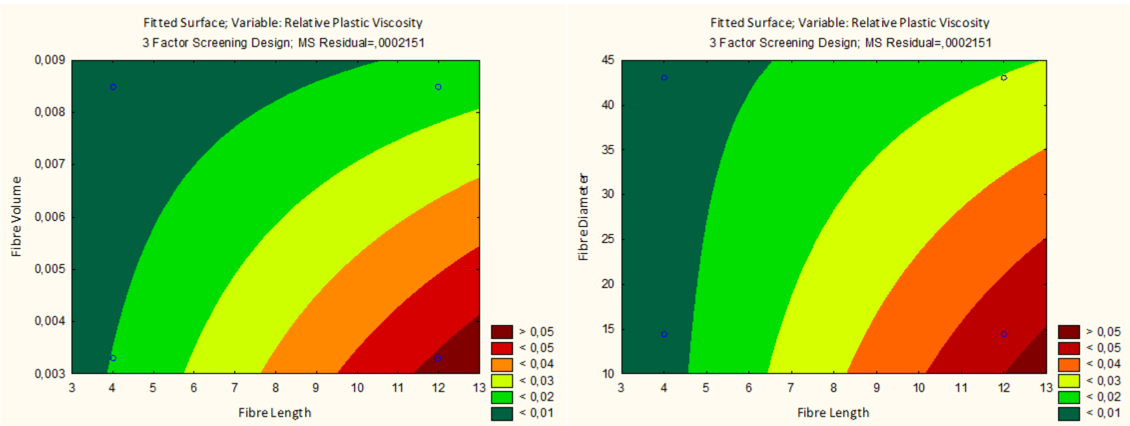


Figure 3 shows at the same condition analyzed for Fig. 2, the influence of fibre variables on the relative plastic viscosity. It can be seen that for any given fibre volume and fibre diameter, the plastic viscosity increase with the increase of fibre length. This effect is related to the fibres tangles formation on the mortar matrix with consequently plastic viscosity increasing.

CONCLUSIONS

The statistical models established using a factorial design approach can be used to quantify the effect of mixture parameters and their coupled effects on rheological parameters of acrylic reinforced mortars.

The effect of acrylic fibres incorporation on mortar was better observed in mortar with typical Herschell-Bulkley behaviour. In a stiff mortar, only the yield stress, determined by Bingham model, shown a significant correlation with the fibres variables. Considering the mortar group 2, for a given value of W/C, SP and a same fibre volume, the yield stress increases with the reduction of fibre length and diameter. Concerning the relative plastic viscosity, for any given fibre volume and fibre diameter, the plastic viscosity increase with the increase of fibre length.

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