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# Effect of low modulus sisal and polypropylene fibre on the free and restrained shrinkage of mortars at early age

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## Abstract

This is the first part of a two-part paper involving the study of the free plastic shrinkage and cracking sensitivity during early drying of mortars reinforced with low modulus sisal, coconut, and polypropylene fibres. This work also evaluates the effectiveness of crack control at early ages on the corrosion of steel bars, which are sensitive to the presence of cracks in the matrix. The performance of cement-based material in the fresh state is expected to improve by reducing the free shrinkage and sensitivity to cracking due to the addition of a low content of polypropylene fibres. This paper discusses the effectiveness of the use of natural sisal fibres for controlling the free and restrained early age shrinkage of mortars and compares their performance with that of polypropylene fibre. In addition, a prediction model for the free plastic shrinkage of natural sisal fibre reinforced mortars is proposed based on a factorial design of experiment. 

*Keywords:* Fiber reinforcement; Shrinkage; Modeling; Composite; Sisal; Polypropylene

## 1. Introduction

Plastic shrinkage is the dimensional change that occurs in all fresh cement-based materials within the first few hours after it has been placed. This type of shrinkage is not unacceptable in itself but it is sometimes accompanied by development of cracks that are unsightly and objectionable. When the cement-based material is placed, the aggregates and cement start to settle and water rises or bleeds to the surface. The disappearance of the sheen from the surface of the concrete, mortar, or paste indicates the time when the rate of evaporation exceeds the rate at which bleeding water rises to the surface. The time required to attain this condition will be influenced by the temperature, relative humidity, wind velocity, and bleeding characteristics of the cementitious material. At this stage, although the surface of the cement-based material has attained some initial rigidity, it cannot accommodate the rapid volume change of plastic shrinkage by plastic flow, and it has not developed sufficient strength to withstand tensile stress. Thus, plastic shrinkage cracks may develop [1]. Besides the use of good concreting and curing practice, the use of fibre reinforcement (in particular low-modulus fibres at content smaller than 0.3% by volume) has been suggested as one of the most effective methods to reduce plastic shrinkage and shrinkage cracking of cement based materials [2–4].

The effectiveness of fibres in reducing early age shrinkage can be evaluated by both free and restrained shrinkage tests. The existing literature on free plastic shrinkage of mortars and concretes reinforced with polypropylene fibres does not report consistent results; reports show reduction in the free shrinkage strain from 0 to 45% [4–6]. Reduction in free shrinkage, however, does not necessarily give and indication of the overall reduction in the crack tendency, which is a function both of the plastic shrinkage and the reinforcing effect of the fibres in the fresh matrix [2]. To establish cracking tendency, restrained shrinkage tests need to be carried out. These tests have been conducted by many researchers in the last 15 years using ring specimens [4,7–9]. In the ring-shaped test, the cement-based material is cast between two rigid rings, with the inner ring (core) providing the restraint. Ring specimens can be exposed to various drying conditions to study the cracking sensitivity of the fresh mix. The extent of cracking depends on the restraint condition and drying environment.

The main objectives of this paper are to determine whether low-modulus sisal fibre might be useful for controlling the free and restrained early age shrinkage of mor-

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Table 1
Chemical and physical properties of Spanish Portland cement CEM I 42.5R

| Chemical properties | | | | | | | | | | Physical properties | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | Loss on ignition | Insoluble residue | Density (g/cm$^3$) | $\sigma_{c28d}$ (MPa) | Setting time (min) |
| 18.9 | 3.8 | 3.9 | 63.3 | 1.2 | 2.9 | 0.15 | 1.05 | 3.17 | 1.89 | 3.14 | 43 | 160/280 |

Table 2
Average properties of sisal fibre

| Diameter (mm) | Density (g/cm$^3$) | Natural moisture content (%) | Water absorption after 5 min under water (%) | Water absorption after saturation (%) | Tensile strength (MPa) | Modulus of elasticity (GPa) | Strain at failure (%) |
|---|---|---|---|---|---|---|---|
| 18.9 | 0.9 | 13 | 82 | 220 | 577 | 19 | 3 |

tar; to compare the performance of sisal fibre with the performance of low-modulus polypropylene fibre; and to present a model for predicting the free plastic shrinkage of natural sisal fibre reinforced mortars (NSFRM).

The performance of sisal fibre in controlling free and restrained plastic shrinkage of cement matrices merits evaluation because it presents comparable mechanical properties to low-modulus polypropylene fibres and is substantially less expensive, providing a cost-effective material. In addition, this kind of fibre is naturally occurring, largely available, and energy efficient.

## 2. Experimental

### 2.1. Materials

Table 1 presents the chemical and physical properties of the ordinary Portland cement, CEM I 42.5R, used in this study. The sand employed followed the Spanish Standard UNE 80.101 with a maximum particle size of 2 mm.

The natural sisal fibre used in this investigation was of Brazilian production and the average properties are presented in Table 2. Fibres of 25 mm were used as reinforcement of plain mortar.

The commercial fibrillated polypropylene fibres used in the experiments have a rectangular cross-section and are 14-mm long, The density, elastic modulus, and tensile strength of these fibres are, respectively, 0.90 g/cm$^3$, 3.5 GPa, and 056–0.77 MPa.

### 2.2. Testing method

The test method proposed by Sanjuán and Moragues [6] was used to measure the plastic shrinkage of sisal and polypropylene fibre-reinforced mortar. This method enables measurement of the horizontal deformation of fresh mortar specimens (150 $\times$ 1200 mm and 15-mm thick), using dial gauge extensometers. The specimens are subjected to forced ventilation in order to accelerate the evaporation of the mix water. Fig. 1 shows the lateral view (not to scale) of the experimental setup.

The device used in this work consists of a chamber in which air flow speed and temperature are held constant by means of a fan (A), an electrical resistance (B), and a control system (C) connected to a thermometer (D). In the interior of the chamber there are two wooden moulds of internal dimensions of 15 $\times$ 150 $\times$ 1200 mm where the specimens (E) are cast. In order to reduce friction between the specimens and the moulds and to avoid water loss from the fresh mix, the moulds were covered internally with a thin polyethylene film before casting. The shrinkage of each speci-

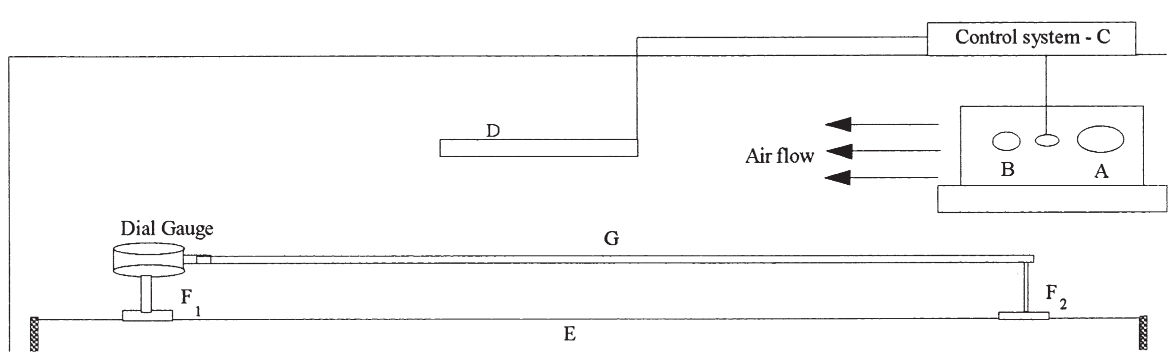


Fig. 1. Lateral view of the experimental setup used for the free shrinkage tests.

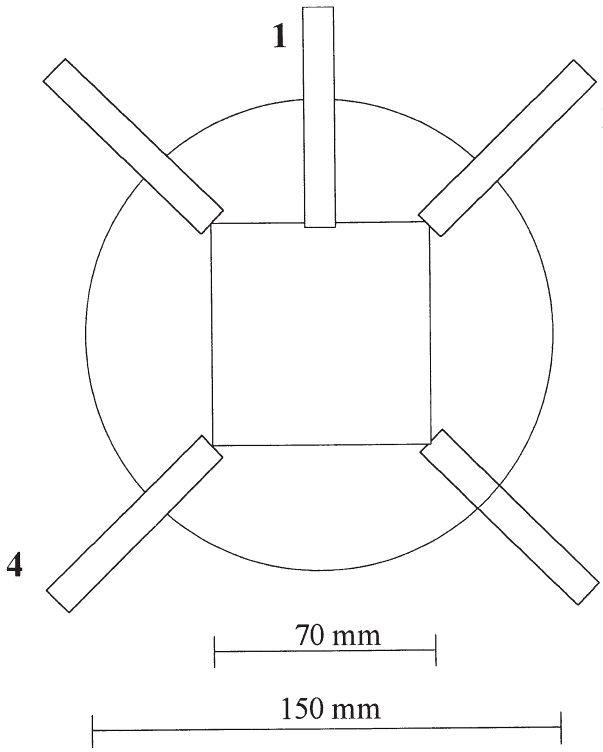


Fig. 2. Restrained shrinkage test setup.

men is measured using a dial gauge extensometer with an accuracy of 0.01 mm located on a steel plate ($F_1$), which is connected to the other steel plate ($F_2$) by means of a steel rod (G).

The restrained shrinkage tests were carried out on a ring-type specimen with a cube-shaped core with a 70-mm side and a cylindrical external mould of 150-mm diameter and 50-mm height. Five steel bars 6 mm in diameter were positioned at the midheight of the mould in a radial orientation, from the circumference to the core. Four bars were positioned to reach the corners of the core where cracking is more likely to occur and the fifth bar was located at an intermediate angle where a crack is less likely to occur. The ring-shaped mould is illustrated in Fig. 2. The steel bars were incorporated into the setup because the effectiveness of cracking control at early age on the corrosion of the bars, which is sensitive to the presence of cracks in the matrix, was also evaluated. The results of this study is presented in the second part of this paper [10].

A conventional pan mixer was used to manufacture the sisal fibre-reinforced mortars. Two specimens were cast for each mix. Immediately after casting, the gauges were located on the samples, the chamber closed and set to wind speed and temperature of 0.5 m/s and 40°C, respectively, in the interior. Free plastic shrinkage tests started at this moment and measurements were recorded at regular intervals of time to 280 min when the free plastic shrinkage was nearly complete (see later).

The mortar mixes used to study restrained shrinkage were cast in the ring mould and immediately exposed to drying on an air flow of 0.4 m/s at 40°C to develop plastic shrinkage in the vicinity of the steel bars. First crack appearance time and crack development were monitored until 210 min.

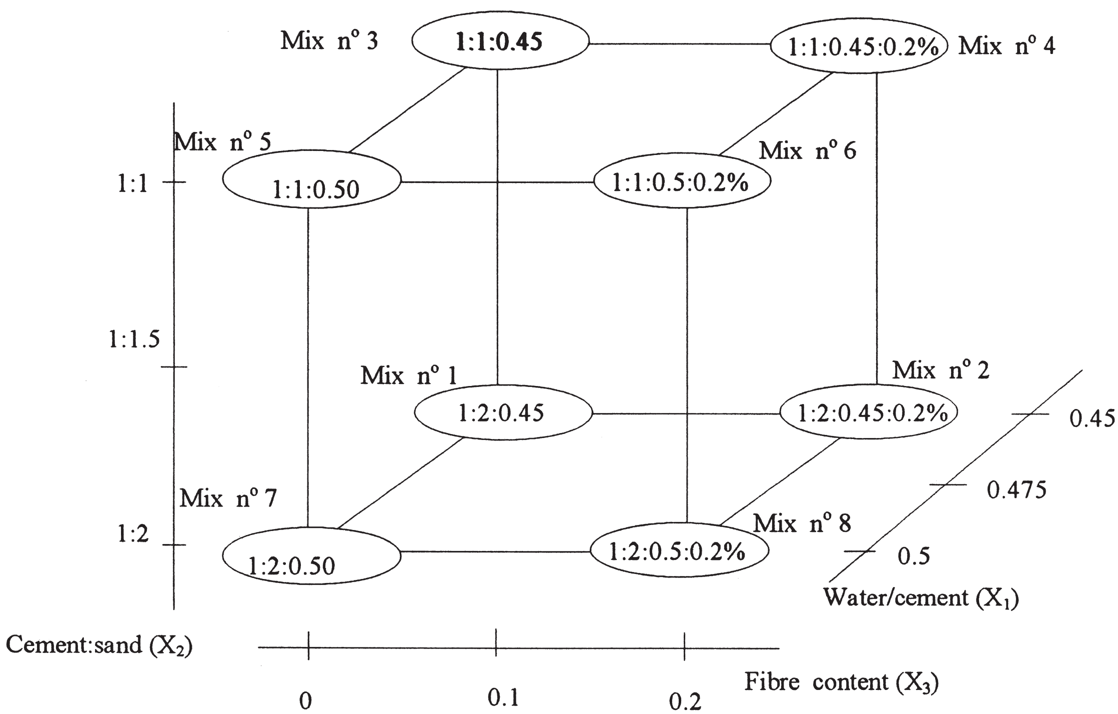


Fig. 3. $2^3$ factorial design.

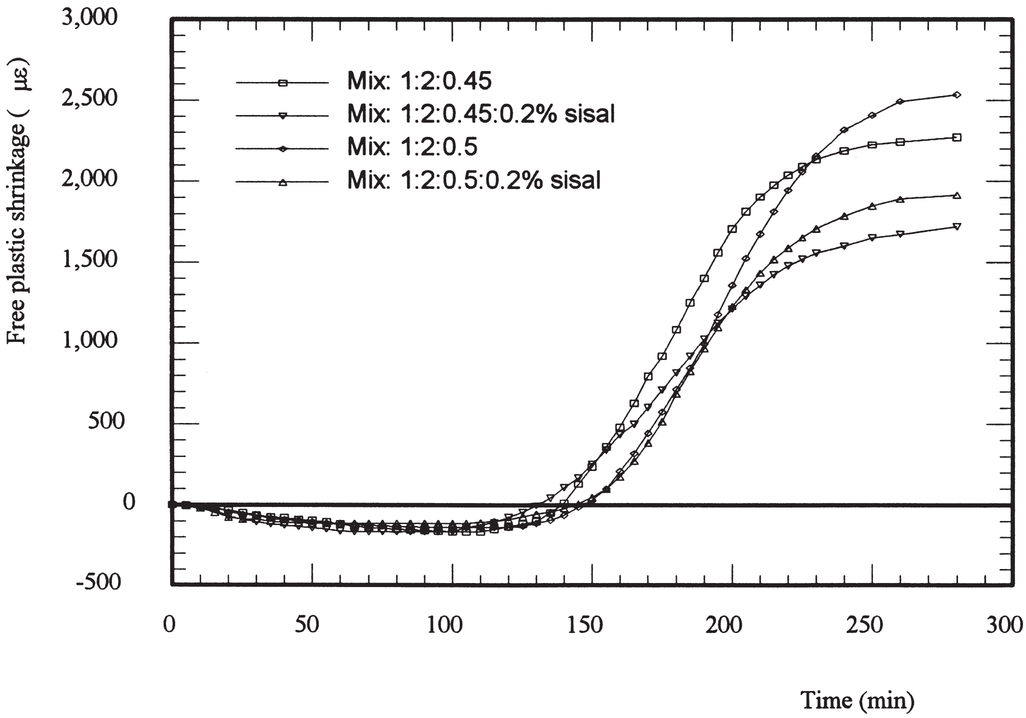


Fig. 4. Shrinkage after placing for the mixes 1, 2, 7, and 8.

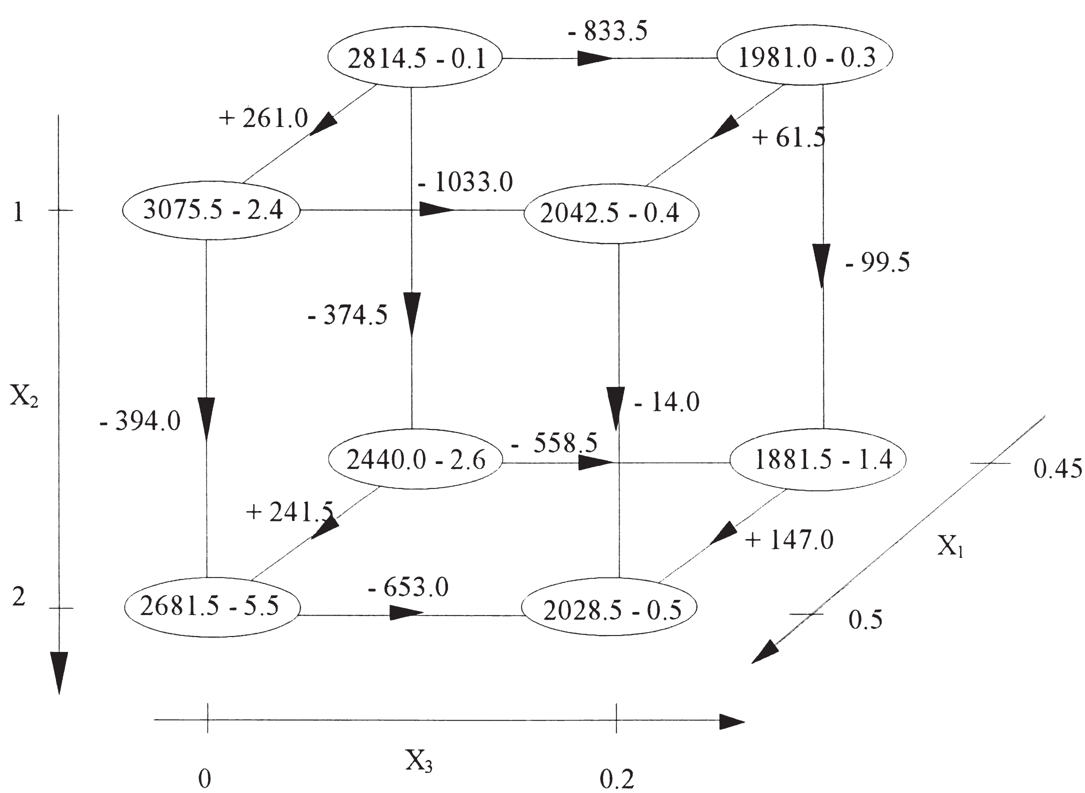


Fig. 5. Free plastic shrinkage test results.

Table 3
Main effects and interactions

| Main effects (με) | | | Interactions (με) | | | |
|---|---|---|---|---|---|---|
| $X_1$ | $X_2$ | $X_3$ | $X_1 \times X_2$ | $X_1 \times X_3$ | $X_2 \times X_3$ | $X_1 \times X_2 \times X_3$ |
| 177.8 | −220.5 | −769.5 | 16.5 | −73.5 | −163.8 | 26.3 |

## 3. Mathematical model for the prediction of free plastic shrinkage of NSFRM

A complete factorial design of experiments was used to define the experimental program to be executed in the study of free plastic shrinkage of NSFRM. Factorial design was selected, in opposition to the classical "one-at-a-time experiments," because it provides an efficient and structured approach to study of properties of a material that are influenced by a large number of factors. Through factorial design it is possible to determine whether the major factors affecting the property of the material being studied have been taken into consideration; which of the factors have significant effects on this property; and the interactions among the factors. In addition, the use of factorial design leads to a mathematical model that allows one to predict the value of the particular property being studied as a function of the factors considered.

To have a complete factorial experiment, one must establish for each factor a number of levels to be investigated. If a factor *A*, for example, is investigated at *r* levels, factor *B* at *c* levels, and a factor C at *s* levels, we have an $r \times c \times s$ complete factorial experiment. If each treatment combination is replicated *n* times, the total number of tests required is given by $r \times c \times s \times n$ [11]. The level of each variable in an experiment can cover a large range. However, the purpose of a factorial design is not to test the extremes of a process, but to sample a rational area of practical interest in the space of the factors. If a variable is significant and the results obtained at a lower level show that the evaluation of the dependent variable at a extreme value is desirable, subsequent experiments can be carried out to explore this new range. A complete factorial design at two levels with three factors and two replications is used to study the free plastic shrinkage of NSFRM.

The factors studied in this investigation were: (a) water/cement ratio ($X_1$); (b) sand:cement ($X_2$); and (c) percentage of fibre ($X_3$). These factors were selected based on the fact that they are the common variables considered in the design of fibre-reinforced cement mixes. The use of a factorial design can determine, however, whether they are primary factors affecting the free plastic shrinkage of mortars. This design is illustrated by the cube shown in Fig. 3. The lower and upper levels selected for each factor are presented in the axis of this Fig. 3. The mix proportions are numbered and shown at the corners of the cube.

Fig. 4 presents typical curves of the free plastic shrinkage tests. These curves are the average results of the two tests carried out for each mixture investigated. The results show that for the test conditions affecting evaporation of the mix water, rapid shrinkage was generally manifested after 2 h, often preceded by a slight swelling. A similar trend was observed with a wide range in free shrinkage test results presented by L'Hermite [12] and Brull et al. [13].

Fig. 5 presents the mean values (in με) and the coefficient of variation (in %) of the free shrinkage at early age of sisal fibre-reinforced mortar. The low values of the coefficient of variation show the repeatability of the experimental setup.

The results presented in Fig. 5 can be combined in seven different ways to estimate different effects. For example, there are four observations of free plastic shrinkage at the high level of the factor $X_1$ and four observations at the low level. The average difference between them is an estimate of the "main effect" $X_1$. Similarly the main effect of the factors $X_2$ and $X_3$ can be calculated. The results given in Table 3 show that the average effect of fibre content ($X_3$) on the free plastic shrinkage of mortars is a reduction of 769.5 με in its value. This reduction, however, is greater with the water/cement ratio of 0.5 than with water/cement ratio of 0.45 as can be seen in Fig. 5. This fact show that the factors $X_3$ and $X_1$ do not present an additive behaviour and that there is an interaction between them. An estimate of the $X_1 \times X_3$ interaction is given by the half difference between the main effect of $X_1$, at the high level of $X_3$, and the main effect of

Table 4
Analysis of variance table for three-factor experiment

| Source of variation | Sum of squares (SS) | Degrees of freedom | Mean square | Mean square ratio ($F_0$ - ratio) | Minimal MSR required for a factor to be significant ($F_{0.05,1,8}$, $F_{0.025,1,8}$, $F_{0.01,1,8}$) | | |
|---|---|---|---|---|---|---|---|
| Main factors | | | | | | | |
| $X_1$ (water/cement) | 126380 | 1 | 126380 | 14.6 | 5.32 | 7.57 | 11.3 |
| $X_2$ (cement:sand) | 188356 | 1 | 188356 | 21.8 | 5.32 | 7.57 | 11.3 |
| $X_3$ (fibre content) | 2368521 | 1 | 2368521 | 273.8 | 5.32 | 7.57 | 11.3 |
| Interacting factors | | | | | | | |
| $X_1 \times X_2$ | 2061.2 | 1 | 2061.2 | 0.24 | 5.32 | 7.57 | 11.3 |
| $X_1 \times X_3$ | 21609 | 1 | 21609 | 2.5 | 5.32 | 7.57 | 11.3 |
| $X_2 \times X_3$ | 107256 | 1 | 107256 | 12.4 | 5.32 | 7.57 | 11.3 |
| $X_1 \times X_2 \times X_3$ | 2756.2 | 1 | 2756.2 | 0.32 | 5.32 | 7.57 | 11.3 |
| Experimental error | 69192.5 | 8 | 8649.1 | | | | |

Table 5
Experimental and prediction results

| Mix | Experimental results (με) | Prediction (με) | Error (%) |
|---|---|---|---|
| 1:2:0.45 | 2440 | 2423 | −0.4 |
| 1:2:0.45:0.2%S | 1881.5 | 1790 | −4.8 |
| 1:1:0.45 | 2814.5 | 2540 | −9.7 |
| 1:1:0.45:0.2%S | 1981 | 2100 | +6.0 |
| 1:1:0.5 | 3075 | 2571 | −16.4 |
| 1:1:0.5:0.2%S | 2042.5 | 2130 | +4.3 |
| 1:2:0.5 | 2681.5 | 2461 | −8.2 |
| 1:2:0.5:0.2%S | 2028.5 | 2020.5 | −0.4 |

Table 6
Predicted and observed results of free plastic shrinkage at intermediate levels

| Mix | Experimental result (με) | Prediction (με) | Error (%) |
|---|---|---|---|
| 1:1.5:0.475:0.1%S | 2245 | 2372 | +5.7 |
| 1:1:0.45:0.1%S | 2505 | 2320 | −7.4 |
| 1:2:0.5:0.1%S | 2333 | 2241 | −3.5 |

$X_1$, at low level of $X_3$. Similarly, the interactions $X_1 \times X_2$, $X_2 \times X_3$, and $X_1 \times X_2 \times X_3$ can be evaluated. The results of the interactions are presented in Table 3.

An analysis of variance was performed to show which effects are significantly large. The significance of each effect was tested at confidence levels of 95, 97.5, and 99% using the F test. Table 4 presents the analysis of variance carried out for the data obtained in this investigation.

On the basis of the values shown in Table 4, it appears that the main factors and the interacting factor $X_2 \times X_3$ are significant at 99% confidence level on the free plastic shrinkage of mortars. These results confirm the importance of the selected factors on the plastic shrinkage strain of mortars and point out the excellent role performed by the fibres on controlling this phenomenon.

To obtain a model for the prediction of the free plastic shrinkage of NSFRM, a multiple linear regression equation was fitted to the set of experimental data. The model in terms of the observations may be written as Eq. (1):

$$\text{FPS} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \quad (1)$$

where FPS is the free plastic shrinkage; $\beta_i$ are the unknown regression coefficients; $X_i$ are the factors; and $\varepsilon$ represents the random error. The fitted model is given by Eq. (2) and Table 5 presents a comparison between the experimental and predicted data calculated using Eq. (2) to show the accuracy of the model [see Eq. (2)].

$$\text{FPS} = 2370 + 622 \times \text{W/C} - 110.25 \times \text{S/C} - 2200 \times \text{\% of sisal} \quad (2)$$

Table 7
Results of FPS for mortars reinforced with polypropylene and sisal fibres

| 1:1:0.45 | 1:1:0.45:0.2%PP | 1:1:0.45:0.2%S | 1:2:0.5 | 1:2:0.5:0.1%PP | 1:2:0.5:0.1%S |
|---|---|---|---|---|---|
| 2814.5 | 2767 | 1981 | 3075 | 2119 | 2333 |

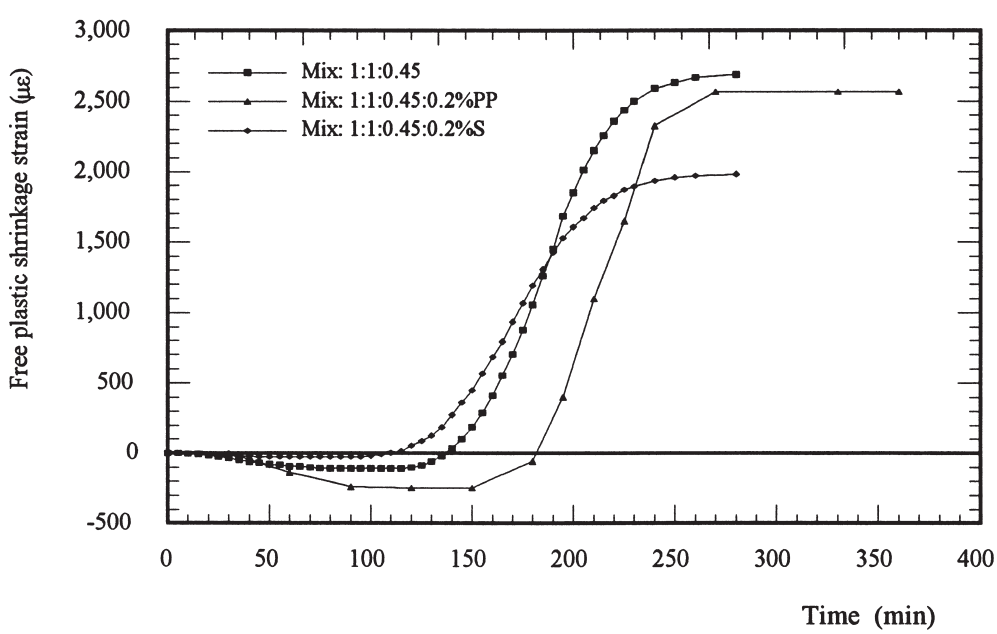


Fig. 6. Plastic shrinkage of mortars reinforced with sisal and polypropylene fibres.

Table 8
Time of crack appearance in fresh mortars exposed to restrained shrinkage

| Mix proportions | 1:2:0.5 | 1:2:0.5:0.5% sisal | 1:2:0.5:0.5% polypropylene |
|---|---|---|---|
| Time of cracking (min) | 90 | 180 | 120 |

Equation 2, which describes a hyperplane in the three-dimensional space of the independent variables $X_i$, is unlikely to be a reasonable approximation of the response surface over the entire space of the independent variables, but for the relatively small region of practical interest studied, the errors observed are acceptable. Table 6 presents results of free plastic shrinkage tests carried out in the central point and at two other intermediate levels of the factors and compares the results with those calculated using Eq. (2).

## 4. Comparison between the effectiveness of polypropylene and sisal fibre in controlling free and restrained shrinkage of mortars at early age

A comprehensive study on the efficiency of polypropylene fibre in controlling free shrinkage and cracking tendency of fresh mortars is presented elsewhere [14,15]. In this paper a comparison is made between the performance of sisal (S) and polypropylene (PP) fibres in controlling these phenomena. Table 7 and Fig. 6 present results of free shrinkage tests carried out with both kind of fibres.

The results presented in Table 7 and Fig. 6 show that the addition of 0.2% of sisal fibre reduces the FPS of the mortar mixes by 29.6 and 24.1%, respectively, whereas the presence of 0.2% polypropylene fibre leads to a reduction of 1.7 and 31%. These results show a more consistent reduction in the FPS when sisal fibre is present in the mix.

Table 8 presents the time of appearance of the first crack in the restrained shrinkage tests. The results show that the first crack appeared in the matrix 90 min after the mix had been placed. For the specimens reinforced with polypropylene and sisal fibres, the first crack appeared after 120 and 180 min, respectively.

The results presented in Table 8 and Fig. 7 show that both fibres are quite effective in retarding the first crack appearance and in reducing the inherent cracking tendency at early age of the matrix. This happen because at early age the elastic modulus of the fibres are still higher than that of the cementitious matrix.

## 5. Conclusions

The free plastic shrinkage of composites reinforced with natural sisal fibre has been studied using a factorial design of experiments. This technique produces great savings in time, resources, and investigation costs and leads to a mathematical model the results of which presented good correlation with the experimental ones in the range of factors investigated.

Low-volume sisal and polypropylene fibre were found to be extremely effective in reducing free plastic shrinkage, in retarding the first crack appearance, and in controlling crack development. This happens because at early age the elastic modulus of these fibres are still higher than that of the cementitious matrix.

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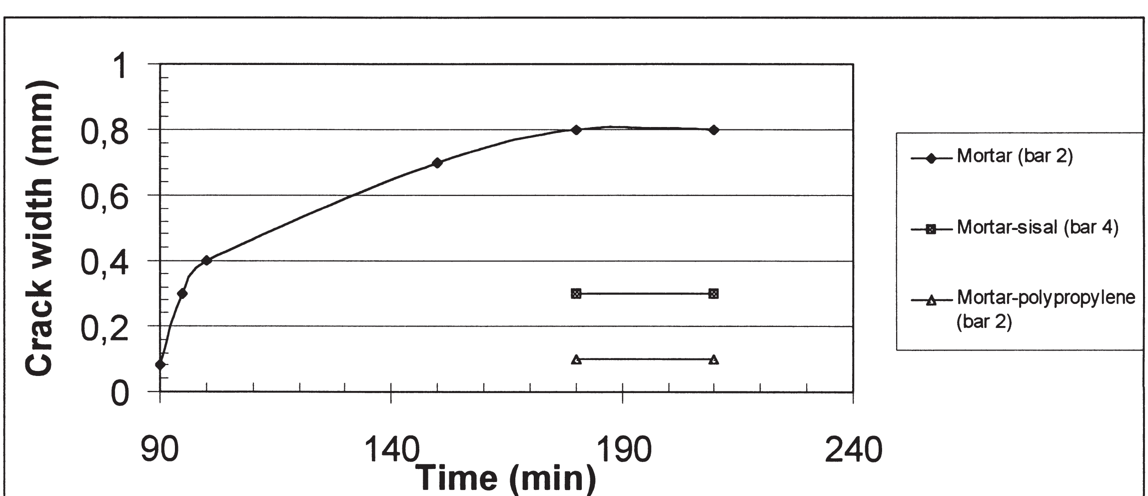


Fig. 7. Firts crack pattern of the mortar, mortar-sisal, and mortar-polypropylene polypropylene at early age.

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