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Free, restrained and drying shrinkage of cement mortar composites reinforced with vegetable fibres

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Abstract

Many investigations are realized to establish the basic mechanical properties of vegetable fibre reinforced composites (VFRC) but not their shrinkage and creep behaviour. Some works have been realized to establish the shrinkage of cement mortar matrices reinforced with cellulose fibres, but very few results has been published with regards to shrinkage of VFRC with short sisal and coconut fibres. In this paper a concise summary of several investigations is presented to establish the influence of sisal and coconut fibres on the free and restrained plastic shrinkage, early drying shrinkage cracking, crack self-healing and long-term drying shrinkage of mortar matrices. The free and restrained shrinkage were studied by subjecting the specimens to wind speed of 0.4–0.5 m/s at 40 °C temperature for up to 280 min. The self healing of cracks of the VFRC was studied by using the same specimens as for the study of restrained shrinkage which were kept further in a controlled environment with 100% relative humidity and temperature of 21 °C for up to 40 days. Drying shrinkage tests were carried out at room temperature with about 41% relative humidity for 320 days. The influence of curing method, mix proportions and partial replacement of ordinary Portland cement (OPC) by ground granulated blast-furnace slag and silica fume on the drying shrinkage of VFRC was also investigated. Finally, based on the obtained results on drying shrinkage an equation using the recommendation of ACI model B3 was adjusted and compared well with the obtained experimental data.
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1. Introduction

Plastic shrinkage is the dimensional change that occurs in all fresh cement based materials within the first few hours after placement when the mixture is still plastic and has not yet achieved any significant strength. Freshly cast concrete shrinks primarily due to water evaporation. This shrinkage has been attributed [1,2] to negative capillary pressure that leads to a volume contraction of the cement paste. The stresses are generated by a complex series of menisci which are formed in the water filled concrete pores when water is eliminated from the paste mainly by evaporation.

If concrete is restrained against shrinkage, tensile stress develops and can cause cracks. Plastic shrinkage cracks are widely evident in bridge decks, industrial and parking garage floors and highway pavement slabs, that have large thickness and exposed areas. The

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development of plastic shrinkage cracks leads to rapid deterioration of the structures when they are exposed to drying and wetting or freezing and thawing conditions [3–6].

The addition of small quantities of fibres such as steel, polypropylene and cellulose can reduce plastic shrinkage and shrinkage cracking of cement based materials [2–12]. The effectiveness of fibres in reducing early age shrinkage should be evaluated from free and restrained shrinkage tests. Reduction in free shrinkage does not necessarily give an indication of the overall reduction in crack tendency, which is a function of the plastic shrinkage and the reinforcing effect of the fibres in the fresh matrix. To establish the crack tendency, restrained shrinkage tests considering different restraint and drying conditions need to be carried out. The shrinkage and cracking potential in hardened concrete follows the same concepts as for plastic shrinkage of the fresh mixture. Here also the cracking sensitivity is a function of the shrinkage strain and the improved toughness due to fibres [7].

Practical experience has demonstrated that cracks in cement based materials maintained at high humidity, have the ability to heal themselves. The self-healing of cracks has been attributed [13] to the swelling and hydration of cement pastes, precipitation of calcium carbonate crystals, blocking of flow path by water impurities or by concrete particles broken from the surface of the crack. In vegetable fibre–cement composites the fibres can act as porous bridging elements across the cracks accelerating the autogenous healing [14,15].

Hardened cement paste has a high drying shrinkage; concrete, on the other hand, shows relatively lower shrinkage because the volume changes are largely restrained by the rigidity of the aggregates [5]. Regarding the effect of fibres on the drying shrinkage of concrete, the few results available are not conclusive [16–19]. It has been reported that steel fibres have no effect on the shrinkage of concrete [16] and that they can reduce the shrinkage by up to 40% [17]. Glass fibres have been reported [18,19] to reduce the shrinkage of mortar matrices by 20–30%. The existing data concerning the influence of sisal and coconut fibres on the drying shrinkage behaviour of cement based composites in the available literature are quite scarce. However, it is known that vegetable fibres are porous and they create moisture paths deep into the matrix which will increase shrinkage as confirmed by the authors' investigations [14,15].

An analytical model for the drying shrinkage of steel fibre reinforced cementitious composites has been developed by Mangat and Azari [20] to predict the influence of randomly oriented fibres on composite drying shrinkage. The model is based on the concept that, shrinkage of cement matrix, in any direction, is restrained by an aligned fibre of effective length parallel to the direction of the shrinkage strain. This analysis requires a knowledge of the values of coefficient of friction at the fibre matrix interface from the drying shrinkage experimental data. Recently a general expression for the drying shrinkage prediction has been proposed by Zhang and Li [21] based on the shear-lag theory developed by Cox [22] considering the properties of both fibres and matrix including free shrinkage behaviour of pure matrix, elastic moduli ratio of fibre and matrix, fibre orientation characteristic, fibre effective aspect ratio and fibre volume fraction. Both formulations are not applicable for the composite reinforced with fibres that have elastic modulus lower than that of the matrix one which is the case of this paper. To predict the drying shrinkage specifically for the vegetable fibres reinforcing cement mortar, an equation using the recommendation of ACI model B3 for concrete has been adjusted and its validity to the experimental data is examined and presented in this paper.

2. Experimental procedures

2.1. Materials

The sisal and coconut fibres used in this investigation were of Brazilian production. The maximum, minimum, mean and the coefficient of variation (CV) of the physical and mechanical properties of these fibres based on a minimum of twenty tests are given in Table 1 [14,23]. Chemical and physical properties of the ordinary Portland cement "OPC" produced in England, ground granulated blast-furnace slag "GGBS" and undensified silica fume (grade 940) are presented in Table 2. The Thames Valley sand used in the drying shrinkage tests had a fineness modulus of 2.81, a specific gravity of 2.65 and a total moisture content of 0.35%. The sand and cement employed in the free and restrained plastic shrinkage tests followed the Spanish Standard with a maximum particle size of 2 mm and OPC CEM I 42.5R, respectively. Tap water was used in all mixes.

2.2. Free plastic shrinkage

The free plastic shrinkage of sisal fibre reinforced mortar composites (SFRMC) was measured using the method proposed by Sanjuán and Moragues [24]. This method enables the measurement of horizontal deformation of fresh mortar specimens of dimensions 150 mm × 1200 mm × 15 mm using mechanical dial gauge extensometers located on the upper face of the specimens. The gauge length was 1000 mm. To accelerate the evaporation of the mix water the specimens were subjected to forced ventilation. A conventional pan mixer was used to manufacture two identical specimens. Immediately after casting, the gauges were located on

Table 1
Physical and mechanical properties of sisal and coconut fibres [14,23]

Property	Sisal fibre		Coconut fibre	
	Lower–upper	Mean–CV (%)	Lower–upper	Mean–CV (%)
Diameter (mm)	0.08–0.30	0.12–23.8	0.11–0.53	0.25–27.30
Density (g/cm^3)	0.75–10.70	0.90–8.90	0.67–10.00	0.80–7.60
Natural moisture content (%)	10.97–14.44	13.30–8.80	11.44–15.85	13.5–10.00
Water absorption after 5 min under water (%)	67.00–92.00	82.00–14.50	22.00–38.00	28.00–16.00
Water absorption to saturation (%)	190.00–250.00	230.00–16.00	85.00–135.00	100.0–19.50
Tensile strength (MPa)	227.80–1002.30	577.50–42.66	108.26–251.90	174.00–24.20
Modulus of elasticity (GPa)	10.94–26.70	19.00–29.50	2.50–4.50	3.50–27.00
Strain at failure (%)	2.08–4.18	3.00–29.15	13.70–41.00	25.00–29.10

Table 2
Chemical and physical properties of the cementing materials

Property	OPC blue circle	CEM I 42.5R	Silica fume grade 940	GGBS
(a) Chemical properties				
SiO_2 (%)	20.7	18.9	91.7	34.4
Fe_2O_3 (%)	3.0	3.9	0.51	1.43
Al_2O_3 (%)	4.6	3.8	1.11	11.7
CaO (%)	64.7	63.3	0.23	41.2
MgO (%)	1.0	1.2	0.70	8.81
SO_3 (%)	3.0	2.9	0.26	–
Na_2O (%)	0.13	0.15	0.25	0.29
K_2O (%)	0.65	1.05	1.11	0.31
P_2O_5 (%)	–	–	0.07	–
TiO_2 (%)	–	–	0.011	0.58
MnO (%)	–	–	0.033	–
Mn_2O_3 (%)	–	–	–	0.30
Loss on ignition (%)	1.3	3.17	2.34	–
Soluble residue (%)	0.38	1.89	–	–
pH		–	6.9	–
(b) Physical properties				
Fineness (m^2/kg)	353	–	15,000–20,000	417
Setting time (initial—min)	134	–	–	–
Compressive strength (MPa) at:				
2 days	26.63	–	–	–
7 day	47.2	–	–	–
14 days	59.2	–	–	–
Bulk density (g/cm^3)	–	–	3.24	–

the fresh samples, the chamber closed and set to maintain the wind speed and temperature at 0.5 m/s and 40 °C, respectively. Free plastic shrinkage measurements were started at this moment and were recorded at regular interval of 5 min up to 280 min when it was nearly complete.

Table 3 presents the summary of the mixes studied. In all the tests the cement, sand and water were measured by weight. The following abbreviations are used to represent the OPC mortar mixtures used to study the free plastic shrinkage, fibre type and fibre volume fraction:

PSM1—mortar mix (1:1:0.45);
PSM2—mortar mix (1:1:0.5);
PSM3—mortar mix (1:2:0.45);
PSM4—mortar mix (1:2:0.5).

Table 3
Plastic shrinkage and drying shrinkage for the W, DC, PDC curing conditions

Plastic shrinkage		Drying shrinkage	
Mix	Mortar mix proportions (by weight)	Mix	Mortar mix proportions (by weight)
PSM1	1:1:0.45	M1	1:1:0.4
PSM1S0.1	1:1:0.45	M2	1:2:0.52
PSM1S0.2	1:1:0.45	M1S325	1:1:0.4
PSM2	1:1:0.5	M1S225	1:1:0.4
PSM2S0.2	1:1:0.5	M1C325	1:1:0.4
PSM3	1:2:0.45	M1C225	1:1:0.4
PSM3S0.2	1:2:0.45	M2S225	1:2:0.52
PSM4	1:2:0.5	M1slagS225	(0.6opc + 0.4slag):1:0.4
PSM4S0.1	1:2:0.5	M1msS225	(0.9opc + 0.1MS):1:0.46
PSM4S0.2	1:2:0.5	M1slagS225	(0.6opc + 0.4slag):2:0.52

W = water-cured samples; DC = damp cloth-cured samples; PDC = pressure + damp cloth-cured samples.

S—sisal fibre length of 25mm was chosen based on previous studies [14,15,23]. Number after the fibre type represents the volume fraction of fibre (0.1% and 0.2%).

2.3. Restrained shrinkage

The restrained shrinkage of VFRC was studied using a ring type specimen with a external plastic cylindrical mould of 150mm internal diameter and 50mm height. The mixes were placed between the outer ring and the central concrete cubic core of 70mm dimensions as shown in Fig. 1. Five steel bars of 6mm diameter were positioned at the mid-height of the mould connecting the external ring to the core. One of the bars was positioned at the centre of a side and the others at the corners of the core, where cracking is most likely to occur. The incorporation of steel bars allowed better formation of shrinkage cracks at the corners, beside permitting to study the influence of early age crack development on the corrosion of steel reinforcing bars [25]. Composites incorporating 0.5% volume fraction of 25mm fibre reinforcement for both sisal and coconut were produced using a cement–sand proportion of 1:0.5 (by weight) and a water–cement ratio of 0.5. The mixes were cast in the ring moulds and half an hour later exposed to an airflow of 0.4m/s at 40°C for up to 210min to develop plastic cracking in the vicinity of the steel bars. During this period it was measured the time of the first crack appearance and its development using an optical lens of 10x magnification. The specimens were afterwards held at room temperature with a 100% RH. Then the crack pattern was registered up to 40 days to investigate the phenomenon of self-healing of cracks.

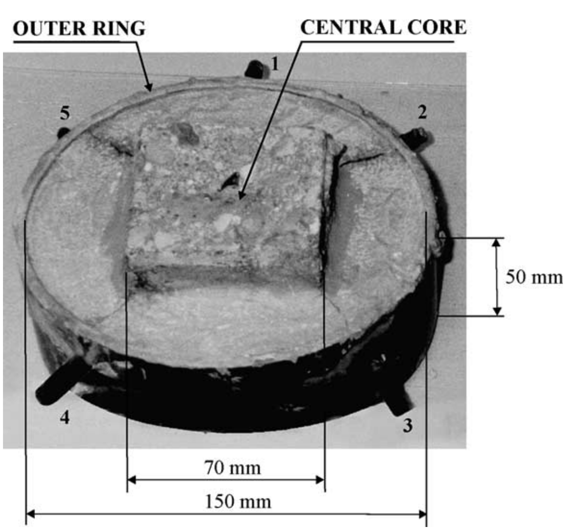

Fig. 1. Restrained shrinkage test set-up.

2.4. Drying shrinkage

The test specimens were cast in plastic moulds of 90mm internal diameter and 300mm height. To measure shrinkage strains along the length of the specimens, three pairs of studs of gauge length 254mm were fixed internally, before casting, in each mould at an angle of 120°. A mechanical gauge with a precision of 2.5×10^{-6} was used. Fig. 2 presents the specimens used in this study. The temperature and relative humidity of the concrete laboratory monitored during the period of test varied between 21.5 and 24.7°C, and 32.4% and 49.6%, respectively.

Composites incorporating random short fibre reinforcement of 25mm length were produced using the following procedure. The mortar matrix and fibres were first mixed in a pan mixer. Forty percent of the total water required was added to the sand in the running mixer. In order to avoid clumping of fibres and to keep the mix wet enough, the fibres and a further 35% of the water were slowly added. After placing all the fibres and the cement, the remaining water was added to the running mixer which was allowed to continue for about 5min to enhance fibre dispersion. The specimens were cast in three layers using external vibration. Time of vibration was established according to the recommendation made by ACI 544.2R [26].

Immediately after casting, one series of specimens was subjected to a pressure of 0.12 MPa. They were

Fig. 2. Specimens used to measure the drying shrinkage of the composites.

covered in their moulds with a damp cloth and polythene sheet for 24h as for the other two series. Then water or damp cloth curing methods was used up to 28 days for the three test series as follows: immersion of specimens in water at a temperature of about 18°C (designated as series W), specimens without and with application of initial pressure covered with damp cloths in a curing box at 18°C and 97% RH designated as DC and PDC, respectively. These alternatives were considered because water curing is the usual method recommended by the standards; damp cloth is the common curing method applied in practice; and application of pressure immediately after casting is one of the procedures that can be used in production of thin products using vegetable fibres.

The influence of fibre type and volume fraction, matrix composition and use of slag and silica fume as cement replacement on the shrinkage of the composites was studied for the series W, DC and PDC. Table 3 presents the summary of the mixes studied. In this table, the following abbreviations are used to represent OPC mortar mix, fibre type, fibre volume fraction and cure condition:

M1—mortar mix (1:1:0.4—cement:sand:water by mass);
M2—mortar mix (1:2:0.52—cement:sand:water by mass);
M1ms—mortar mix M1 with 10% by mass of cement replaced by silica fume;
M1slag—mortar mix M1 with 40% by mass of cement replaced by slag;
M2ms—mortar mix M2 with 10% by mass of cement replaced by silica fume;
M2slag—mortar mix M2 with 40% by mass of cement replaced by slag;
S, number after the fibre type—as described for the free shrinkage tests;
C—coconut fibre.

3. Results and discussion

3.1. Free plastic shrinkage

The mean value of two tests results for the free plastic shrinkage of sisal fibre reinforced mortar composites measured at the 5min interval are presented in Fig. 3. For the imposed conditions affecting rapid evaporation of the mix water, shrinkage appears after 130–150min, preceded by a slight swelling. A similar trend was observed in the studies carried out by L'Hermite [27] and Brull et al. [28].

The addition of sisal fibre was quite efficient in restraining the plastic shrinkage of the matrices, the restraint being greater with increasing the fibre volume fraction. For example, the addition of 0.2% of sisal fibre to the matrices PSM1, PSM2, PSM3 and PSM4 reduced their shrinkage by about 30%, 34%, 23% and 24%, respectively. A similar behaviour was observed by Mangat and Azari [29] for steel fibre reinforced concrete. The fibres provide restraint to the sliding of the matrix through frictional resistance.

Keeping the water/cement ratio constant the increase in the aggregate content from 1:1 to 1:2 reduced the plastic shrinkage strains of the material by about 13% (see curves A, F and D, H of Fig. 3). For the same cement:sand ratio an increase of the water/cement ratio from 0.45 to 0.5 increased the plastic shrinkage of the material by about 9,5% (see curves A, D and F, H of Fig. 3). A comprehensive statistical analysis of the plastic shrinkage results based on factorial design of experiments has been presented in Ref. [15].

3.2. Restrained plastic shrinkage

The crack opening patterns at early ages observed in the plain mortar specimens along the fixed bars are presented in Fig. 4(a). The first cracks appeared at two diagonal corners along bars 2–4 and 3–5 of the core,

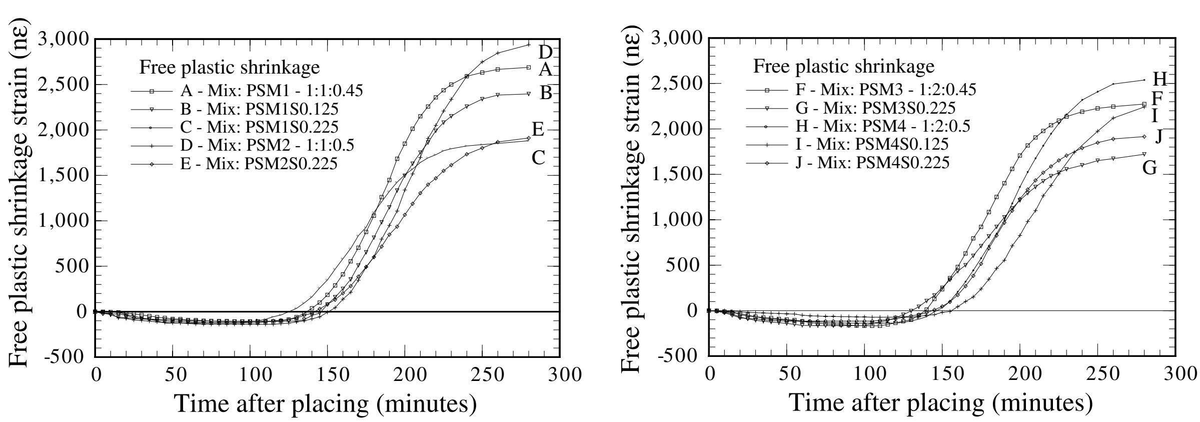

Fig. 3. Free plastic shrinkage of the composites after placing.

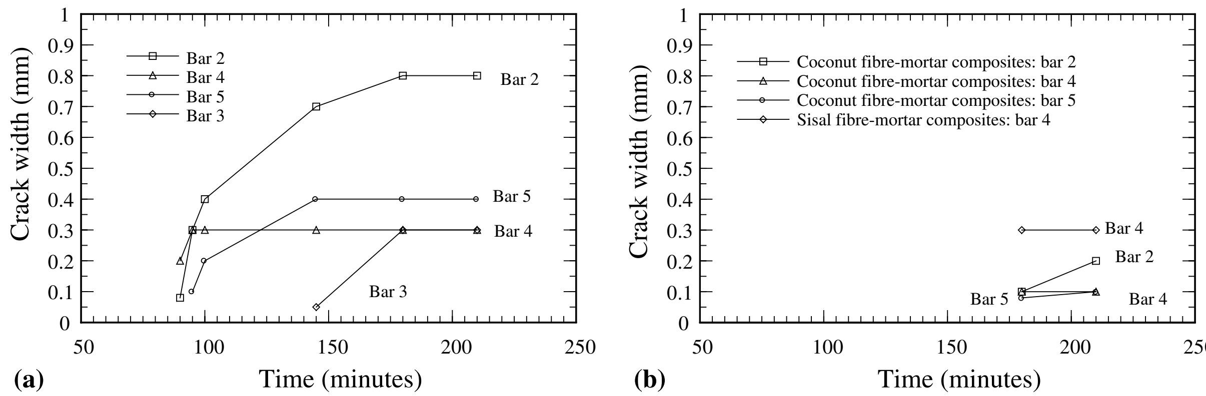

Fig. 4. Restrained shrinkage cracking of the mortar mix (a) and composites (b) at early ages.

90 min after the mix had been placed. After 95 and 145 min, two new cracks appeared. The crack opening widths significantly increased from the time of appearance until 210 min of exposure to the accelerated drying. As an example, it can be seen that the crack in bar 2 increased its width from 0.08 to 0.8 mm after 210 min.

The matrices reinforced with sisal fibres show the first crack appearance at 180 min after the mix has been placed in the mould as can be observed in Fig. 4(b). No further cracks appeared at the specimen. The crack width did not increase within 210 min of exposure to accelerated drying. In the cement mortar composite reinforced with coconut fibre, three cracks appeared in the specimen after 180 min from casting. No further cracks appeared within 210 min. When comparing the results presented in Fig. 4(a) and (b) at 210 min the crack widths are narrower for fibre reinforced specimens than for the plain mortar ones.

The results indicate that inclusion of vegetable fibres was quite effective in delaying the first crack appearance and in reducing the inherent cracking tendency at early age of the matrix. This is most probably attributed to the elastic modulus of the fibres which is higher than that of the cementitious matrix, in addition to the fibres' bridging effect which may prevent the crack opening at early age.

3.3. Self-healing of cracks

To study the self-healing behaviour of the cement mortar and composites reinforced with vegetable fibres the cracked specimens used in the restrained shrinkage investigation were kept at 100% RH and room temperature of 22 °C during 40 days. The healing of cracks for the cement mortar mix is given in Fig. 5(a). Except for bar 3 where the width of the crack reduced from 0.3 to 0.2 mm none of the other cracks closed during this period. The tendency to self-healing of cracks can be observed in Fig. 5(b) for the cement mortar composites.

For the sisal fibre–mortar composite, for example, the 0.3 mm wide crack observed on bar 4 was healed completely after 40 days. A crack width of about 0.05 mm which appeared at the third day in bar 2 was the only one that could be seen on the sample at the age of 40 days. For the composite reinforced with coconut fibres the crack self-healing tendency was also observed. For example, the 0.2 mm wide crack on bar 2 and the 0.1 mm crack on bar 5 were both reduced to

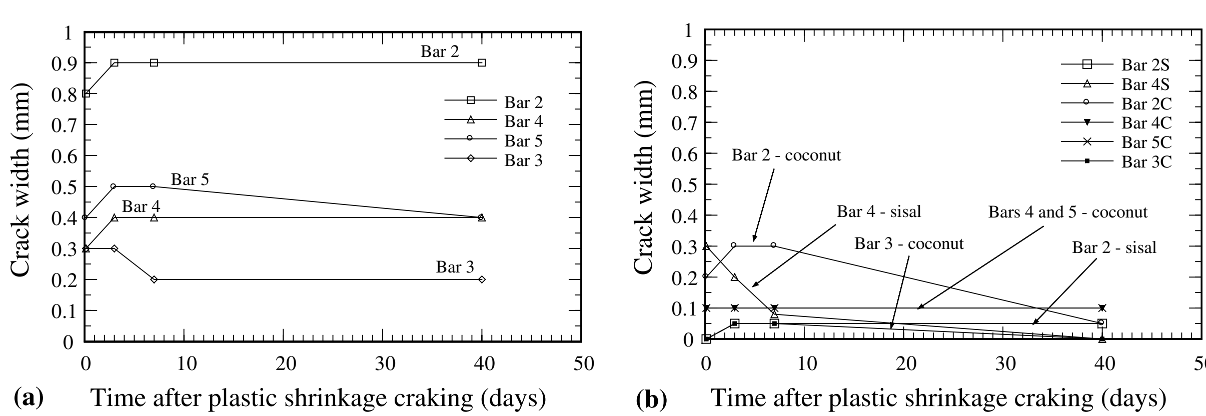

Fig. 5. Self crack healing of the specimens held at a 100% RH up to 40 days. (a) Mortar mix and (b) vegetable fibre mortar composites.

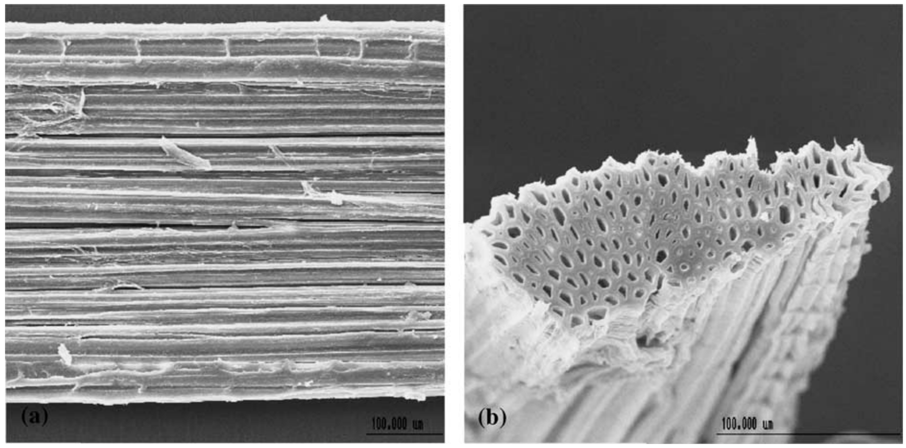

Fig. 6. View of sisal fibre showing the porous nature of its micro-structure. (a) Surface and (b) cross section.

0.05 mm after 40 days. The 0.05 mm crack observed on the third day in bar 3 was closed after 40 days. Both vegetable fibres acted as porous bridging elements across the crack surfaces increasing the flow path and permitting the deposition of new hydration products leading to the closure of cracks. The porous nature of the vegetable fibres can be seen from the results of water absorption presented in Table 1 and from the scanning electron micrograph of the sisal fibre shown in Fig. 6. The higher water absorption of sisal fibre, 230% compared to 100% for coconut fibres, may be the main reason for the rapid healing exhibited by the composites reinforced with the later.

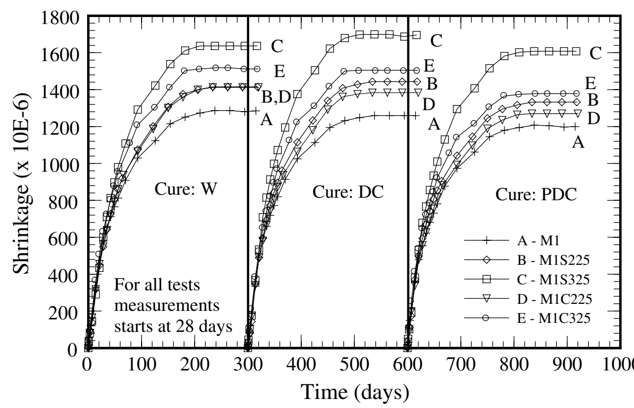

Fig. 7. Influence of fibre type and volume fraction on the drying shrinkage of the matrices.

3.4. Drying shrinkage

3.4.1. Influence of fibre type and volume fraction

The drying shrinkage increases when vegetable fibres are present in the cement matrices. The higher the volume fraction of fibres the greater the drying shrinkage of VFRC. This tendency is observed for all three different initial curing conditions (W, DC and PDC) as it is evident from Fig. 7 where the influence of fibre type and volume fraction on drying shrinkage of matrix M1 is presented. By adding 2% and 3% of sisal fibres the drying shrinkage increases by 10% and 27%, respectively, for the matrix M1 cured in water and dried in the laboratory condition for 320 days. Shrinkage is also influenced by the type of fibre considered. Composites reinforced with 3% of sisal fibres present shrinkage of 8.2% higher than the one reinforced with the coconut fibres after 320 days of drying.

As it is known, the shrinkage of cement matrix mainly is related to the magnitude of its porosity and the size, shape and the continuity of the capillary system in the hydrated cement paste [30]. The addition of the vegetable fibres increase the matrix porosity, therefore contributing to the higher drying shrinkage of the VFRC observed in this work (see Fig. 7). The porous nature of the used fibres at the micro-structure level creates more moisture paths into the matrices which is also confirmed by the mass loss. The mass loss due to drying of water cured VFRC increases by 12% when 3% sisal fibres are added to the matrix M1 as compared with the increases of 4.4% for composites with 2% fibres after 320 days of drying (see Table 4). The same trend occurs for the composites reinforced with coconut fibres but with slightly lower mass loss. The higher shrinkage and loss of mass of VFRC reinforced with sisal fibres are mainly related to their higher water absorption (see Table 1) and less smooth surface as compared to that of coconut fibres.

3.4.2. Influence of mix proportion and Portland cement replacement on VFRC

An increase in the sand content would result in a reduction of shrinkage strain for the same water/cement ratio, in turn for the same sand/cement ratio the increase of water/cement ratio would increase the amount of drying shrinkage [31]. In contrast the addition of the sisal fibres increases the shrinkage of the VFRC as has been

Table 4
Drying shrinkage and loss of mass after 320 days

Mix	Shrinkage (με)			Loss of mass per specimen (g)		
	W	DC	PDC	W	DC	PDC
M1	1285.00	1259.00	1199.17	216.25	208.75	180.00
M1C225	1412.50	1383.33	1270.00	228.75	209.00	189.25
M1C325	1511.67	1505.00	1378.33	235.75	211.50	180.25
M1S225	1416.00	1443.33	1332.50	226.75	209.00	190.75
M1S325	1636.67	1695.83	1607.50	242.25	226.25	210.50
M1slagS225	1541.67	1548.33	1344.17	182.25	166.50	134.50
M1msS225	1420.00	1485.00	1296.67	187.25	177.75	155.75
M2	935.00	911.67	910.00	252.50	225.75	197.50
M2S225	1239.17	1215.00	1174.17	253.00	210.75	200.50
M2slagS225	1345.83	1295.00	1157.50	214.75	190.75	158.50

W = water-cured samples; DC = damp cloth-cured samples; PDC = pressure + damp cloth-cured samples.

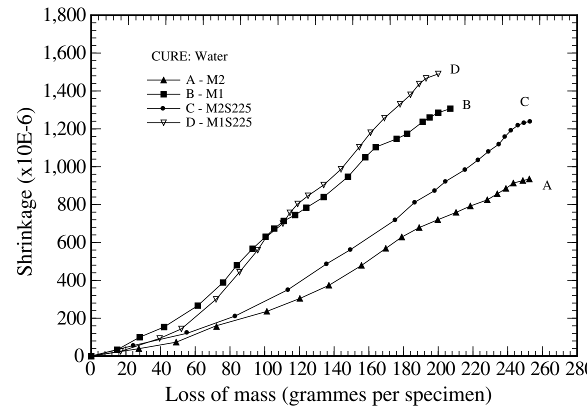

Fig. 9. Shrinkage-loss of mass curves for the mixes M1, M2, M1S225 and M2S225.

discussed in section 3.4.1. The test results for M1, M2 and M1S225, M2S225 has shown that the shrinkage of matrix M1 cured in water was 27% higher than that of matrix M2 and the addition of 2% sisal fibres into the matrix M1 produced 15% higher shrinkage than for matrix M2 (see Fig. 8). This is compatible with the data obtained for the loss of mass measurements, as it is evident from Fig. 9 where for the same mass loss, the shrinkage of mixes M1 and M1S225 is higher than that for the mixes M2 and M2S225. The differences between them are getting larger along the drying period. After 320 days of drying the ratio between loss of mass of M2 to M1 and M2S225 to M1S225 are 1.17 and 1.11 whereas their shrinkage ratio are 0.73 and 0.88 respectively (see Table 4).

To improve the durability of the VFRC the Portland cement was partially replaced by silica fume and blast furnace slag [32]. In this paper only their influence on the drying shrinkage behaviour is presented. The addition of slag and silica fume to the OPC mixes reduced its initial rate of shrinkage. After 150 days the drying shrinkage of the mix M1msS225 was about 80% of that

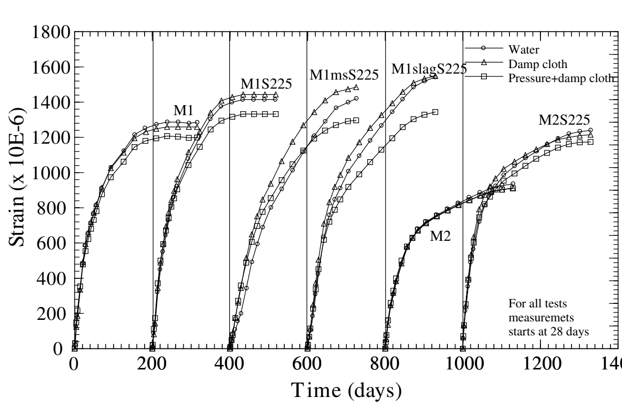

Fig. 8. Influence of initial curing condition and binder on the drying shrinkage of the composites.

observed in M1S225 (see Fig. 8). At the age of 320 days this difference was reduced to less than 3% for the W, DC and PDC curing conditions. However, slag-cement mixes presented after an equal period of time a drying shrinkage up to 9% higher than those observed for the OPC mixes (see Table 4). The slow rate of drying shrinkage of the partially replaced OPC by silica fume is principally related to the pore refinement of the mixture.

3.4.3. Influence of curing condition

For the OPC specimens the shrinkage strain-time curves are nearly coinciding up to the age of 40 days (see Fig. 8). Thereafter, the shrinkage of the PDC specimens showed a lower rate of increase in relation to the other two test series reaching the maximum difference of 8% after 320 days as can be noted in Table 4. The lower shrinkage of the former can be mainly attributed to the reduction of the water/cement ratio due to the squeezing out of water from the mixture during the application of pressure to the specimens. The mass of the W specimens series after curing are almost the same as those of the DC specimens (maximum difference of 1.7%) [14]. A similar trend occurred for the drying shrinkage behaviour of W and PDC specimens after 320 days, with the maximum difference of 3.4% for OPC specimens.

The influence of different curing conditions on the loss of mass-shrinkage of two representative mixtures (M2 and M2S225) of the VFRC presented in Fig. 10 show that water curing method produced higher loss of mass than DC method and in turn the PDC presented higher values than the later one. For example, after 320 days of drying the specimens series W of mixture M2 lost 252.5 g whereas the specimens series DC lost 225.75 g (see Table 4) but this higher loss of mass of W series specimens caused almost no extra shrinkage. The shrinkage of mixture M2 is plotted against the normalised loss of mass (mass loss of time/final loss of mass) in Fig. 10 part (a), where it can be observed that up to a normalised loss of mass of 0.12 there is no

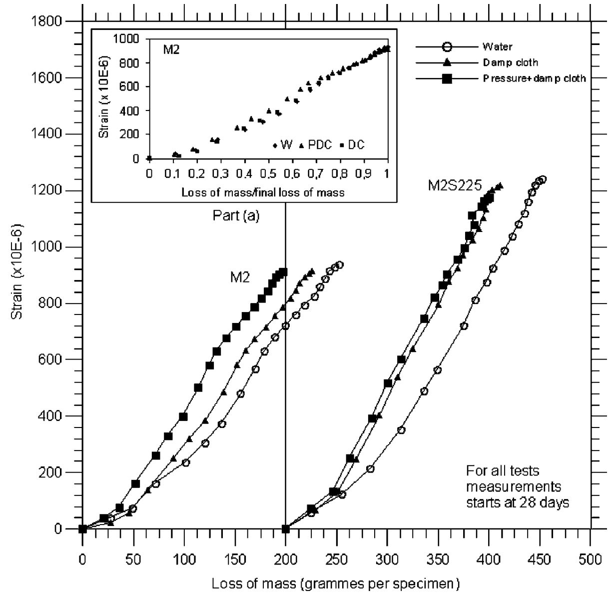

Fig. 10. Influence of different initial curing condition on the loss of mass–shrinkage curve for mixes M2 and M2S225.

shrinkage. This is because up to this stage the loss of mass is mainly due to removal of free water. After this period there is a nearly linear relationship between drying shrinkage and normalised loss of mass.

3.4.4. Modelling the drying shrinkage of vegetable fibre–mortar composites

The well known B3-model described in ACI 209 [33] was adapted by including the coefficient κ_f which considers the influence of fibre volume fraction (V_f) and its aspect ratio $\left(\frac{L_f}{\phi_f}\right)$ on the matrix shrinkage. The influence of the type of the vegetable fibres was introduced through the coefficient β_f which were established to be $\beta_f = 0.7 \times 10^{-6}$ for sisal fibre and $\beta_f = 2.0 \times 10^{-6}$ for coconut fibre for the experimental data presented in this paper. Modified equations (1) and (2) are proposed to predict the shrinkage behaviour of the OPC composites of series W.

$$\varepsilon_{sh}(t, t_0) = -(\kappa_f \varepsilon_{sh\infty})(1 - h_e^3) \tanh \sqrt{\frac{t - t_0}{\tau_{sh}}}, \tag{1}$$

$$\kappa_f = \beta_f \left(V_f \frac{L_f}{\phi_f} \right)^2 + 1, \tag{2}$$

where $\varepsilon_{sh}(t, t_0)$ is the shrinkage strain for $t - t_0$ duration of drying which started at t_0 = 28 days; $\kappa_f \varepsilon_{sh\infty}$ is the final value of the shrinkage strain; κ_f, given by Eq. (2), is a coefficient that introduces the influence of fibre reinforcement on the matrix shrinkage; h_e is the environmental relative humidity (expressed as a decimal number; not as percentage); $0 \leqslant h_e \leqslant 1$. The $h_e = 0.41$ was registered during the experimental investigation; τ_{sh} is the shrinkage half-time in days; β_f is a coefficient depending on the type of the fibre; V_f, L_f and ϕ_f are, respectively, the fibre volume fraction, fibre length and fibre diameter.

The $\varepsilon_{sh\infty} = 0.00155$ and τ_{sh} = 115 days were obtained from the experimental results. The predicted and measured shrinkage strains presented in Fig. 11 show a satisfactory result. More data need to be obtained to confirm and improve the proposed relation.

4. Conclusions

Free plastic shrinkage is significantly reduced by the inclusion of 0.2% volume fraction of 25 mm short sisal fibres in cement mortar. An addition of 0.2% volume fraction of 25 mm sisal and coconut fibres delays the initial cracking for restrained plastic shrinkage and effectively controls crack development at the early age of composite. The presence of sisal and coconut fibres

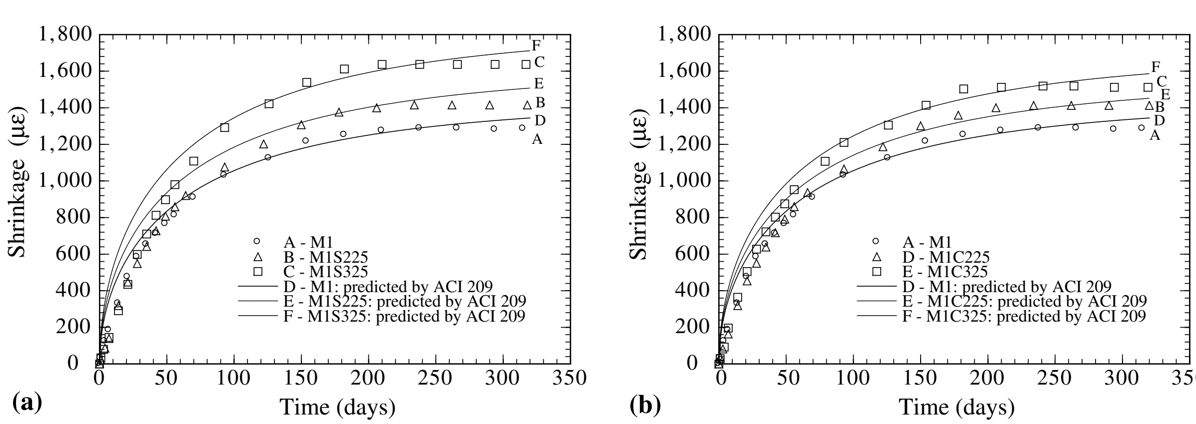

Fig. 11. Comparison of measured and predicted drying shrinkage for the OPC composites of series W. (a) Sisal fibre mortar composites and (b) coconut fibre mortar composites.

promotes an effective self-healing of plastic cracking after 40 days at 100% RH.

The drying shrinkage is increased by up to 27% when up to 3% volume fraction of sisal or coconut fibres is present. The curing conditions influence both the initial rate of the drying and the ultimate values of shrinkage. Application of a initial pressure (PDC series) reduces subsequent drying shrinkage by about 8% as compared to normal water curing. Mainly due to an increase of water content during the curing period, the weight loss is greater for water-cured than for damp cloth cured specimens. A long-term drying shrinkage remains essentially similar. The addition of slag and silica fume only decrease the initial rate of the drying shrinkage. During longer time spans this effect is absent or becomes reversed. The shrinkage strains per unit weight loss during the drying process are greater for specimens containing slag or silica fume than for those made of normal Portland cement mortar.

The modified B3 model predicts the drying shrinkage of the composites satisfactory. More data need to be obtained to confirm and improve the proposed relation.

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