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On the Strengthening of Cement Mortar by Natural Fibers

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The purpose of this work is to evaluate mechanical behavior of sisal fiber reinforced cement mortar. The composite material was produced from a mixture of sand, cement and water. Sisal fibers were added to the mixture in two different lengths. Mechanical characterization of the composite and the plain mortar was carried out using three point bend, compression and impact tests. Specimens containing parallel sided notches of different root radii were loaded in three point bending in order to determine the effect of the fibers on the material fracture toughness in the presence of discontinuities. According to the results, while fiber reinforcement leads to a decrease in compressive strength, J-integral calculations at maximum load for the different notch root radii have indicated, particularly for the case of long fibers, a significant superiority of the reinforced material in comparison with the plain cement mortar, in consistence with the impact test data.

Keywords: *composite material, impact energy, fracture initiation, J-integral*

1. Introduction

It is well known that the presence of short randomly dispersed fibers in a cementitious matrix can result in an appreciable improvement in the mechanical behavior of the produced composite. This improvement is clearly manifested by the significant superiority of the composite's toughness in comparison with that of the plain matrix. The increase in toughness, due to the incorporation of fibers, can be attributed, largely, to the fiber bridging mechanism, whereby the fibers take an active part in supporting tensile loading, in controlling matrix microcracking and in reducing the rate of crack propagation. The fiber reinforced concrete will, therefore, exhibit a pseudoductile behavior, maintaining considerable load carrying capacity after cracking of the matrix.

Different types of fibers, both metallic and nonmetallic, have been used as reinforced elements in cementitious matrices. More specifically, a number of investigations[1-4] were conducted using randomly dispersed short steel fibers, polymeric fibers and hybrid combinations of both. One could verify that the presence of fibers in, for example, high strength concrete resulted in enhancing both its flexural strength and toughness. This was attributed to energy absorbing mechanism (bridging action) and to delay in microcrack formation[1].

Environmental awareness and an increasing concern with greenhouse effect have stimulated several industries to look for sustainable substitutes that can replace conventional synthetic fibers. In this respect, natural fibers seem to be a good alternative to steel and polymeric fibers since they are readily available in fibrous form and can be easily extracted from their proper plants at very low cost[5]. Further, their adoption as reinforcing elements is also associated with overall reduction in CO_2 emissions as well as reduced amounts of energy needs[5].

Starting early seventies, a number of studies[6-10] have been made regarding the use of natural fibers, such as sisal and bamboo, as reinforcing elements in cement mortars and in concretes. The focus in these works has been on the evaluation of the mechanical properties of the resulting composites as a function of the characteristics of their constituents, and the results obtained have indicated the viability of using natural fibers as reinforcing agents. Cement composite laminates reinforced with long sisal fibers, manufactured using a cast hand lay up technique, were found to exhibit high energy absorbing capacity reflected in high toughness values under tension and bending loads[11]. Ultimate strength, on the other hand, achieved average levels of 12 and 25 MPa for tensile and bend loading, respectively[11].

It can thus be stated that, despite a tolerable degradation in their compressive strength, flexural strength and fracture toughness of the reinforced composites were significantly enhanced due to the presence of natural fibers, consistent with experimental data reported by Abu-Lebdeh and co-authors[3]. It is to be noted, though, that the susceptibility of natural fibers to degradation, due to ambient and biological factors, requires appropriate surface treatment in order to improve their durability. For example, long

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term embrittlement can be markedly reduced by immersing sisal and coconut fibers in a silica fume slurry prior to their incorporation by the cementitious matrix[12]. Long term properties of the treated specimens were thus found to be very proximate to those of 28 days untreated apecimens[12].

In view of their numerous advantages, natural fiber reinforced composites have been considered as potential candidates for structural applications, such as low cost residential compounds in developing countries. Structural components are expected to support the applied loads without suffering critical or subcritical fracture during their projected lifetime, and since the presence of discontinuities (notches and cracks) can lead to premature failure, the cement base composite should be tolerant to such defects. The notch sensitivity exhibited by a given material depends on its toughness level and this in turn can be expressed by appropriate parameters such as the value of the J-integral at physically significant events (for example, fracture initiation and maximum load attainment). Higher toughness signifies lower notch sensitivity; however, one should point out that toughness level depends on the notch geometry, particularly the notch root radius.

The present work was initiated with the purpose of evaluating the effect of sisal fibers on the compressive strength and fracture resistance of hardened cement mortar. As the presence of natural fibers is generally detrimental to the compressive strength, it is imperative to strike a good balance of properties, so as to guarantee adequate toughness level together with acceptable compressive strength. For evaluating the fracture toughness, the J-integral approach was adopted and specimens containing deep notches of different root radii were cast in appropriate molds, cured and then loaded in three point bending. The J-integral values at maximum load were determined and correlated with the notch root radius, for both plain and reinforced mortars. Finally, the J-integral results are also correlated with the impact energy of unnotched prismatic bars having the Charpy dimensions.

2. Material and Methods

The mortar mixture used in the present study was composed of Portland cement PC 32, washed dry sand and tap water, in the proportions of 1:1: 0.4, respectively. The sand had fineness modulus of about 3.33, a maximum particle size of 2 mm and an apparent density of 1.6 g/cm³.

As to the production of the reinforced mortars, 25 and 45 mm long sisal fibers, amounting to 3% of the combined weight of cement and sand, were thoroughly dispersed throughout the dry mixture before water was gradually added. The fibers had an average specific weight of 9.1 kN/m³ and average mechanical properties of 400 MPa tensile strength, 4% elongation and 18 GPa elastic modulus[5].

The mixing process resulted in a homogeneous pulp which was cast in appropriate molds for compression and bend test specimens. Twenty four hours later, the specimens were taken off the molds and then immersed in water for 35 days. The hardened specimens of the reinforced mortars had a fiber volume fraction of about 0.081, corresponding to the quantity of fibers incorporated by the matrix.

Compressive strength of the mortars in question was determined using cylindrical specimens (50 mm in diameter and 100 mm in length) which were loaded at room temperature (23 °C) in a universal testing machine with a cross-head speed of 10^{-5} m/s.

The fracture resistance of the mortars was evaluated making use of notched prismatic specimens (50×50×300 mm) which were submitted to three point bending, with 270 mm loading span. The bend test was carried out at room temperature at a cross head speed of 2×10^{-5} m/s and load-displacement (P-δ) curves were obtained for both plain and reinforced mortars. The bend specimens contained a 25 mm deep parallel sided notch with 0.5, 1, 1.5, 2 and 2.4 mm root radius. Unnotched specimens with a geometry identical to that of the notched bars were also tested in three point bending.

Impact testing was carried out on unnotched prismatic specimens (10×10×50 mm), using a low capacity Charpy type impact machine appropriate for low toughness brittle materials.

3. Results and Discussion

3.1. Compressive strength

Plain mortar specimens loaded in compression suffered a highly unstable mode of failure, whereas the fiber-reinforced mortars exhibited a more stable behavior, characterized by larger deformations with a gradual drop in the applied load. This increased capacity for deformation can be attributed to the interfacial bond between the sisal fibers and the cement mortar matrix.

The values of the compressive strength were calculated from the ultimate load and are presented in Table 1, for the three mortars in question.

From this table it can be verified that the presence of sisal fibers has a deleterious influence on the strength level. Moreover, this influence turns out to be more significant for the long fibers in comparison with the shorter ones. This can be attributed to a decrease in the mortar's density, associated with an increase in its porosity[10-13]. However, it should be mentioned that the specimen integrity was preserved over a wider deformation range in the presence of longer fibers.

To a first approximation, the ultimate compressive strength of the composite can be estimated from the relation

$$\sigma_C = V_M \, \sigma_M \tag{1}$$

where σ_C and σ_M are respectively the composite and matrix strength and V_M the matrix volume fraction given by

$$Vm = (1 - Vf) \tag{2}$$

where V_F is the fiber volume fraction.

Table 1. Compressive strength of the plain and reinforced mortars.

Mortar	Compressive Strength (MPa)
plain	28 ± 1
reinforced with 25 mm sisal fibers	25 ± 1
reinforced with 45 mm sisal fibers	22 ± 1

The validity of Equation 1 is derived from the hypothesis that the fibers do not play an active role in supporting compressive loads applied to the composite. Accordingly, for the sisal fiber volume fraction of 0.081, σ_C is estimated to be about 25.7 MPa, which is close to the compressive strength level of 25 MPa experimentally determined for the mortar containing the 25 mm fibers. However, for the long fibers (45 mm), the lower compressive strength of 22 MPa listed in Table 1 does not agree well with the strength level estimated by Equation 1, indicating that higher porosity can be associated with the incorporation of such fibers.

3.2. Flexural strength

As expected, the use of sisal fibers as reinforcing element resulted in a significant increase in the load carrying capacity of the unnotched bend specimens. The ultimate load values, corresponding to the average of three bend tests, amounted to 1.5, 2.2 and 2.5 kN, for the plain, 25 mm and 45 mm fiber reinforced mortar, respectively. Considering the specimen geometry and dimensions, the maximum flexural stress σ, within the linear elastic loading regime, can be related to applied load P as

$$\sigma = 3.24\, P \qquad\qquad\qquad (3)$$

where P is in kN and σ in MPa.

Equation 3, which is based on the theory of beams, can be applied to the plain mortar, as it behaves essentially in an elastic manner, yielding a flexural strength level of about 5 MPa. To a first approximation, the same equation may also be applied to the fiber reinforced mortars, resulting in strength levels of about 7 and 8 MPa, for the 25 and 45 mm fiber reinforcement, respectively. These values are considered to be rough estimates, in virtue of the nonlinear behavior that precedes the ultimate load achieved by the fiber reinforced bend specimens. Accordingly, one may be able to conclude that the reinforced mortar can achieve a flexural strength level, representing a 60% improvement over the plain matrix of similar formulation. A common theme in the literature[14-15] refers to the notion that fibers serve as bridging elements when crack traverses the cement matrix, thus maintaining the specimen integrity and allowing the ultimate load and deformation capacity to increase.

The strengthening effect due to fiber presence is also related to the interfacial bond between the fibers and cement matrix, which allows the former to take an active part in supporting the applied load. Sisal fibers present irregular cross section with different shapes that may be beneficial for the bond strength. Three different cross sectional geometries were reported in the literature[16]: horse-shoe, arched and twisted arch shape, with the highest bond stress related to the twisted arch fiber type. Average adhesional bond for all three cross sectional geometries is reported to be in the range of 0.59 to 0.67 MPa[16].

Macro and micro fracture aspects of fiber reinforced bend specimens are presented in Figures 1 and 2. As depicted in Figure 1, fracture mode of the fiber reinforced bend specimens is characterized by a pull-out failure mechanism. This figure refers to the profile of a 45 mm fiber reinforced specimen, showing the sisal fibers as exposed due to fiber pull-out. Figure 2, on the other hand, presents the fracture surface features of a 25 mm fiber reinforced bend specimen, also attesting to the pull-out phenomenon as a dominant mode of failure. At this point, it is important to mention that the pull-out force increases as the embedded fiber length increases[16], which is seen to be consistent with the fact that long (45 mm) fibers are more effective in promoting flexural strength than the 25 mm fibers.

3.3. Fracture resistance

Examples of the load-displacement curves obtained in three point bending of the composite mortar are presented in Figure 3, for the different notch root radii. The load-displacement curves corresponding to the plain and reinforced mortars are depicted in Figures 4, 5 and 6, for the 0.5, 1.5 and 2.4 mm root radii, respectively, indicating the marked influence of the presence of sisal fibers on both load carrying capacity and deformability of the notched specimens.

The variation of the maximum load, P_U, with the notch root radius, ρ, is presented in Figure 7, for the mortars in question. Compared to their respective unnotched counterparts, the notched specimens had a much lower load
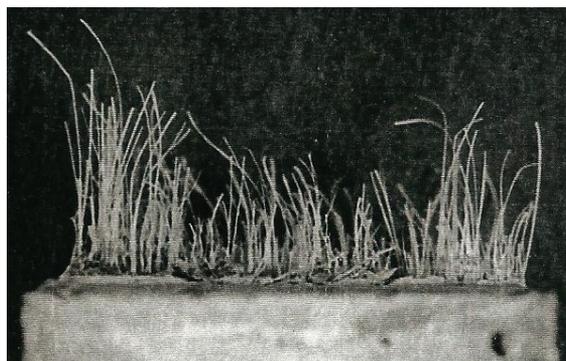

Figure 1. Fracture profile of a 45 mm fiber reinforced specimen.

Figure 2. Fracture surface of a 25 mm fiber reinforced bend specimen.

carrying capacity, as a result of the significant reduction of the specimen cross section in the notch plane. As to the influence of the notch root radius, Figure 7 indicates that P_U decreases as the notch becomes sharper and that, for a given root radius, the incorporation of the sisal fibers is associated with an appreciable increase in the load carrying capacity, with the long fibers being more effective in that respect. This is seen to be consistent with the results obtained on the flexural strength of unnotched beams, as sisal fibers contribute significantly to the tensile strength and more effectively so for longer fibers in virtue of the increase in the interfacial force, between fibers and matrix, with the increase in fiber length.

3.3.1. Toughness estimation

The J-integral values at maximum load (J_M) were calculated from the integrated energy (U) under the load-displacement curve, using the Rice estimation formula[17].

$$J = \frac{2U}{B(W-a)} \tag{4}$$

where B and W are the specimen cross sectional dimensions (50 x 50 mm), a the notch depth (25 mm) and U the integrated energy under the P-δ curve up to $P = P_U$.

At this point, it is important to mention that toughness evaluation of concrete using fracture mechanics is considered to be applicable to large scale initially cracked structures[18-19], where structural aspects, such as the size of coarse aggregates, are to be small compared to the concrete size. Thus, the effect of specimen size should be considered in determining the fracture toughness of concrete. For the mortars considered in the present study, the relevant microstructural scale, which is related to the

sand used as aggregate, is in fact very small in comparison to the bend specimen dimensions. Accordingly, Equation 4 is considered to be applicable to toughness determination of cement mortar.

The variation of J_M with the root radius is shown in Figure 8, for the plain mortar. One can observe that such a variation is in agreement with the effect normally detected
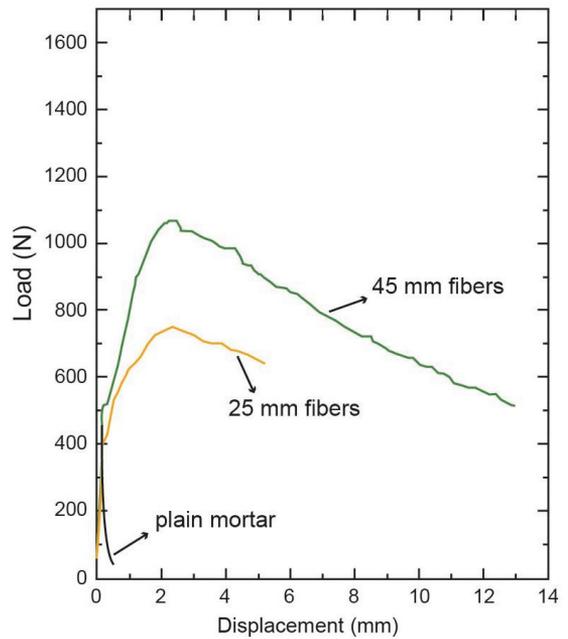

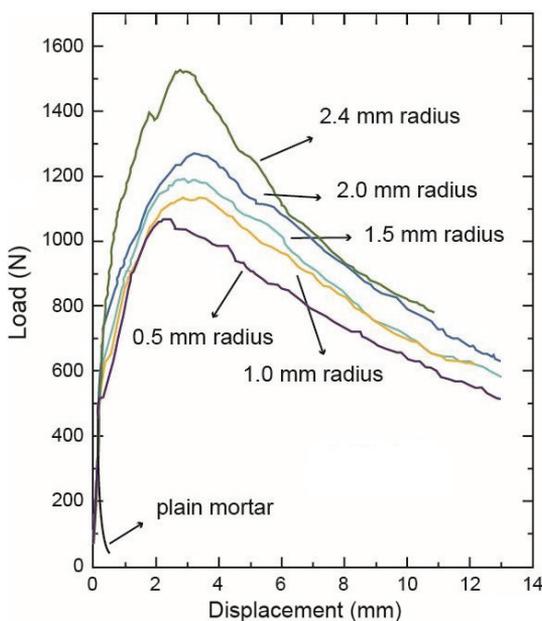**Figure 4.** Mortars' load-displacement curves in three point bending for 0.5 mm root radius.

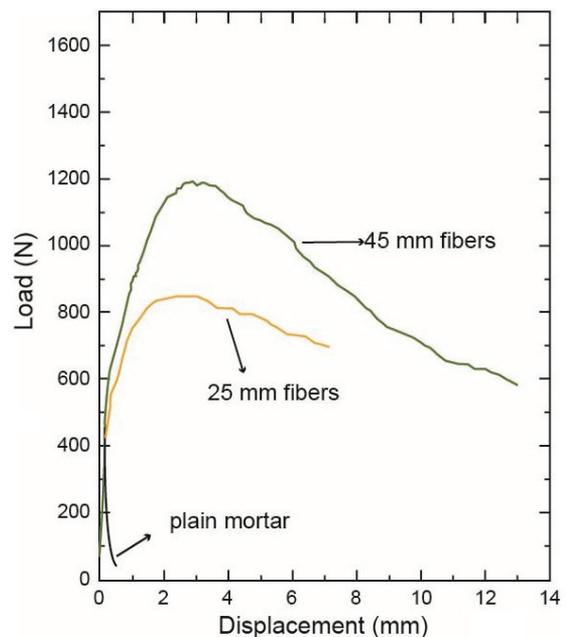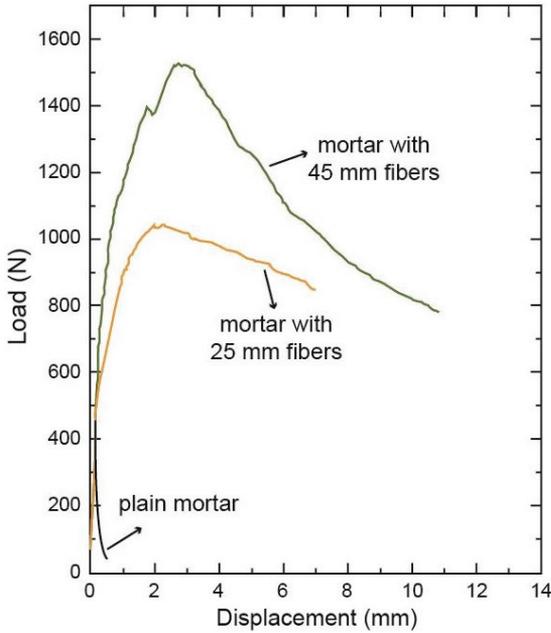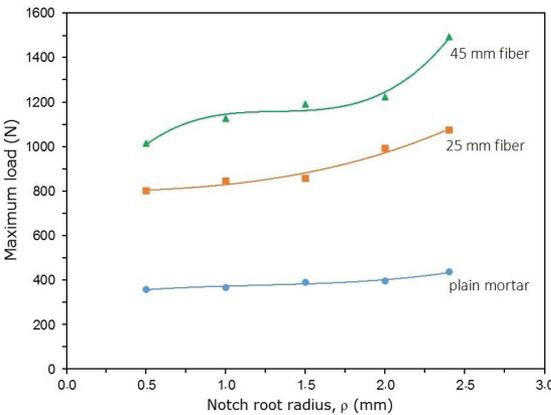**Figure 3.** Load-displacement curves of the 45 mm fiber composite mortar.

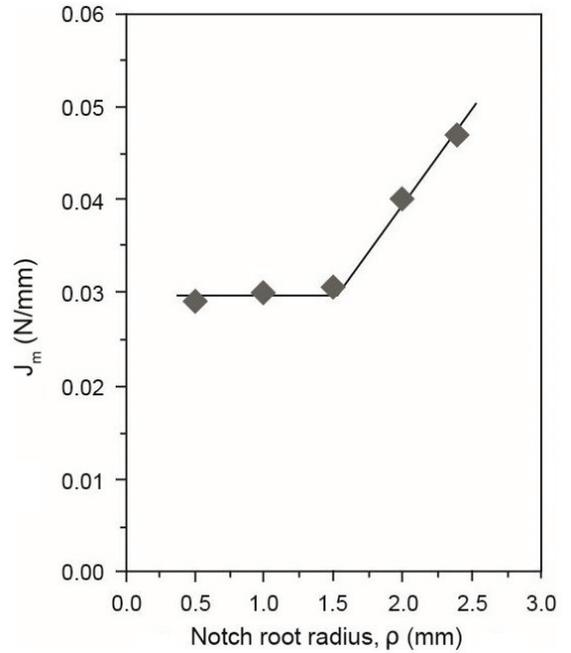**Figure 5.** Mortars' load-displacement curves in three point bending for 1.5 mm root radius.

Figure 6. Mortars' load-displacement curves in three point bending for 2.4 mm root radius.

Figure 8. Variation of J_M with the notch root radius for the plain mortar.
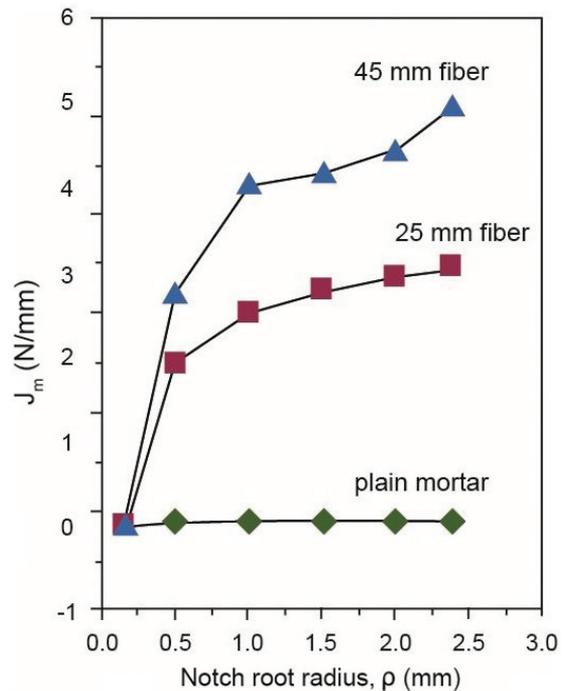

Figure 7. Influence of the notch root radius on the maximum load for the different mortars.

for metallic and nonmetallic materials, where the J-integral value at fracture initiation varies linearly with the root radius. As fracture initiation in the plain mortar occurs essentially at the maximum load, J_M can, therefore, be considered a good estimate of the J-integral value corresponding to the event of failure initiation in the mortar. For small root radii ($\rho \leq 1.5$ mm), though, J_M becomes independent of ρ, remaining at a constant level discriminated as J_{IC} and considered as a material characteristic. The limiting root radius, which is equivalent approximately to 1.5 mm, is also considered a material constant of microstructural significance, apparently compatible with the fact that the sand, used as a constituent of the mortar mixture, had a maximum particle size of 2 mm.

As to the reinforced mortars, the variation of J_M with the notch root radius is presented in Figure 9, for both the 25 and


Figure 9. Variation of J_M with the notch root radius for the plain and reinforced mortars.

45 mm sisal fibers, in comparison with the J_M level of the plain mortar. In addition to the extremely beneficial effect of fibers on the mortar's fracture resistance expressed by J_M, the figure also indicates that a better fracture resistance of the mortar was associated with the use of 45 mm sisal

Table 2. Impact energy of the plain and reinforced mortars.

Mortar	Impact energy (J)
plain	0.45 ± 0.05
reinforced 25	2.04 ± 0.22
reinforced 45	3.28 ± 0.35
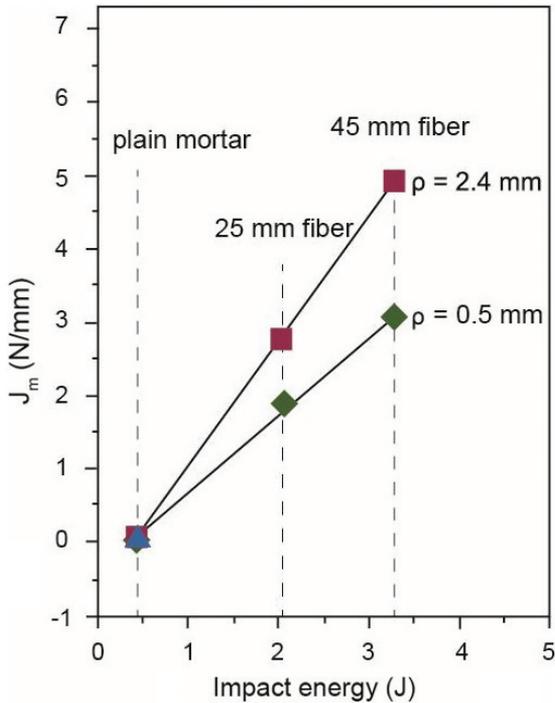
Figure 10. Correlation between J_M and impact energy for the reinforced mortars with notch root radius of 0.5 and 2.4 mm.

fibers. The beneficial effect on toughness is the result of an improvement in both strength and ductility of the mortar due to sisal fiber presence and as can be verified from the P-δ curves, this effect is more pronounced for the longer fibers.

The impact energy results are presented in Table 2, for the three mortars in question. The individual energy levels shown in the table correspond to the average of five tests with a standard deviation of about 12%.

The analysis of Table 2 leads to conclude that the use of sisal fibers as a reinforcing element in mortar results in a considerable increase in the impact resistance and that such an increase is considerably more significant for the longer fibers. Results obtained by Ramakrishna and Sundararajan[20] have shown that the addition of natural fibers to cement mortar slab can increase its impact resistance by a factor ranging between 3 and 18. This beneficial influence is attributed to the fact that, even as the matrix cracks, the load carrying capacity is replenished by invoking fiber loading. This maintains the specimens' integrity as they continue to deform and hence to absorb more energy. The superiority of long fibers in promoting impact resistance is related to the higher load carrying capacity, as well as deformability, of the mortars reinforced with such fibers.

The correlation between the impact energy levels and J-integral results is presented in Figure 10, whereby an essentially linear relationship is seen to exist between the two parameters.

4. Conclusions

Regarding the study described herein, the following conclusions can be drawn:

- The use of sisal fibers decreases the mortar's compressive strength. However, the fiber reinforced mortars exhibit retardation of the failure process, characterized by larger deformations and gradual drop in the applied load, when compared with the plain mortar.
- The deleterious influence of sisal fibers on the compressive strength of reinforced mortar seems to be more significant for long fibers than for shorter ones.
- The presence of sisal fibers in cement mortar considerably improves its fracture resistance. This improvement is manifested by an increase in the J-Integral values determined at maximum load in the presence of deep notches with different root radii.
- Results of impact tests on unnotched specimens indicate a pronounced improvement in impact energy levels due to sisal fibers incorporated to cement mortar.
- Longer sisal fibers are seen to be more effective than shorter ones in promoting fracture resistance of reinforced mortars.

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