CHAPTER 5

CONCLUSIONS

5.1 GENERAL

In this chapter, salient conclusions, based on the extensive experimental investigations carried out and the comprehensive discussion on the rheological, strength and durability characteristics of sisal fibre cementitious composites, are presented. The relative performance of the sisal fibre roofing sheets, has also been highlighted. A few specific recommendations based on overall assessment / usefulness of the present study, are also given.

5.2 CONCLUSIONS

Salient conclusions, based on the comprehensive experimental investigations carried out and on the range of various parameters considered in the present study, are summarized below.

5.2.1 Salient Fibre Characteristics

(1) The maximum water absorbed by sisal fibres is about 160% and that saturation capacity has reached at the end of six hours itself. The above percentage of water absorption is found to be higher than the reported value for Brazilian sisal fibres. However, the resulting problem is overcome by adopting suitable mixing procedure to produce composites.

(2) ‘Water retention capacity’ of sisal fibres as evident from the results of ‘alternate wetting and drying’ test, is negligible.

(3) There is no change in the diameter of the fibre and hence in the volume of the fibre, when the fibres are subjected to ‘alternate wetting and drying’.

5.2.2 Flyash Characteristics

(1) Flyash obtained from ‘lignite ash’ source and used in this study, has substantial quantities of fine particle below 75 and 45 microns.

(2) Flyash used, mainly composed of silica, alumina, iron oxides and calcium oxide (CaO). The presence of CaO exceeding 10%, makes it to exhibit ‘ self hardening’ property during early age and ‘pozzolanic property’ during later – ages.

5.2.3 Workability of Sisal Fibre Composites

(A) At Various Aspect Ratios (r = 0 -300)

1. ‘Mobility’ of the mortar composite, in general, is impaired by incorporation of sisal fibres and that there is a desirable aspect ratio (of sisal fibres), beyond which, the mobility of the mortar composites is drastically affected and hence not desirable from practical considerations.
2. Influence of the aspect ratio and fibre content on the ‘mobility’ determined in terms of flow values of all sisal fibre cement mortar composites (1:3 1:4 and 1:5), is similar over the range of the above parameters considered. However, reduction in mobility in terms of flow values for the highest aspect ratio (i.e.200 – 300) and highest fibre content (i.e. 2%) for 1:4 and 1:5 sisal fibre mortar composites, are nearly 40% of 1:3 mortar composites.

3. Maximum fibre content that can be used in the sisal fibre cement mortar composite, in case, it is intended to achieve atleast 50% of the mobility of the reference mortar, then, (i) aspect ratios less than 65 and upto 1.0% of sisal fibres or a maximum fibre content of 0.5%, for aspect ratios greater than 65 for 1:3 composites; (ii) the entire range of fibre contents and aspect ratios considered in this study, for 1:4 and 1:5 composites, are recommended to be adopted.

4. Linear regression relationships obtained for all sisal fibre cement mortar composites and aspect ratios ranging from 0 -300, will help to select proper aspect ratios and fibre contents, considering the ‘mobility’ of the composites.

(B) At Constant Aspect Ratio (r = 200)

5. There is additional demand for water due to incorporation of flyash, to achieve a particular flow value, for the cementitious mortar. The above phenomenon is found to be independent of the range of flow values considered. It is found that the increase in W/B ratio at maximum flyash content (i.e. 70%) in the mortar, is about 40%, 40% and 35%, higher than the W/B ratio of reference mortar, over the range of flow values (i.e. 50 -120) and the mortar mixes (1:3, 1:4 , and 1:5, respectively), considered.

6. Flow behaviour of 1:3, 1:4 and 1:5 sisal fibre cement mortar composites are similar, under constant aspect ratio (= 200). W/B ratio required for a desired flow value is ‘insensitive’ at low fibre contents (i.e.0.5%) and beyond that becomes ‘sensitive’. The above phenomenon is independent of the range of flow values considered.

7. Increase in W/B for cement mortar composites (1:3 ; 1:4 and 1:5; r = 200) is primarily due to incorporation of sisal fibres in the cement mortar. There is an increase of about 17% in the W/B ratio of 1:3 cement mortar, at maximum fibre content (i.e.2.0%) to achieve a desired flow.

8. Leaner sisal fibre cement mortar composites (1:4 and 1:5; r = 200) require about 30% increase in W/B ratio over the corresponding reference mortar, at maximum fibre content (i.e. 2.0%) to achieve a desired flow. In other words, the leaner cement mortar composites, require about 70% increase in W/B ratio over 1:3 sisal fibre cement mortar composites, at maximum fibre content, to achieve the desired flow values.

9. There is a ‘cumulative demand’ for additional water, due to incorporation of flyash and sisal fibres in the cementitious composites (1:3; 1:4 and 1:5; r = 200), for a desired flow value. The above phenomenon is found to be valid for the range of parameters considered.

10. W/B ratio required to achieve a particular flow value is maximum, when the sisal fibre content and flyash content in the cementitious mortar composites (1:3; 1:4 and 1:5; r = 200) are maximum (within the ranges considered). The average
percentage increase in W/B ratio, under the above conditions is about 47% for 1:3 cementitious composites, over the corresponding reference mortar, which is quite substantial.

11. Leaner sisal fibre cementitious mortar composites (1:4 and 1:5; r = 200), require about 76% and 84% increase in maximum W/B ratio over the corresponding reference mortar, to achieve a particular flow value, under identical parameters and conditions. In other words, there is an average increase of 60 - 80% maximum W/B ratio over 1:3 cementitious mortar composites (i.e. richer composites), under identical conditions.

5.2.4 Rheology of Sisal Fibre Composites

(A) At Various Aspect Ratios (r = 0 - 300)

1. Rheological behaviour of the cementitious mortar / composite i.e. ‘cohesion’ – which is a measure of the ‘stability’ of the mortar / composite, bears an ‘inverse relationship’ with that of ‘flow value’ – which is a measure of ‘mobility’, over the range of fibre contents and aspect ratios considered.

2. Influence of fibre contents and aspect ratios on the ‘stability’, determined in terms of ‘cohesion values’ of all sisal fibre cement mortar composites (1:3, 1:4 and 1:5), is similar, over the range of the above parameters considered.

3. Higher cohesion values are obtained when the sisal fibre content in the cement mortar composite is higher, for all aspect ratios considered. Maximum cohesion values of 1:3, 1:4 and 1:5 cement mortar composites are almost equal and it is about 140 kPa and attained at identical aspect ratio (i.e. 200 – 300) and fibre content (i.e. 2.0%) of the composite.

4. Highest cohesion value obtained for the 1:3 cement mortar composite is about 4.4 higher than the cohesion values of the corresponding reference mortar. Even though, similar behaviour is exhibited by leaner mixes (i.e. 1:4 and 1:5 cement mortar composites), they have gained 6 and 8 times the cohesion values of the corresponding reference mortar. In other words, leaner mixes have gained higher cohesion, when compared to the rich mix (1:3), due to incorporation of sisal fibres, over the respective reference values of corresponding plain mortar.

5. Linear regression relationships obtained for all sisal fibre cement mortar composites and covering the range of aspect ratios 0 - 300, will help to select proper aspect ratios and fibre contents, considering the ‘stability’ of the composites.

(B) At Constant Aspect Ratio (r = 200)

6. Rheological behaviour of ‘stability’ in terms of cohesion values of flyash – cement mortar (1:3, 1:4 and 1:5), with respect to flow values, flyash content in the mortar mix and maximum cohesion value for a chosen flow value, are similar, under identical condition.

7. Incorporation of flyash has contributed to the improvement in the ‘stability’ i.e. cohesion values of cementitious mortar and that there is an increase of about 2.5 times in the cohesion value of the cementitious mortar, at maximum flyash content (i.e. 70%) and the range of flow values considered. The above phenomenon is found to the same for all the mortar mixes considered.
8. Incorporation of sisal fibres in cement mortar composites has contributed to substantial enhancement in the cohesion values, irrespective of mortar mixes considered. Cohesion value of the composite is maximum when the sisal fibre content is maximum. The above phenomenon is found to be independent of the range of flow values and mortar mixes considered.

9. In terms of percentage increase, the cohesion values at maximum sisal fibre content in the cement mortar composite ranges from about 30 – 180%, over the range of flow values considered and the cohesion values of respective reference mortar (i.e. 1:3, 1:4 and 1:5).

10. Cohesion values of the cementitious mortar composites are maximum, when the sisal fibre content in the composite is also maximum, for the range of flyash contents considered. The above phenomenon is found to be independent of flow values considered and also similar for all the mortar mixes (1:3, 1:4 and 1:5), considered.

11. In terms of percentage increase, the cohesion values of flyash – cement mortar composites at maximum flyash content (i.e. 70%) and sisal fibre content (i.e.2.0%; r = 200) ranges from about 60 – 275% over the respective reference mortar and over the range of flow values considered. The above trend is similar to the behaviour of flyash – cement mortar and cement mortar composites, under identical conditions. There is a four – fold increase in the cohesion value of flyash – cement mortar composites (1:3, 1:4 and 1:5), in spite of 2.5 times increase in the flow values, which is a tremendous improvement in the cohesion value of the composite.

12. There is 'no cumulative effect' in the gain of cohesion values due to the incorporation of flyash and sisal fibres in the cementitious composites (1:3, 1:4 and 1:5) which is attributed to the 'sensitivity' of flyash to water content in the mix. In spite of the above behaviour, there is positive and substantial influence of sisal fibres and flyash contents in the composite, in enhancing the ‘stability’ of the composite.

5.2.5 Strength Behaviour of Mortar Composites

(1:3, r = 200; flyash = 0 - 70%; V_f = 0.25% - 2.0%)

1. Compressive, flexural and split-tensile strength behaviour of sisal fibre cement mortar composites (1:3) and sisal fibre cementitious composites, are similar over the range of parameters and ages (normal age i.e. at 28 days, and at later – ages upto 120 days), considered. All the above strengths attain the maximum at identical fibre content and flyash content in the mortar composite (i.e. flyash content = 20%; sisal fibre content = 0.50%).

2. In case, comparable / higher strengths (compressive, flexural, split – tensile) are desired for the cementitious composites, to / than that of reference mortar strength (i.e. flyash = fibre content = 0%), then, the maximum flyash content be limited to 20% and the sisal fibre content to 1.5%, in the cementitious composite.

3. The ‘cementitious’ and ‘pozzolanic’ properties of the flyash used have contributed to the improvement in the various strengths both at early – age and at later-ages. Moreover, there is ‘combined positive effect’ of the flyash and sisal fibres, in enhancing the performance of the mortar composites.
4. Maximum compressive strength attained by the cement mortar composite is about 26 MPa \((V_f = 0.5\%\), at the normal age. The above maximum strength attained by the cement mortar composites \((1:3\) is about 25 – 61\% higher than the plain cement mortar strength, for the range of ages considered. The maximum long-term strength-gain ratio of the cement mortar composite \((i.e. \text{ratio of compressive strength } @ 120 \text{ days to that at normal age})\) is about 2.1.

5. Maximum compressive strength attained by the flyash – cement mortar composite \((i.e. \text{the cementitious mortar composite})\) is about 39.5 MPa \((V_f = 0.5\%; \text{flyash content } = 20\%)\), at the normal age. The above maximum strength attained by the cementitious mortar composites, is 60 – 130\% higher than the reference mortar strength, for the range of ages considered. The maximum long – term compressive strength – gain ratio of the cementitious composite is about 1.9, and comparable to the behaviour of cement mortar composite, under identical conditions.

6. Maximum flexural strength attained by the cement mortar composite is 4.5 MPa \((V_f = 0.5\,)\), at the normal age. The above maximum strength attained by the cement mortar composites is about 30 – 50\% higher than the reference mortar strength and for the range of ages considered. It is found that the long – term (maximum) flexural strength - ratio is nearly the same as that of the compressive strength - ratio.

7. Maximum flexural strength attained by the cementitious – mortar composite is about 6.4 MPa \((V_f = 0.5, \text{flyash content } = 20\%)\), at the normal age. Maximum flexural strength attained by the cementitious mortar composites is 70-113\% higher than the reference mortar strength for the range of ages, considered. Long – term maximum strength – ratio of the above composite, nearly equals that of the strength – ratio of the composite, in compression.

8. Maximum split – tensile strength attained by the cement mortar composite is 5.0 MPa \((V_f = 0.5\,)\), at the normal age. The above maximum strength attained by the cement mortar composites is about 20 – 30\% higher than the reference mortar strength and for the range of ages, considered. It is found that the long-term (maximum) split- tensile strength ratio is about 1.6, which is slightly less than the other two strengths considered.

9. Maximum split – tensile strength attained by the cementitious mortar composite is about 5.9 MPa \((V_f = 0.5, \text{flyash content } = 20\%)\), at the normal age. The above maximum strength attained by the cementitious composites is about 30 – 48\% higher than the reference mortar strength, for the range of ages, considered. Long – term (maximum) split – tensile strength – ratio of the composite is 1.6, which is same as that of cementitious composites, but, slightly less than the other two strengths, considered.

10. Ratio of the maximum split-tensile strength to the compressive strength of cement / cementitious mortar composites evaluated under identical conditions, is about 15\% \((\text{average})\). The above ratio indicates once again the good performance of the composites, under direct tension.
5.2.6 Impact Strength of Slabs: Mortar and Composite

1. Performance of sisal fibre cementitious mortar composites including the durability of the composite, can be evaluated with ease and confidence by ‘residual impact strength factor’ (Iₙ) and ‘flexural toughness factor’ (Iᵢ).

2. Residual impact strength ratio (Iₙ) which is measure of ductility inherent in the material ranges from 1.18 to 1.74, for the cement mortar composite slabs relative to that of the reference cement mortar slab, at normal-age and the range of sisal fibre contents considered.

3. There is only a marginal improvement in the ductility (as measured by Iₙ) of the cement mortar composite slabs, over the early – age behaviour, within the range of later – ages considered.

4. Flyash – cement mortar slabs with flyash content = 20% gives a better performance in terms of ductility over the cement mortar slab and flyash – cement slabs with higher flyash contents (i.e. > 20%), under all ages considered.

5. Impact strength behaviour of flyash – cement mortar composite slabs are similar to that of cement mortar composite slabs, at normal and later ages with respect to the energy absorbed, and the range of flyash contents considered. However, there is further improvement in the energy by the cementitious composite slabs at later - ages. The energy absorbed by the cementitious composite slab is maximum, when the flyash content is 20%, for the range of fibre contents considered.

6. In terms of residual impact strength ratio (Iₙ), the relative improvement in ductility of flyash-cement mortar composite slabs at normal-age is 1.39 and 2.48, over the reference mortar slab and corresponding to the minimum (0.25%) and maximum (2.0%) fibre content and at optimum flyash content (20%).

   Iₙ is maximum and ranges from 1.81 to 2.82 (at 120 days, flyash content = 20%) for the range of sisal fibre contents considered.

7. In case, comparable or higher impact strength is desired to be achieved, for the flyash – cement mortar composite slab, to / than that of reference mortar slab at normal and later-ages, then, the maximum flyash content be restricted to 20% and the fibre content to 1.5% in the cementitious composite.

8. Impact strength behaviour has found to be greatly influenced by the combined action of sisal fibres and the ‘cementitious’ and ‘pozzolanic’ action of the flyash used, in enhancing the ductility of the composites, at all ages.

5.2.7 Flexural Strength of Slabs: Mortar and Composite
(by four – point loading method)

1. Flexural strength behaviour of composite mortar slabs are generally similar to that of standard specimens (of mortar and composites), within the range of parameters and ages considered.

2. However, the maximum strength obtained by the composite slabs are always less ( by 30% - average) than that attained by the specimens (under flexure), at all ages considered, which may be attributed to the ‘residual stress’ present in the slab specimens by virtue of the earlier impact load subjected on them.
5.2.8 Durability of Sisal Fibre Mortar Composite Slabs

1. $I_n$ and $I_f$ values could reflect the changes in the strength due to the interaction between the matrix and the medium considered (i.e. NaOH) and hence can be used with confidence evaluate the durability of the mortar composites.

2. Deviation in $I_n$ and $I_f$ values are minimum (irrespective of the mortar / composite) when the flyash content is 20% and hence it can be considered that the matrix and the fibres are least affected when the flyash content in the composite is 20%, for all fibre contents.

5.2.9 Sisal Fibre Corrugated Roofing Sheet

(1:3; flyash content = 0 – 30%; $V_f$ = 0.25 – 2.0%)

1. Sisal fibre corrugated roofing sheets of (mortar / composites) couldn’t match the high strength exhibited by the commercial type corrugated roofing sheet considered, with respect to the flexural and splitting loads and with in the range of sisal fibre contents (0 – 2%) and flyash contents (0 – 30%) considered in this study.

2. Flexural and splitting loads of cement mortar (1:3) and flyash – cement mortar corrugated sheets are comparable, within the range of flyash contents (10 – 30%), considered.

3. Incorporation of sisal fibres into cement mortar and flyash – cement mortar matrix has contributed to the enhancement in the flexural and splitting loads and that the above loads are maximum at sisal fibre content of 1.0% in the above composite roof sheets, over the range of flyash and fibre contents, considered.

4. Maximum flexural load of about 180 kg carried by the cement / cementitious mortar composite corrugated sheets, is about 25% higher than the load carried by the reference mortar roofing sheet, at sisal fibre content of 1.0% and considering the range of flyash and fibre contents. The above maximum flexural load is about 85% of the ‘commercial type roofing sheet’, tested under identical conditions.

5. There is tremendous improvement in the splitting load carried by of the flyash – cement mortar composite roofing sheet and that the above load is maximum (i.e. 922 N or 92.2 kg) at flyash content = 20 % and sisal fibre content = 1%. The above maximum load is about 87% of the load carried by the ‘commercial type roofing sheet’, evaluated under identical conditions.

6. Even though, the actual energy absorbed by the commercial type roofing sheet is higher under the impact load, the ductility of the above roofing sheet, measured in terms of $I_n$ values are lower, than all mix combinations considered for the impact studies of the sisal fibre composite.

7. From the point of actual energy absorbed (i.e. at initiation of crack and at failure) and ductility in terms of $I_n$, corrugated sheets with flyash content = 20% and sisal fibre content = 1% in the composite, are better / as comparable to that of i.e. cement mortar corrugated sheets).

8. Flyash cement mortar composite roofing sheets (flyash = 20%; $V_f$ = 1%) have shown the best performance in terms of lowest water absorption (i.e. 36% lower than commercial roofing sheet), and in terms of water tightness, when compared to
the ‘commercial type’ and cement mortar composite roofing sheets. The above phenomenon is generally attributed to the impermeability imparted by the flyash to the mortar matrix.

9. From an overall assessment, the performance of sisal fibre flyash – cement mortar composite roofing sheet (V_f = 1%; flyash content = 20%) developed and investigated, is comparable to that of a commercial type roofing sheet and hence the above product can be considered as an effective alternative to the commercial / conventional roofing sheets, so far widely used.

10. However, further improvement in the performance of sisal fibre flyash – cement mortar composite roofing sheet is possible (i) by adopting better casting procedures, which may incidentally lead to incorporation of higher fibre content in the composite and (ii) by optimizing the shape and size of corrugations of the sheet through refinement of tests and procedure for load and energy required to ‘split the corrugations’.

5.3 RECOMMENDATIONS

Following few specific recommendations are made from an overall assessment / usefulness of the present study:

(i) The mixing procedure advocated in the study is recommended to be followed to ensure workability, strength and durability of the natural fibre composites.

(ii) Fibre characterization and rheological studies are recommended to be adopted for mix proportioning of natural fibre cementitious composites so as to achieve the desired workability, strength characteristics and to ensure a relative durable material/ product.

(iii) It is necessary to develop a few field – oriented and cost – effective methods to measure rheological and workability characteristics of natural fibre cementitious composites and product/(s) based on them.

5.4 SUMMARY

Based on the comprehensive experimental investigations, the importance and role of rheological studies of natural fibre (say sisal) cementitious composites in influencing their various characteristics in wet and hardened states have been brought out clearly. The positive influence of the flyash used (which has both cementitious and pozzolanic properties) and the interaction of sisal fibres in such a matrix, which have contributed to the enhancement various strength and durability properties of the cementitious composites, have been highlighted. The ease and the confidence with which, certain simple tests and procedures could help to evaluate the properties of cementitious composites, have been presented. A few recommendations which need the attention of Professionals have been made.