SP 154-11

Influence of Rice Husk Ash on Properties of Sisal Pulp-Mortar Composites

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Synopsis: In order to improve durability, it is necessary to find remedial solutions to counteract the embrittlement process of natural fiber reinforced composite materials. One solution to alleviate fiber degradation is to reduce the alkalinity of the pore fluid in the cement paste. This can be achieved by replacing a part of the normal portland cement with a highly active pozzolanic material. The purpose of this research study was to investigate experimentally the mechanical behavior of sisal pulp-mortar composites containing cement blended with a modified rice husk ash, hereinafter referred to as MRHA. The main variable was the pulp volume fraction. The results of sisal pulp-mortar composites were compared to those using bamboo and pine pulps. The water-cementitious and sand-cementitious ratios by weight were kept constant. The dosage of superplasticizer was fixed. The tests on the composites included strengths under direct tension, axial compression, anticlastic and bending. The material performance tests were conducted for moisture content, water absorption, expansion, drying shrinkage and impact resistance. The durability of the composites was investigated by simulated aging cycles. The results showed that after being subjected to 48 simulated aging cycles, the sisal pulp-mortar containing 5% pulp volume fraction showed the highest modulus of toughness. Other tests showed that pulp-mortar composites were impervious, durable, possessed high strength and good impact resistance, and therefore can be considered as suitable substitutes for asbestos-fiber board.

Keywords: Bending; composite materials; compression; mechanical properties; mortars (material); rice husk ash; sisal; tension

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INTRODUCTION

Cellulose fibers obtained by chemical pulping processes are the dominant types used for the production of thin-sheet cement products in developed countries. These cellulose fibers contain negligible amounts of lignin and are thus expected to better withstand alkaline attack in cement. There are, however, other aging mechanisms which may lead to the embrittlement of cellulose fiber reinforced cement composites. In particular, in the presence of moisture, the gradual filling of the fiber cell cores with hydration products and the densification of matrix in the vicinity of fibers (1) encourages brittle fracture of fibers under stress, leading to the embrittlement of the cellulose-fiber-reinforced cement composite; a similar phenomenon is partly responsible for the embrittlement of glass-fiber-reinforced cement composites under long-term environmental effects. This phenomenon, in the case of chemical pulps with low lignin content, can lead to increased flexural strength and modulus of elasticity of cellulose-fiber-cement composites (2).

The present study is aimed at investigating the mechanical properties of fiber-reinforced composites in which the matrix contained a modified rice husk ash, and sisal pulp was used as reinforcement. The main variable was the pulp volume fraction. The gradation of sand was maintained constant throughout the whole experimental program. The MRHA was used to replace normal portland cement and its percent replacement was kept constant at 10%. The water-cementitious and sand-cementitious ratios by weight were also kept constant and equal to 0.40 and 2.0, respectively. The dosage of superplasticizer was kept constant at 2.4% of cementitious material by weight. Sisal pulp-mortar composites were produced by using pulp volume fractions of 0%, 3%, 5%, 7% and 9%. The results were also compared to bamboo and pine pulps taken from commercial sources in Thailand.

This study was undertaken with the following objectives:-
(i) To investigate experimentally the physical and mechanical properties of pulps, namely specific gravity, moisture content, water absorption, ultimate tensile strength and modulus of elasticity.
(ii) To investigate experimentally the mechanical properties of sisal pulp-mortar composites containing modified rice husk ash. The tests included strengths under direct tension, axial compression, anticlastic and bending. Moisture content, water absorption, expansion, drying shrinkage and impact resistance were also determined. The durability of the sisal pulp-mortar composites was investigated by simulated aging cycles. The number of cycles varied from 0-48 cycles. One cycle consisted of wetting of specimens for 30 minutes, followed by heating in an

oven at a temperature of 105 °C for five and a half hours.
(iii) To compare the results from experiments with those from theoretical analysis in order to establish predictive equations for mechanical properties of composites.

NOTATION

E_c, E_t = effective modulus of elasticity of composite in compression and tension, respectively;

E_p = modulus of elasticity of pulped fiber;

E_{mc}, E_{mt} = modulus of elasticity of cement paste in compression and tension, respectively;

G_c, G_m = shear modulus in the uncracked range of composite and cement paste, respectively;

V_m, V_p = total volume fraction of cement paste matrix and pulped fiber, respectively;

υ_c = Poisson's ratio in compression;

σ_{cu}, σ_{tu} = ultimate strength of the composite in compression and tension, respectively;

σ_{pu} = ultimate strength of pulped fiber; and

σ'_{mu} = crushing strength of cement paste matrix.

EXPERIMENT

Materials

(a) Modified Rice Husk Ash--The major characteristics of RHA are its high water demand and low fineness as compared with condensed silica fume. Another important problem is the dispersion of RHA particles uniformly in the mix. To increase fineness, the recommended grinding time for RHA was 45 minutes (3, 4). However, the degree of fineness achieved was not sufficient to make high-strength concrete. To solve this problem, rice husk ash must be ground in the grinding machine for a long duration of time in order to achieve a very high degree of fineness. A grinding time of 1 hour and 15 minutes was proposed and this was maintained throughout the whole testing program.

(b) Sisal Pulp Fibers--A chemical pulping process called "kraft process" is introduced in this study by using a boiler having temperature of 100 °C to treat the fibers. NaOH and N_2S having concentrations of 48 and 32 gm/L respectively were combined and used as chemical agents for the treatment of fibers. The boiling time, beating time and casting pressure were fixed at 8 hours, 30 minutes and 0.28 MPa, respectively.

(c) Other Constituent Materials
Portland Cement : Normal portland cement was used.
Mixing Water : Ordinary tap water was used.
Fine Aggregate : Natural river sand passing 9 mm sieve.
Superplasticizer : The superplasticizer was a naphthalene based product of Japanese origin.

Formwork and Casting Procedure

Since the mixture of sisal pulp and mortar is a lightweight composite material, the casting process should be done under pressure. The formwork was made of wood and a 1.6 mm-thick steel sheet. The formwork consisted of the upper and lower parts which were connected together with 16 mm diameter bolts. The details of the formwork are shown in Fig. 1.

The pulp was beaten for 30 minutes to disintegrate the pulp which was mixed with the cementitious material for 5 minutes. The mixing was done in such a way that all the pulps were coated with mortar uniformly. The mixing was done in two operations. When the mixing procedure was finished, the mixture was then placed in the formwork and pressed by hands in order to check the uniformity. The casting process had to be done under pressure by applying load through a hydraulic cylinder. In this study, the load corresponded to the required casting pressure. All bolts were fastened tightly. The specimens were kept for 24 hours before being removed from the formwork and cured in the fog room at 100% relative humidity at 28 °C for 28 days. Subsequently, specimens were cut into small pieces according to the type of testing. For durability test, the specimens were subjected to simulated aging cycles until the time of testing.

The dimension of fiber-reinforced cement composite for direct tension, axial compression, anticlastic, bending, moisture content, water absorption, expansion and drying shrinkage, impact resistance and durability tests were 126x430, 100x150, 300x300, 150x580, 100x150, 300x300, 100x300, 230x250 and 150x580 mm, respectively. The thickness of specimens was 15 mm whereas that of sisal pulp-mortar and bamboo pulp-mortar specimens was 25 mm.

RESULTS AND DISCUSSION

Properties of Sisal Fiber and Pulps

The physical and mechanical properties of sisal fiber and pulps were determined, and are shown in Table 1. With a natural organic fiber, it is rather difficult to obtain the exact value of the ultimate tensile strength or modulus of elasticity of sisal fiber and pulps because of the variation in cross section, moisture content, age of fiber and pulp and some defects existing in them.

Durability of Composites Containing MRHA and Pulped Fibers

(a) Modulus of Rupture--Toughness data are shown in Table 2 and plotted in Figs. 2 and 3. From Fig. 2, it was observed that the moduli of rupture of the sisal pulp-mortar composite boards decreased when the pulp volume fraction increased. The control composite showed the highest modulus of rupture whereas the sisal pulp-mortar composite containing 9% pulp volume fraction exhibited the lowest. This is due to the high volume fraction of sisal pulp. In this case, the control composite contained MRHA. After 48 simulated aging cycles, the decreasing in modulus of rupture for the sisal pulp-mortar composite was lower when compared to the control composite. In this regard, the high volume fraction of sisal pulp could provide some resistance after simulated aging cycles. Although the modulus of rupture of the control board was higher than that of the sisal pulp-mortar boards, it was brittle while the sisal pulp-mortar boards were more ductile.

Regarding the effect of pulp type on the flexural strength (Fig. 3), for simulated aging cycles the durability of the composite containing 5% bamboo pulp was found to be better than that of composites containing 5% pine and sisal pulps. After 48 simulated aging cycles, the increase in strength of the bamboo pulp-mortar composite was remarkably higher than that the control composite. It was noted that in this respect the bamboo pulp-mortar composite and pine pulp-mortar composite showed a similar behavior.

(b) Modulus of Resilience--The elastic resilience of a material is the amount of energy recovered for unit volume of the material when it is stressed to its elastic limit and then the stress is relieved. The highest value of the modulus of resilience is obtained in a material with a high elastic strength and a comparatively low modulus of elasticity. The modulus of resilience was determined from the area under the load-deflection curve within the elastic range represented by area *OAJ* of Fig. 4.

From Fig. 5, it can be observed that the moduli of resilience of the sisal pulp-mortar composite boards increased with the pulp volume fraction. In addition, the rate of decrease in the modulus of resilience after being subjected to simulated aging cycles was rather low compared to the control. This can be explained by the fact that more the pulp content, the less the cement mortar, and consequently less alkalinity in the system. This means that the pulp suffered less attack from alkaline pore water.

Regarding the effect of pulp type on the moduli of resilience of pulp-mortar composite boards, it is indicated that, when subjected to simulated aging cycles, the composite boards containing 5% bamboo pulp showed a higher modulus of resilience. The test result is graphically shown in Fig. 6. It was noted that the control, sisal pulp-mortar, and pine pulp-mortar composites exhibited a similar trend.

(c) Modulus of Toughness--Toughness is the capacity of materials to absorb energy during the application of load to fracture. It depends upon both strength and ductility. A tough material will withstand great deformation under high stress. The modulus of toughness is expressed in term of the work performed in deforming a material to fracture and therefore is represented by the area *OABF* under the load-deflection diagram shown in Fig. 4.

The results are graphically presented in Fig. 7. It was observed that the effect of using chemical fiber treatment resulted in higher toughness than the control when subjected to simulated aging cycles. The results indicated that fiber treatment using some chemical agents (NaOH and N_2S) and MRHA as cement replacement were effective in improving the ductility of the pulp-mortar composites subjected to simulated aging cycles. After 0-12 simulated aging cycles, the sisal pulp-mortar composite containing 5% pulp volume fraction showed the highest modulus of toughness. The toughness of the sisal pulp-mortar composite containing 7% pulp volume fraction was similar to that of the sisal pulp-mortar composite containing 9% pulp volume fraction. For both the control composite and the sisal pulp-mortar composite containing 3% pulp volume fraction, it was found that the toughness was the lowest. This can be explained by the fact that the more the cement mortar, the less the pulp content, and consequently, the more the alkalinity. This means that the alkaline attack was relatively stronger.

Regarding the effect of pulp type on the moduli of toughness of pulp-mortar composites, it was also noted that when subjected to simulated aging cycles, the composite containing 5% sisal pulp exhibited a higher modulus of toughness (Fig. 8).

According to ASTM C1018, the energy absorbed by the specimen is represented by the area under the complete load-deflection curve. The load-deflection curve has been observed to depend on (a) the specimen size; (b) the loading configuration; (c) type of control; and (d) the loading rate. To minimize at least some of these effects, normalization of the energy absorption capacity is necessary. This can be accomplished by dividing the energy absorbed by the fiber-reinforced concrete beam by that absorbed by an unreinforced beam of identical size and matrix composition, tested under similar conditions. The resultant nondimensional index, I_t, represents the relative improvement in the energy absorption capacity due to the inclusion of fibers, as shown in Fig. 4. It is an index for comparing the relative energy absorption of different fiber mixtures.

The data from the nondimensional index study are presented in Table 2. It was also observed that the effect of using pulp resulted in higher index than the control when subjected to simulated aging cycles. A decrease in the rate of nondimensional index was also observed in the case of sisal pulp-mortar composites containing 5% pulp volume fraction. Regarding the effect of pulp type, it was also found that, when subjected to simulated aging cycles, the composites containing 5% bamboo pulp showed a 9% increase in the nondimensional index. This index was compared to that of the control composite which was not subjected to any simulated aging cycle.

(d) Comparison with Previous Study--Fig. 9 shows the relationship between modulus of rupture and number of simulated aging cycles of composites. In case of Wu's study (6), the modulus of rupture of composites containing only 14% pulp volume fraction of sisal fiber sharply decreased within 8 simulated aging cycles. This was probably due to rapid fiber decomposition in the alkaline pore water present in the mortar which reflected the poor durability of the composite. In order to increase the durability of the fiber, 30% RHA was used to replace the normal portland cement in mortar. This can be explained by the fact that the silica present in RHA reacts with calcium hydroxide liberated as a result of cement hydration, thus causing a marked reduction in the alkalinity of mortar and the decomposition of natural fibers. It was also observed that after 48 simulated aging cycles, the moduli of rupture of composites containing 10% replacement of MRHA with pulp fiber were increased as compared to those containing 30% replacement of RHA and 14% pulp volume fraction of sisal fiber. The results revealed that using both fiber treatment and MRHA in making the pulp-mortar composites resulted in slowing down the decomposition of natural fibers caused by alkaline attack. An important point which should be emphasized is that among the sisal pulp and fiber investigated, the durability of composites containing MRHA and sisal pulp treated by the proposed method is better than that of composites containing RHA and sisal fiber.

(e) Other Tests--The results from tests on moisture content, absorption, expansion, drying shrinkage and impact resistance are summarized in Table 3. It was noted that both the moisture content and water absorption increased as the pulp volume fraction increased. The water absorption for all test specimens was found to be lower than 10% as specified by ASTM C208-72 except for sisal pulp-mortar composite containing 9% pulp volume fraction. Regarding the effect of pulp type, it was found that the composite containing 5% bamboo pulp showed a higher water absorption than that containing 5% sisal pulp. The water absorption of pine pulp-mortar composite was lower than the control composite. The moisture content for all specimens were found to be less than 9.2%. Regarding the effect of pulp type, the results were similar to those of water absorption.

In the expansion test, it was observed that most of the expansion occurred during the first 24 hours of submersion and, in general, the expansions were quite low. The maximum expansion for all tested specimens was found to be much less than 0.5%, as specified by ASTM C208-72. The composite containing 5% sisal pulp resulted in a higher expansion than that containing the same amount of pine pulp. The expansion for the bamboo pulp-mortar was one of the lowest.

Shrinkage of the materials results from the removal of moisture on drying. The rate of shrinkage is dependent on the amount of drying that can take place, consequently it is influenced by the ambient temperature and humidity, the rate of air flow over the surface and the ratio between surface area and volume of the material. It was observed from the shrinkage test that the shrinkage rate of the composite decreased with time. The percentage of equilibrium shrinkage for all tested specimens was found to be lower than 0.1%. Regarding the effect of pulp type, it was noted that the composite containing 5% bamboo pulp gave higher shrinkage than that containing the same amount of sisal pulp. The shrinkage of the control composite was similar to the sisal pulp-mortar composite. The shrinkage of the pine pulp-mortar composite was the lowest.

The results from the impact resistance test showed that an increase in pulp volume fraction caused an increase in impact resistance. The maximum index of impact resistance for the sisal pulp-mortar composites was 33.25, especially at 9% pulp volume fraction when very tiny cracks appeared on the unloaded face. The index for the control composite was 26.25. A ductile failure for the pulp reinforced composites was observed in contrast to the brittle failure exhibited by the control composite. Regarding the effect of pulp type, it was found that the composite board containing 5% sisal pulp exhibited a higher index value than that containing 5% bamboo pulp. The index values for the pine and bamboo pulps composites were lower than the control.

Comparison between Experimental and Theoretical Results

(a) Direct Tension Test--Table 4 shows a comparison between the theoretical and experimental values for ultimate strength and modulus of elasticity from direct tension test. It was observed that as the pulp volume fraction increased, the ultimate strength increased whereas the modulus of elasticity decreased. The ultimate strength of the composite in tension σ_{tu} was calculated from the equation:-

$$\sigma_{tu} = 0.108 V_p \sigma_{pu} \tag{1}$$

The modulus of elasticity of the composite in tension E_t was calculated from the equation:-

$$E_t = E_{mt} V_m + 0.061 E_p V_p \tag{2}$$

(b) Axial Compression Test--Tables 5 and 6 show the theoretical and experimental values for ultimate strength, modulus of elasticity, and Poisson's ratio from axial compression test. It was noticed that as the pulp volume fraction increased, the ultimate strength and modulus of elasticity decreased, whereas the Poisson's ratio increased. The ultimate strength, modulus of elasticity and Poisson's ratio in compression of the composite, σ_{cu}, E_c and υ_c, were calculated from the following equations:-

$$\sigma_{cu} = \sigma'_{mu} V_m \tag{3}$$

$$E_c = E_{mc} V_m + 0.061 E_p V_p \tag{4}$$

$$\upsilon_c = \frac{E_c}{2G_c} - 1 \tag{5}$$

The theoretical and experimental values of $E_c/(1-\upsilon_c^2)$ are also summarized in Table 7.

(c) Anticlastic Test--The theoretical and experimental values of the shear moduli for the anticlastic test are also included in Table 7. It was noticed that the shear moduli of the composites depended largely on the shear modulus of the control mortar, and the contribution of the pulp was small. The shear moduli decreased as the pulp volume fraction increased. Regarding the effect of pulp type, the shear modulus of bamboo pulp-mortar composite was higher than that of sisal pulp-mortar composite. The shear modulus of the composite G_c was calculated from the equation:-

$$G_c = G_m V_m + 0.020 E_p V_p \tag{6}$$

CONCLUSIONS

Based on the experimental results obtained in this study, the following conclusions can be drawn:-

After subjected to 48 simulated aging cycles, the moduli of rupture of composites containing 10% replacement of MRHA and pulped fiber were significantly increased as compared to those containing 30% replacement of RHA and 14% pulp volume fraction of sisal fiber. The use of pulp and MRHA in the mortar matrix considerably increased the durability of the mortar. Regarding the effect of pulp type on the modulus of toughness of pulp-mortar composites, the sisal pulp-mortar containing 5% pulp volume fraction showed the highest modulus of toughness.

Other tests showed that pulp-mortar composites were impervious, durable, possessed high strength and good impact resistance, and therefore can be considered as suitable substitutes for asbestos-fiber board.

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