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MORPHOLOGICAL AND FLEXURAL PROPERTIES OF LIGHTWEIGHT GYPSUM BASED FIBER REINFORCED COMPOSITE

Pablo A. Jorillo Jr., Dr. Eng.
Associate Professor
Department of Civil Engineering
Integrated Research and Training Center
Technological University of the Philippines
San Marcelino, Manila

ABSTRACT

This paper describes the results of the experimental investigations of the properties of lightweight gypsum based fiber reinforced composites. Two general types of fiber reinforcement were examined, namely, polymer based fibers and natural fibers. The study is essentially a developmental research with the objective of evaluating the properties of natural fibers in comparison with synthetic fibers of the same density in a gypsum matrix. A gypsum-cellulose pulp and a gypsum-Shirasu balloon sand were used as lightweight gypsum matrices. Experimental and analytical results on both standard specimens and full scale structural elements such as wall panel are presented.

INTRODUCTION

Fiber reinforced composite or fiber concrete is essentially a hydraulic cement material (cement or gypsum binder) with aggregates and in the main discrete fiber reinforcement. The concept of addition of fibers into a brittle matrix is an attempt: (a) to locally restrain the propagation of internal cracks or flaws into adjacent material, (b) to delay and control tensile cracking, (c) to dissipate energy at its interfacial region, and (d) to improve the thixotropic and rheological properties of plain matrix (RILEM, 1990; Hannant, 1981; Swamy, 1990). However, the degree and the effectiveness of reinforcement depends on the type of fiber. Generally, fiber suitable of reinforcement are divided into categories of high modulus and low modulus fibers. High modulus fibers such as glass or steel are capable of producing strong composites with high stiffness and load carrying capacity. Low modulus fibers such as polypropylene and natural fibers on the other hand, are capable of producing composites with high ductility and toughness with little increase in strength.

The relatively high cost of man-made or synthetic fibers such as polypropylene, polyethylene, and glass used in fiber reinforced composites make it desirable to evaluate natural fibers such as sisal and coconut fibers as possible substitutes. The author believes that the

potential of natural fiber composite in building construction is very significant. Fiber cement sheeting, panel and precast building components are few of many possible applications of natural fiber cement composites. However, at present there are very limited development on the utilization of this type of composites especially with α-gypsum cement as binder mainly due to scarcity in information on the precise structure-properties of the composite system, especially in the form of structural elements.

Gypsum is obtained by calcining raw gypsum ($CaSO_4.2H_2O$) at around 175^0C, and if water is added the resulting hemihydrate (α-gypsum or ß-gypsum) rehydrates back to the dehydrate form in about 20-30 minutes (Joshi et al., 1992; Singh et al., 1992, Evans et al., 1980). Currently, gypsum cement is categorized as either α-gypsum or ß-gypsum depending on the product of processing. ß-hemihydrate gypsum is more commonly used in building construction in the form of pre-cast elements because of its slower setting time rate and lower cost compared to α-gypsum, but it is relatively of lower strength. In this study, the feasibility of using α-hemihydrate gypsum as the binding medium for building elements was investigated. The lightweight and fire resisting property of gypsum cement plaster makes it very suitable for panel elements in building construction. The low alkalinity of gypsum compared to Portland cement makes it an advantageous cementing material for natural fiber cement composites, where alkali attack on cellulose components of fibers is most critical.

Hence, a developmental and comparative study was undertaken to examine the properties of a lightweight gypsum based composite reinforced by polymer based fibers (vinylon and polypropylene), and natural fibers (sisal and coconut). The study is directed towards the investigation of properties of a fiber composite in the form of structural pre-cast element such as wall panel. This experiment was conducted with the objective to:

(a) examine the morphological properties of gypsum matrix and the aggregate constituents,
(b) examine the effect of fiber type to the mechanical properties of gypsum based matrix,
(c) examine the effect of lightweight aggregates and mineral admixtures to the properties of fiber composite.

EXPERIMENTAL PROGRAM

In order to limit the experimental program to more significant variables, previous work done by the author on natural fiber concrete were considered (Jorillo, 1993; Shimizu and Jorillo, 1992). In this study the variables considered in the testing program are listed in Table 1.

Physical property tests like x-rays, fluorescence spectral analysis and scanning electron microanalysis were conducted. Likewise, mechanical property tests such as compression, bending, and deformation analysis were also undertaken in accordance with ASTM standards.

The following information obtained from the tests are:

(a) Fiber and interface morphological analysis
(b) Stress-deformation diagram considering the load at first crack and post-cracking stage and,
(c) Mechanical properties of composite.

Materials and Testing Methods

α-gypsum (α-$CaSO_4$ + ½H_2O) with 95% concentration (ASTM C-22) was used as binding medium. The chemical properties are shown in Table 2. Processed cellulose pulp from recycled paper and sankelite sand (Shirasu balloon of volcanic origin) with dry rodded density of 90 and 80 kg/cm^3 respectively were used as lightweight fine aggregates. An inorganic retarder with chemical composition of P_2O_5, SO_3 and CaO of 1.7, 59.8 and 38.5% respectively was used at a dosage rate of 1% by weight of gypsum. Mineral admixture such as silica fume (S), white silica (CS), and fly-ash (F) were used with gypsum-pulp mortar. The chemical properties of these materials as determined from X-ray fluorescence test are enumerated in Table 3. Also, typical x-ray fluorescence results for the chemical analysis of silica fume and white silica are shown in Figures 2(a) and 2(b) respectively., Furthermore, SEM micrograph of the materials (e.g. fly-ash, white silica, cellulose pulp, and sankelite) are shown in Figures 3-6.

Table 1
Variables Considered in the Gypsum Composite Test Program

Parameter	Variable	Range	Limitations*
Gypsum Binder (G)	Water/Gypsum (W/G)	W/G = 35, 45 %	α- Gypsum cement
Aggregates (Sand/Binderratio)	Gypsum-Cellulose (GP) Gypsum-Sankelite (GS)	Cellulose Pulp P = 10, 15, 20, 30%	Lightweight Pulp GP- series Lightweight Sand GS-series
Mineral Admixture (% substitution by wt. of cement)	Silica Fume (S) White Silica (CS) Fly-ash (F)	S/(S +G) = 5, 10% CS/(CS + G) = 5, 10% F/(F+G) = 5, 10%	Tests conducted with mineral admixture are for GP Mix series with Pulp sand only
Fiber Reinforcement A. Type of Fiber B. Fiber Proportion	1. Polymer-based fibers 2. Natural fibers Vf = (% volume of matrix)	1. Vinylon, Polypropylene 2. Coconut, Sisal If = 8-12 mm Vf = 1, 2% Vf = 2, 3%	Mix series with Pulp Mix series with Sankelite Mix series with Pulp Mix series with Sankelite
Specimen Preparation	Ordinary casting method	Specimen dimension 40x40x160 20x150x300 20x300x600	 All Mix series Mix series with Sankelite

* limitations indicate where a specific variable was applied

Table 2
Physical and Chemical Properties of α-Gypsum

Properties		Ave. Values	Oxides**	Value (%)
Specific Gravity		2.40	SO_3	60.1
Blaine's Fineness (cm^2/g)		3000	CaO	34.7
Consistency * and Setting Time	Stucco-water consistency (%)	40	Re_2O	5.1
	Init setting time (h-min)	0-14		
	Final setting time (h-min)	0-20		
Strength (kgf/cm^2)	Bending strength	23.0		
	Compressive strength	240		

* per ASTM C-22 specification
** Chemical composition listed are summarized from the x-ray fluorescence spectral analysis and not from the oxides analysis prescribed by ASTM

Table 3
Chemical Composition of Mineral Admixture and Aggregate

Chemical compound	Silica Fume	White Silica	FLy-ash	Coarse Cellulose Pulp	Fine Cellulose Pulp	Sankelite Shirasu sand
Na2O	0.15	0.12	0.10	-	1.8	0.5-2.0
MgO	0.29	0.22	0.30	2.4	-	0.4-0.6
SiO2	83.3	74.5	81.1	79.9	39.8	54-75
CiO2	0.21	-	-	-	-	-
K2O	15.8	16.8	0.60	15.7	17.1	0.1 - 4.0
CaO	0.071	0.18	1.40	0.91	0.40	1.5 - 2.5
In2)	0.22	0.17	-	0.18	0.19	-
TiO2	-	0.12	-	-	0.33	-
Sb2O5	-	7.9	-	-	11.6	-
Fe2O3	-	-	1.0	0.44	1.2	1.0 - 4.0
Al2O3	-	-	15.5	-	2.27	11 - 16
P2O5	-	-		-	-	-

* Chemical composition listed are summarized from the x-ray fluorescence spectral analysis and not from the oxides analysis prescribed by ASTM

For fiber reinforcement, two general types of low density fibers were used, namely, polymer based fibers with specific gravity of 0.98-1.3 (i.e., vinylon and polypropylene) and natural fibers with specific gravity of 1.0-1.15 (i.e., coconut and sisal). The properties of these fibers are listed in Table 4. Coconut (*cocos nucifera*) fibers extracted from mature coconut fruit, and commercial grade sisal (*agave sisalana*) fibers were used for natural type of fibers. While, a hydrocarbon polymer based polypropylene fiber and polyvinyl alcohol derivative vinylon fibers were used for synthetic fiber reinforcement. SEM micrographs of fibers shown in Figures 7-10 reveal their morphological structure which governs the properties of the composite as a whole system.

Table 4
Properties of Fibers

Fiber	Diameter (mm)	Length (mm)	Density (kg/cm^3)	Young's Modulus (Gpa)	Tensile Strength (Mpa)	Elongation at Break (%)
Vinylon (PVA) monofilament	0.20 - 0.25	12	1300	31	900	6 - 8
Polypropylene strand type	0.10 - 0.15	8	910	12	500	8 - 10
Glass* strand type	0.15 (30x)	10	2700	70	1250	3 - 5
Coconut monofilament	0.20 - 0.45	12	1180	8 - 12	100 - 150	20 - 25
Sisal monofilament	0.05 - 0.20	12	1270	12-15	400-460	13 - 15

* High modulus fiber used for comparison of strength properties

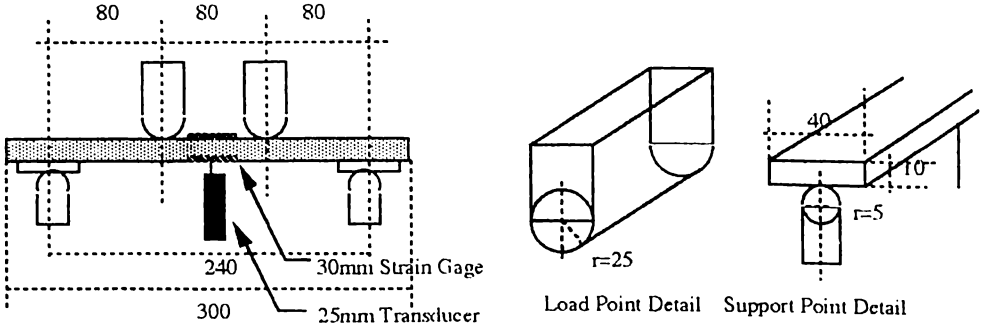
Mix Proportioning, Method of Mixing and Casting

The adopted mix proportion has a W/C=35 and 45%, sand-cement ratio (S/C) of 10, 15, 20, and 30%, retarder admixture dosage of 1.0% by weight of gypsum, mineral admixture dosage of 5 and 10% by weight of cement, and a fiber volume of 1-4% per total volume of matrix. A simple mix code designation is adopted in the experiments, for example a code G35-P10 means a plain gypsum mortar with W/G=35% and pulp (P) content of 10%. Likewise for fiber composite series a code V2-G45 refers to a vinylon fiber composite (V) with 2% fiber volume in a gypsum-pulp (G) with W/G=45%. For the series of gypsum-sankelite matrix a code of GS was used.

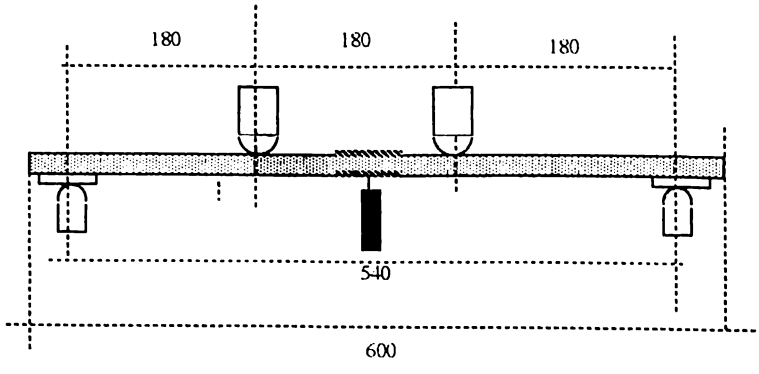
The concrete were mixed in a 5-liter Hobart mixer in the following order, that is (1) half of the dry materials and three-fourths water, (2) gradual introduction for fibers (half volume) and, (3) addition of remaining water and fiber. The total mixing time was about 10 minutes on the average. The designed workability of the base mortar is 180-200 mm, which is workable enough to dispersed a fiber volume of up to 3%. The mixture were then cast in its respective mold and stored in temperature controlled room (20°C, 80% RH) for 24 hours. After which the specimens were demolded and stored in 20°C water until the testing age of 7 and 28 days.

Test Set-up

Bending and compressive properties were taken from 40x40x160 mm standard beam specimen and fractured beam specimen respectively in accordance with ASTM standards (ASTM C-348, C-349). As for the 20x150x300 panel specimen, a special jig was made similar to the JIS A-1408 specification, as shown in Figure 1. Also, for larger panel specimen (20x300x600 mm) four-point loading test set-up was used. To measure the modulus of elasticity and the Poisson's ratio of various specimen, a 30 mm strain gage were placed at the mid span of both compression and tensile side. Likewise, a pair of 25 mm (LVDT) transducers measured the mid span deformation of the specimen.



(a) Test set-up for the 20x150x300 mm panel



(b) Test set-up for the 20x300x600 mm panel specimen

Figure 1
Flexural Set-up Adopted in the Experimental Program

RESULTS AND DISCUSSION

Morphological Properties of Gypsum-Pulp and Gypsum-Sankelite Fiber Composite

Microstructural study can provide plenty of insights and understanding to the structure-property behavior of the composite system up to the engineering level. Through microstructural analysis, knowledge and information on the mechanism of the reinforcing action of the fiber, the transfer of stresses from and to the fiber, and the rheological relationships between aggregates, fibers and binder can be evaluated.

Figures 3 and 4 show the typical structure of fly-ash and white silica from *Chuo* Electric Plant, Japan (hereafter called *white silica*), respectively. Note the angular and porous structure, as well as the relatively bigger particle size of white silica compared to the smooth and round structure of fly-ash under the same SEM magnification. This morphology presumably may be one of the major reasons for the high water absorption, decreased workability of the paste, and relatively less contribution to strength development of mortar by the white silica compared to fly-ash.

Figures 5 and 6 show the typical structure of cellulose pulp processed from recycled paper and Shirasu balloon (Sankelite) lightweight sand of volcanic origin. It can be seen that the smooth and hollow structure of Shirasu sand are its major attributes in providing lightweightness and added workability to the matrix. The pulp sand on the other hand showed a highly porous and angular structure which consequently lead to high water absorption and reduced workability of the gypsum mixture. This appears to be the major reason why the gypsum-pulp matrix can only accept a maximum fiber volume addition of 2% compared to the 3% by the gypsum-sankelite matrix at the same W/G and S/G ratio.

SEM micrographs in Figures 7-10 show the surface and section properties of the fiber reinforcement used in this study. It can be seen that sisal and coconut fibers basically possessed a multi-cellular structure typical of natural cellulose fibers. A single strand of fiber is composed of elongated oriented fibrils (principally crystalline cellulose) bound by a matrix (non-crystalline lignin complex). Both sisal and coconut fiber showed a fibril diameter range of 8-15μm. On the other hand, SEM micrographs (Figure 9) of polyvinyl alcohol (PVA) vinylon fiber showed a monofilament structure with fairly smooth and close surface with elongated marks left by polymer film drawing. Whereas, microstructure of the polypropylene fiber shows a synthetic multi-strand structure for additional bond strength efficiency (cf. Figure 10).

Figures 11 and 14 show typical fiber-matrix bond condition for various fiber in gypsum-pulp and gypsum-sankelite matrix. Also, the matrix-aggregate condition of these two type of matrices are shown in Figure 11. The following observations show:

(a) For the gypsum matrix, the interfacial region appears to be highly porous compared to the more solid and dense structure of cement matrix. At higher magnification, elongated needle like gypsum crystals ($CaSO_4 \cdot nH_2O$) are clearly identifiable in Figure 14. Capillary voids can be seen to be many times larger than cement matrix, and this observed characteristics were found to be common for both gypsum-pulp and gypsum-sankelite.

(b) It can be seen in the micrographs in Figure 11-14 that bonding mechanism is essentially a mechanical interlocking and physicochemical bonding. The rough surface and multi-strand structure of fibers offered extra anchoring points to the matrix especially in the case of sisal and polypropylene fiber hence giving an excellent mechanical bonding strength property. Crystal growth deposited at the surface interstices of the fibers are also revealed physicochemical bonding. It is a point of interest to see that crystal deposits at the polypropylene fiber surface are minimal compared to the PVA vinylon and natural fibers (Figure 12). This confirms the hydrophobic surface quality of the polypropylene fiber. However for the same polymer based vinylon fiber, it was observed that strong bond of matrix to the fiber existed, including that its physicochemical bonding is far excellent than the polypropylene. Akers (1989) noted that PVA fibers have good affinity with water and cement matrix because of its polymer structure, that is, the possession of hydroxyl group essential for bonding with water-based binder such as cement or gypsum. In the case of natural fibers, as expected, the excellent surface wettability of natural fibers provided an increased physicochemical bonding with gypsum matrix (Figure 13). It can be seen that crystal deposits presumably gypsum gel and $CaSO_4 \cdot nH_2O$ crystals accumulated at the fiber surface and interstices.

(c) Gypsum crystal formed at the interfacial region seemed to provide a good interlocking mechanism. However, the aggregate-matrix interfacial bond appears porous and, a closer look at the sankelite sand surface would show that there is no clear evidence of physicochemical bonding between the rich SiO_2 sankelite sand and the gypsum hydration crystals.

Effect of W/G ratio and lightweight aggregate (pulp and sankelite) to the Fresh and Mechanical properties of plain gypsum mortar

Table 5 lists the fresh and mechanical properties of plain gypsum mortar. Figures 15-19 show the various parameters which affects the fresh and mechanical properties of a gypsum pulp or gypsum-sankelite mortar. Findings show:

(a) Significant decrease in the workability in terms of flow value of the gypsum paste with an increasing cellulose pulp or sankelite sand content was observed (Figure 15). This decrease is due to the filler effects of aggregates and the high water absorption of pulp and sankelite aggregates. However this property can be greatly improved through the introduction of superplastisicer. For this two types of lightweight aggregate the cellulose pulp showed the greatest water absorption, which can later pose some problems with workability and effective fiber volume addition. The angular and porous structure as observed from the SEM micrograph are believed to be the major factors causing this behavior (cf. Figures 11-13).

(b) It is generally known that α-gypsum sets very fast leaving no ample time for proper casting and vibration of the mixture in forms. Hence, an inorganic retarder was used to delay the setting time, and various percentage dosage to gypsum matrix were examined. Figure 16 shows the effect of retarder to setting time. Based from this results, an

optimum dosage of 1% is most recommendable, such that a delay in the final setting time to about 1.25 hours can be achieved.

(c) The effect of W/G ratio to both bending and compressive strength shows that it follows the typical trend found in cement based composite, that is, at an increasing C/W ratio a linearly increasing (Fc') strength occurs. It can be seen in Figure 17 that variation in the linear relationship is affected by the aggregate proportion, especially in the case of cellulose pulp where inherent high water absorption property lead to reduce workability and overall change in the effective W/G ratio of the mixture.

(d) The maximum proportion of lightweight pulp or Shirasu aggregate that will still produce a highly workable mix were found to be in the range of 10-20%. Since the objective of the study is to fabricate lightweight, low-cost but of sufficient mechanical strength building element, it is necessary to adopt a high aggregate proportion of 10 and 15 % were found to be the most appropriate proportions based on the criteria of workability and strength. Figure 18 shows the relationship of gypsum-mortar unit weight to its strength properties. Note that for a typical unit weight of 1400 kg/m^3 a compressive and bending strength of about 200 and 60 kgf/cm^2, respectively, can be attained at various proportions.

(e) The flexural modulus of elasticity as computed from the bending stress-strain curves shows that for a typical compressive strength of 150-250 kgf/cm^2 and unit weight of 1600 kgf/m^3, the elastic modulus ranged from 150000 to 200000 kgf/cm^2 (Figure 19). Compared with the empirical equation of the elastic modulus given by the AIJ (Architectural Institute of Japan, 1993) or ACI (American Concrete Institute, 1993), the gypsum mortar likewise follows the same trend as the typical concrete.

(f) Figure 20 shows the bending and compressive strength development of various gypsum-pozzolan-pulp mortar at standard curing condition. It can be observed that increase in strength by as much as 20% occurred as early as 7 days, and tapered off to 11% at 63 days. This behavior can be seen for all pozzolanic material especially at 10% gypsum replacement. The order of strength increase contribution of various pozzolanic materials was seen as (1) silica fume (2) white silica and (3) fly-ash. Contrary to expectation, the 10% substitution by mineral admixture showed marginal strength increase which the author presume to be caused by increase viscosity in the gypsum mixture due to the absence of superplastisicer. Otherwise it might produce a more appreciable strength increase which is commonly evident for matrices with pozzolanic additions.

Effect of fiber reinforcement to gypsum-pulp and gypsum-sankelite mortar

Table 6 list the fresh and mechanical properties of gypsum fiber composite. Figure 21 to 23 show the effect of various parameter to the flexural and deformation properties of various gypsum fiber concrete. From these results, it can be observed that:

(a) Due to the lesser workability of the gypsum-pulp matrix caused by the higher absorption index of cellulose pulp, the introduction of fiber was limited to a maximum of 2%, that

is in the absence of high range water reducing admixture (HRWR) or superplastisicer. While, for gypsum-sankelite a fiber introduction of 3% was attained with still sufficient workability property. The difference in the workability of the two matrices is due to the rheological relationship of aggregates and fiber, and this can be confirmed from SEM micrographs.

(b) It can be seen in Table 6 that there is no significant increase in the compressive strength of the composite with an increase in fiber such as polypropylene and the natural fibers especially at higher fiber volume. This trend is generally expected for low-modulus types of fibers because such fibers do not contribute any reinforcement against compression. Theoretically, this behavior can be proven by the simple *law of mixture*, that is

$$E_c = E_m\left(1 - V_f\right) + \eta_o, \eta_l, \eta_b E_f V_f \qquad (1)$$

where E, V, σ, ϵ refer to elasticity, volume fraction, general stress and strain of constituent material, and subscripts c, m and f refer to composite, matrix and fiber respectively, *no, nl, nb* are efficiency factors for fiber orientation, length and bonding condition, respectively. The equation refers to the contribution to strength of matrix and fiber components of the fiber composite.

If Equation 1 is normalized by the elastic modulus of matrix (*Em*),

$$\frac{E_c}{E_m} = \left(1 - V_f\right) + \eta_o, \eta_l, \eta_b \frac{E_f}{E_m} V_f$$

$$\frac{E_c}{E_m} = 1 + V_f\left(\eta_o, \eta_l, \eta_b \frac{E_f}{E_m} - 1\right)$$

Assuming that the strain developed by the fiber and the matrix at the interface is equal ($\epsilon_f = \epsilon_m$), equation 5 becomes

$$\frac{\sigma_c}{\sigma_m} = 1 + V_f\left(\eta_o, \eta_l, \eta_b \frac{E_f}{E_m} - 1\right)$$

$$\sigma_c = \sigma_m\left(1 + V_f\left(\eta_o, \eta_l, \eta_b \frac{E_f}{E_m} - 1\right)\right) \qquad (2)$$

$$\sigma_c = \sigma_m \cdot \psi \qquad (3)$$

Hence if the elastic modulus of the fiber (E_f) is far less than the elastic modulus of matrix (E_m) and coupled with a relatively large fiber volume fraction (V_f), then the factor ψ would be less than one, thereby resulting to a compressive strength (σ_c) less than that of the plain unreinforced matrix. This simple derivation confirm the trend observed in Table 6. Furthermore as a confirmation, in the case of vinylon and glass fiber having an elastic modulus of about 30 and 70 GPa which is about 1.25-3 times that of the plain matrix, test results showed a slight improvement in the compressive strength.

(c) For both gypsum-pulp and gypsum-Shirasu matrix, increase in first crack strength at 7 days age due to reinforcement of vinylon, polypropylene, sisal and coconut fiber is quite significant, that is, at the range of 15-25%. This characteristic may be due to relatively low elastic modulus (Ec $\approx$ 130,000 kgf/cm^2), flexural strength ($\sigma_c \approx$ 50 kgf/cm^2) and ductile deformation property of the gypsum matrix, hence giving the fiber adequate chance to transfer and redistribute stresses throughout the matrix system. This characteristic is different to that observed in cement matrix where increase in first crack strength even with high modulus fiber like steel and glass where only limited to about 15% (ACI-544, 1989; Swamy, 1990).

(d) For fiber volume of 1% improvement to ultimate bending strength is fairly negligible as can be seen in the load-deformation diagram for various fiber reinforcement and for both gypsum-pulp and gypsum-sankelite matrix (cf. Figures 21 and 22). However as fiber volume expected, the relatively strong PVA-vinylon and sisal fiber showed an excellent post-crack characteristics, indicating a high energy absorption capability. This may be attributed to their excellent fiber-matrix bond condition as shown by the SEM micrograph (cf. Figures 5-8). The polypropylene and coconut fiber, on the other hand, showed only a fair ductile characteristics. This observed lower post-crack property is presumably due to lesser fiber-matrix bond strength as seen from the relatively smooth surface of coconut fibers and to the hydrophobic surface of polypropylene fiber. Hence the difference in the post-crack strength and toughness of a fiber composite can be greatly attributed to its varying fiber-matrix bonding mechanism.

(e) Since one of the aim for this developmental study is on the investigation of the feasibility of gypsum-natural fiber mortar for building elements, various panel sections were investigated. Figure 21-23 show the variation of strength according to shear-span ratio or specimen dimension. It can be seen that the ultimate bending strength of the panel decreases with the decrease in the shear-span ratio or volume of stressed material. In spite of this, the load-deformation behavior is fairly consistent in all specimen dimension especially in terms of toughness and ductility of the gypsum-fiber composite material. It was also observed that for efficient fiber reinforcement such as sisal, the effect of fiber volume to strength under various specimen scale dimension is very significant, that is, for thinner sections the ductility and strength contribution of efficient and strong fibers are more significant compared to other efficient fibers such as coconut.

CONCLUSION

This comparative and developmental research study has shown that the utilization of natural fibers such as coconut and sisal to a gypsum matrix is highly feasible. Utilization of natural fibers can solve two significant problems, namely, elimination of solid waste and the provision of a valuable construction materials. Based from the experimental results, the following significant conclusion can be drawn:

1. SEM micrograph revealed insights on the structure of various pozzolan and various lightweight aggregate materials. Morphological characteristics that influences workability, strength development and bonding to cement matrix of pozzolan and lightweight material were clearly observed. Morphological and physicochemical interlocking between gypsum hydrated products and fibers govern both the bonding mechanism, crack deflection and arrest mechanism.

2. Increasing the lightweight aggregate volume can considerably decrease the flowability of the gypsum matrix. Hence, a highly flowable but relatively strong gypsum matrix with W/G=35-45% and S/G ratio of 10-20% was adopted as the most appropriate mix, which at the same time can enable a 2% fiber volume reinforcement to its matrix.

3. The gypsum matrix with either pulp or sankelite follows the same linear C/W-strength relationship as the cement matrix. A typical compressive strength of 150-200 kgf/cm^2 and bending strength of 50-60 kgf/cm^2 can have an average unit weight of 1500 kgf/cm^2 and an elastic modulus of 150000-200000 kgf/cm^2.

4. Mineral admixture can increase the strength by 20% at 7 days and 11% at 63 days, and continuously to increase with time. Apparent optimum gypsum substitution by weight in this experiment showed to be 10%. Ability of either pozzolanic material or lightweight aggregate to improve workability are highly dependent on its physical and morphological structure.

5. Fiber reinforcement to gypsum matrix showed positive results compared to cement based matrix. Increase in 7-day strength by 15-25% due to either vinylon, polypropylene, sisal and coconut fiber reinforcement occurred. The principle of *Law of Mixture* also satisfactorily describes the contribution of both the fiber and matrix to every mechanical properties of gypsum fiber composite.

6. In terms of ductility and toughness, gypsum matrices reinforced with vinylon and sisal showed an excellent load-deformation behavior, followed by the polypropylene and coconut fiber. The observed difference in ductility are attributed to the different degree of bonding between fiber and matrix.

7. Scale effect is very significant for fiber concrete in various panel dimension. Strength efficient fiber such as sisal magnifies the scale effect at various fiber volume fraction, while for lesser efficient fiber such as sisal magnifies the scale effect at various fiber volume fraction, while for lesser efficient fiber such as coconut this effect appears to be negligible. Generally from the test results, the fiber volume fraction followed by the gypsum matrix proportions are the two major factors that influence the scale effect in panels.

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Table 5
Fresh and Mechanical Properties Plain Gypsum Mortar at
Various W/G and S/G Ratio

MIXCODE	FIBER		MIX PROPORTION			FRESH PROPERTIES		BENDING STRENGTH				COMPRESSIVE STRENGTH kgf/cm²	
	TYPE	VF (%)	W/G (%)	S/G (%)	POZZ F/F+C (%)	UNIT WT (g/cc)	FLOW (mm)	FIRST CRACK 7-DAY	FIRST CRACK 28-DAY	POST CRACK 7-DAY	POST CRACK 28-DAY	7-DAY	28-DAY
G35	PLAIN GYPSUM	0	35	10	0	1.85	248	69.5	78.3	0.0	0.0	208	244
SERIES		0	35	15	0	1.85	176	70.6	68.0	0.0	0.0	230	250
		0	35	20	0	1.89	138	70.0	79.5	0.0	0.0	207	282
G45	PLAIN GYPSUM	0	45	10	0	1.83	flowing	63.5	89.1	0.0	0.0	194	226
SERIES		0	45	15	0	1.82	235	58.3	68.1	0.0	0.0	183	206
		0	45	20	0	1.81	155	63.6	61.2	0.0	0.0	201	217
GS35	PLAIN GYPSUM	0	35	10	0	1.42	173	45.1	51.0	0.0	0.0	195	228
SERIES		0	35	15	0	1.39	143	40.0	55.2	0.0	0.0	180	213
GS45	PLAIN GYPSUM	0	45	10	0	1.34	flowing	38.8	49.6	0.0	0.0	150	195
SERIES		0	45	15	0	1.30	220	36.3	52.3	0.0	0.0	159	198
		0	45	20	0	1.22	160	29.3	51.6	0.0	0.0	119	190

Table 6
Fresh and Mechanical Properties of Gypsum Fiber Mortar at 7-Days

MIX-CODE	FIBER	MIX PROPORTION				FRRESH PROPERTY		BENDING STRENGTH (kgf/cm2)		COMPRESSIVE STRENGTH
	TYPE	VF (%)	W/G (%)	S/G (%)	POZZ F/F+C (%)	UNIT WT (g/cc)	FLOW (mm)	FIRST CRACK	POST CRACK	(kgf/cm2)
V1-G45	VINYLON	1	45	15	0	1.548	203	71.8	70.0	231
V2-G45		2	45	15	0	1.605	185	720	98.0	252
V1-G35		1	35	10	0	1.585	168	76.6	42.3	265
P1-G45	POLYPROPYLENE	1	45	15	0	1.660	172	63.7	37.0	227
P2-G45		2	45	15	0	1.548	140	63.1	53.5	237
P1-G35	POLYPROPYLENE	1	35	10	0	1.617	148	70.4	45.3	274
S1-G45	SISAL	1	45	15	0	1.603	183	67.4	43.0	247
S2-G45		2	45	15	0	1.600	147	68.8	67.0	232
S1-G35	SISAL	1	35	10	0	1.585	150	74.5	43.4	217
C1-G45	COCONUT	1	45	15	0	1.470	180	69.1	22.0	223
C2-G45		2	45	15	0	1.550	152	76.8	38.0	209
C2-GS35	COCONUT	2	35	10	0	1.457	148	52.4	36.2	218
C2-GS45		2	45	15	0	1.301	163	36.1	27.7	142
C3-GS45		3	45	10	0	1.245	153	36.3	37.0	183
S2-GS35	SISAL	2	35	10	0	1.505	145	58.1	55.4	219
S2-GS45		2	45	15	0	1.303	158	69.5	72.0	156
S3-GS45		3	45	10	0	1.303	146	72.2	100.0	161
P2-GS35	POLYPROPYLENE	2	35	10	0	1.512	145	54.7	48.2	217
P2-GS45		2	45	15	0	1.321	151	32.4	36.0	136

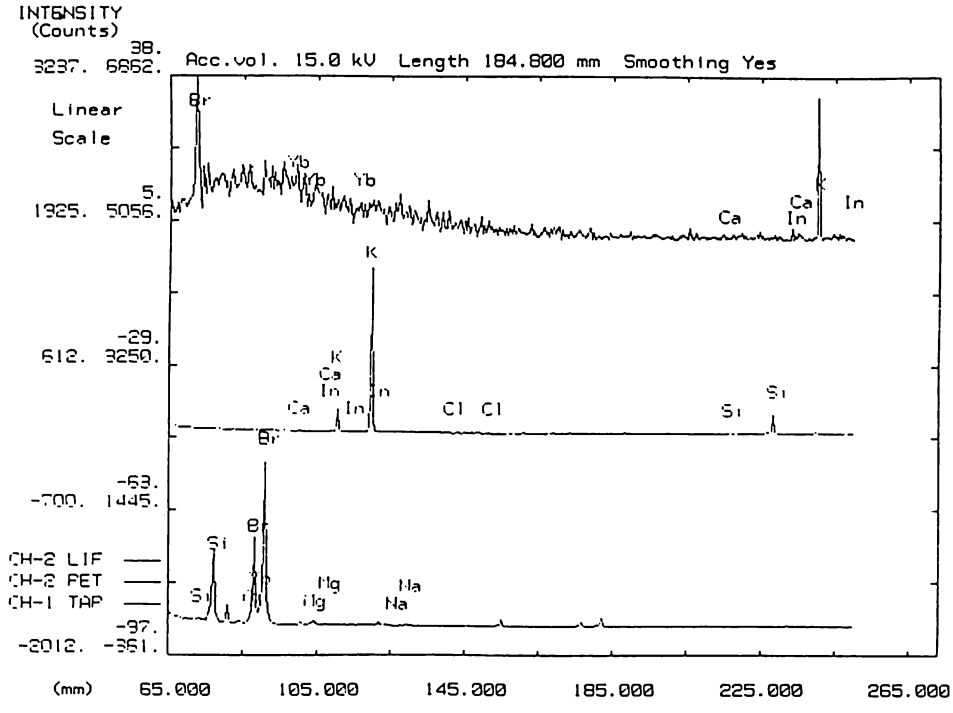

Figure 2(a) X-ray Flouresence Spectral Analysis of Silica Fume

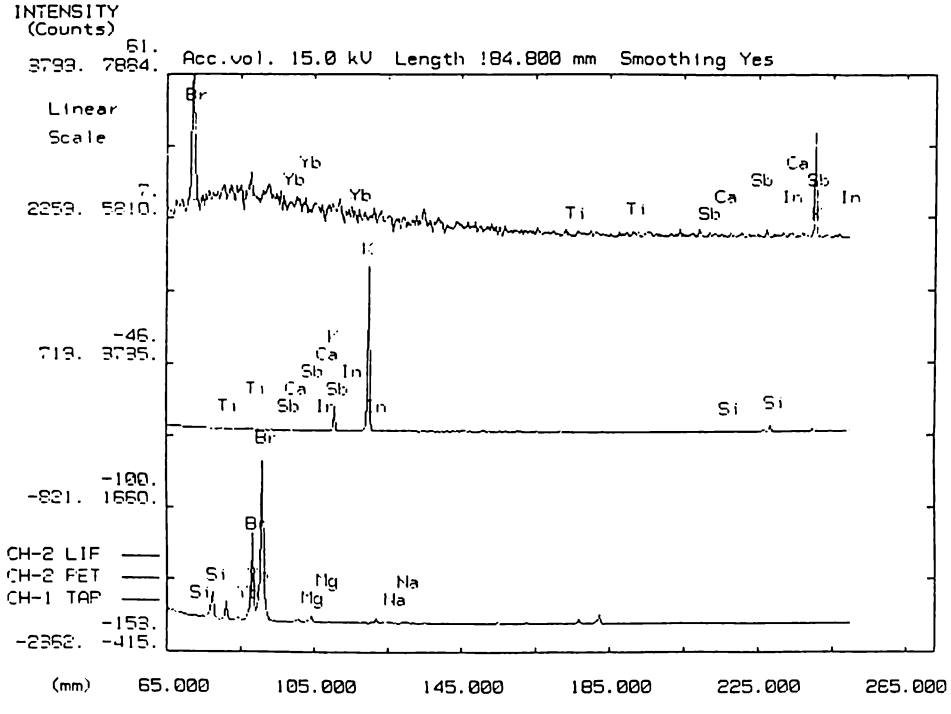

Figure 2(b) X-ray Flouresence Spectral Analysis of White Silica

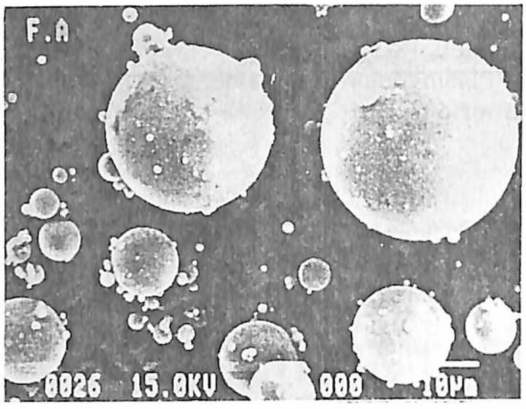

Fig.3. SEM micrograph of Fly-ash showing the smooth-round morphology

Fig.4. Morphology of White silica showing the angular and porous structure

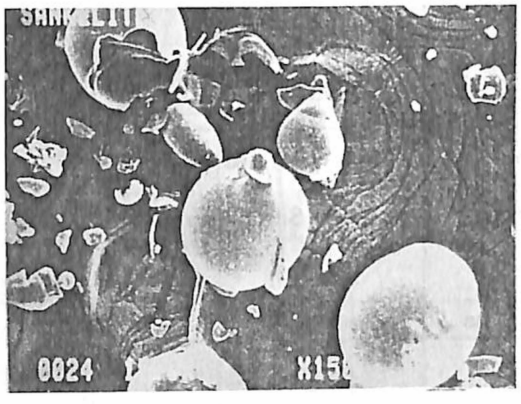

Fig.5. Hollow and smooth structure Shirasu balloon (sankelite sand)

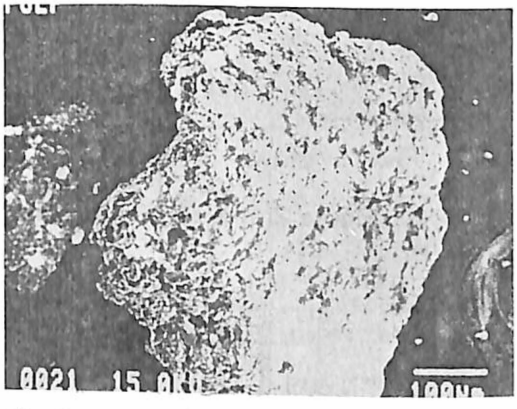

Fig.6. Angular and porous structure Cellulose (paper)pulp

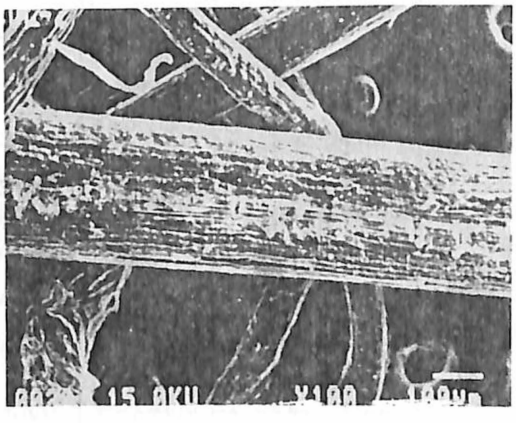

Fig.7. Surface and section morphology of Coconut fibers

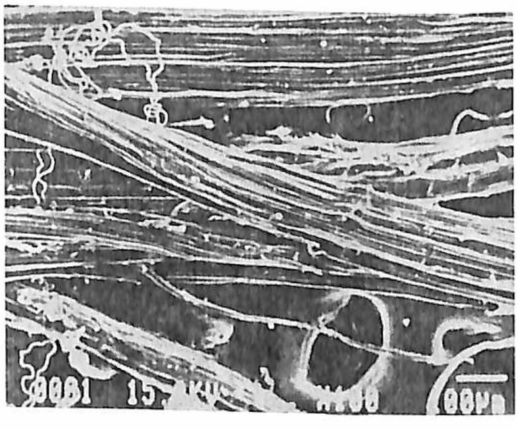

Fig.8. Structure of surface and section of Sisal fibers

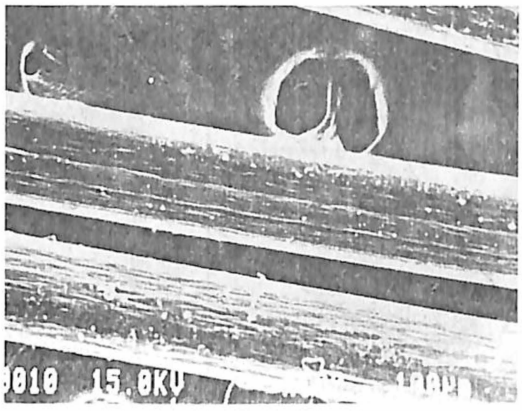

Fig.9. Morphology of vinylon fiber, showing the close and dense surface

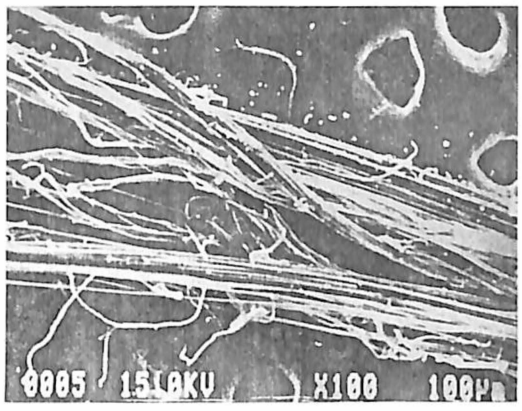

Fig.10. Morphology of polypropylene, showing the synthetic multi-strand structure

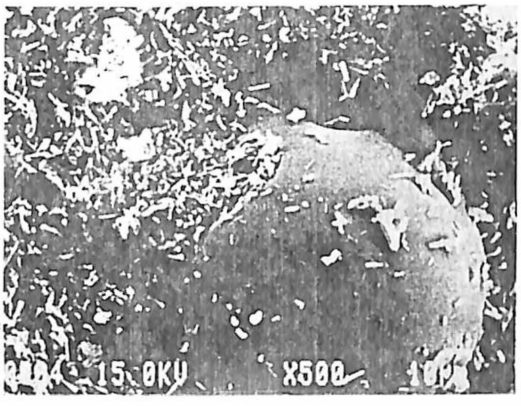

Fig.11. Sankelite aggt-matrix interfacial structure,showing the porous gypsum

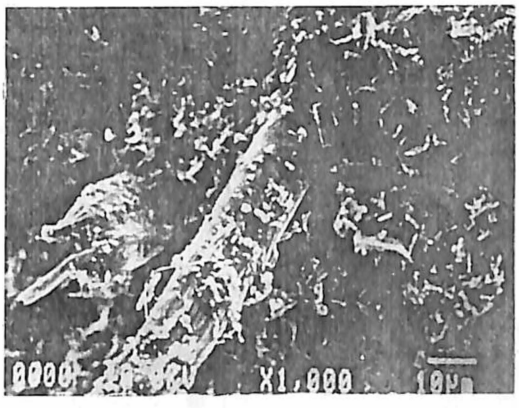

Fig.12. Vinlyon-gypsum matrix interfacial structure

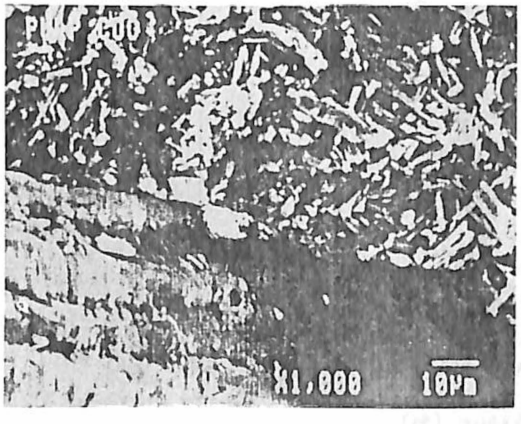

Fig.13. Coconut fiber-matrix morphology

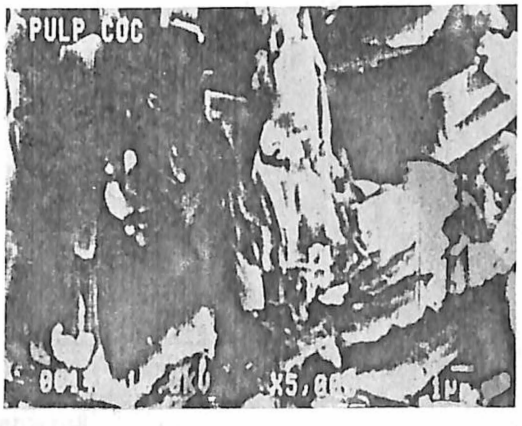

Fig.14. Magnified gypsum crystals at interfacial region of fiber and matrix

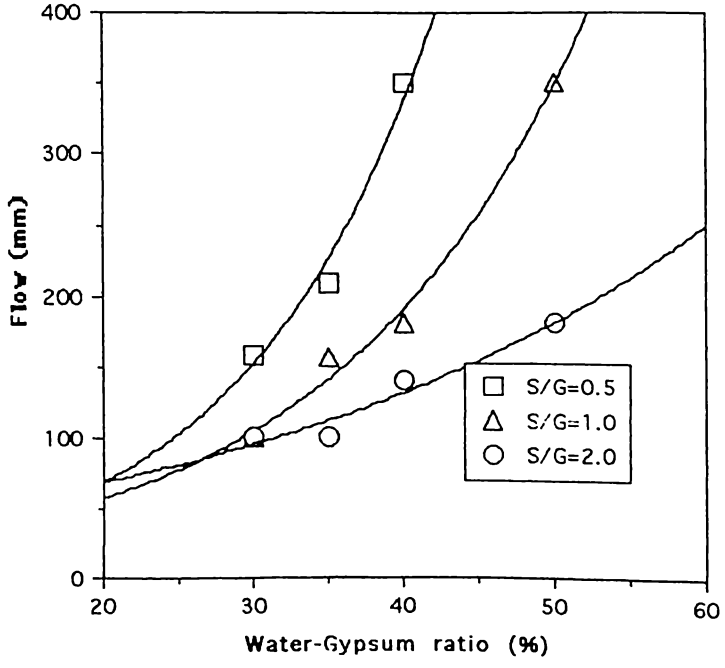

Fig.15. Trend of flow values for gypsum mortar without superplastisicer at various pulp content

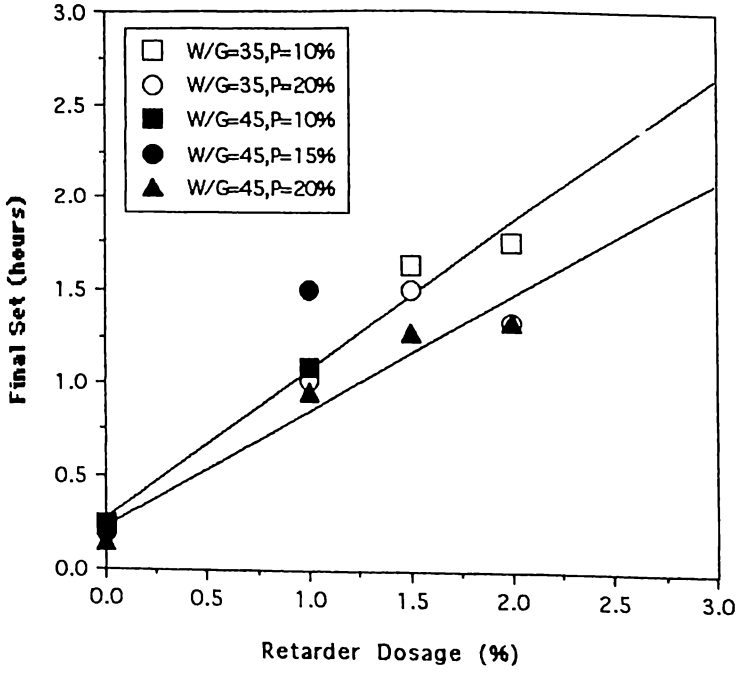

Fig.16. Effect of retarder dosage to final setting of plain gypsum-pulp mortar

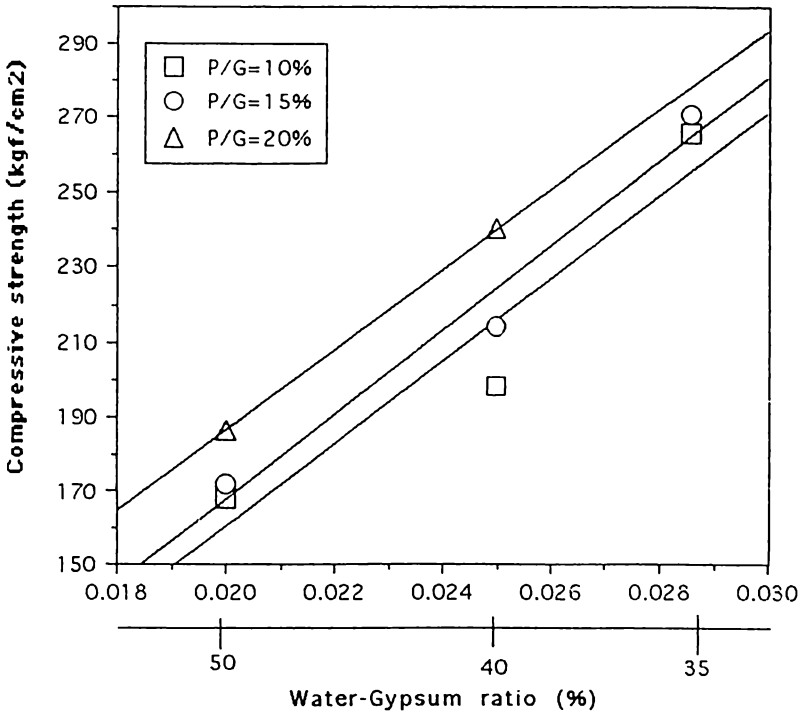

Fig. 17. Effect of W/G ratio to the compressive strength of plain gypsum mortar

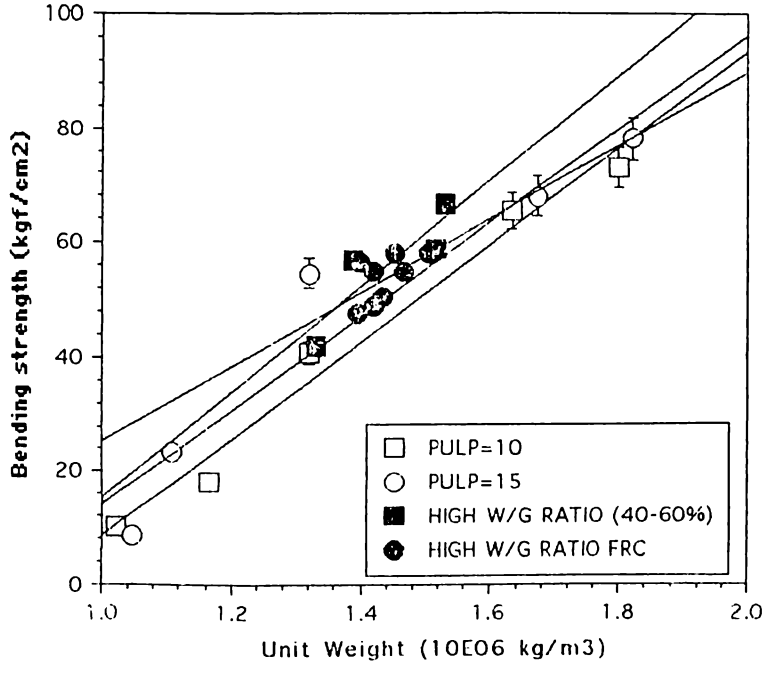

Fig.18. Relationship of unit weight and bending strength at 7 days for gypsum mortar with W/G = 35%

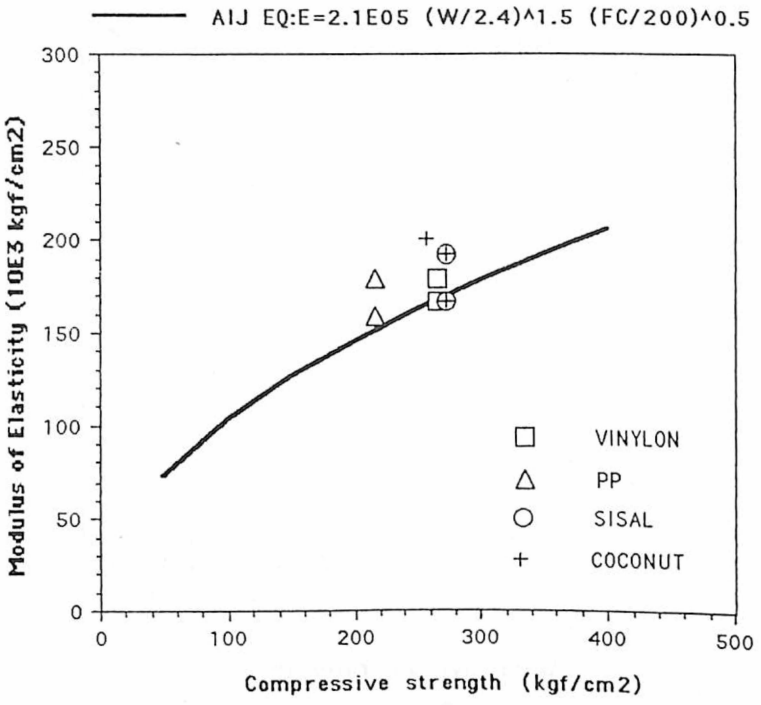

Fig.19. Modulus of Elasticity and strength relationship of gypsum mortar at 7 days

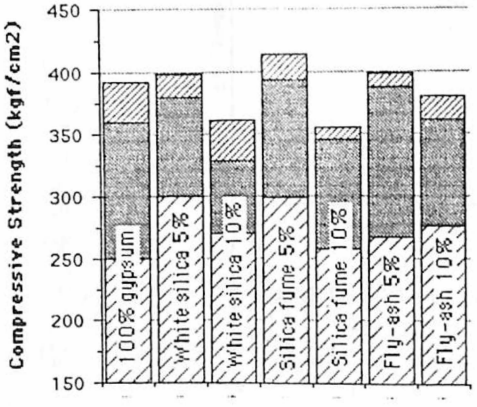

Fig.20(a) Rate of increase of compressive strengthat 20°C Curing

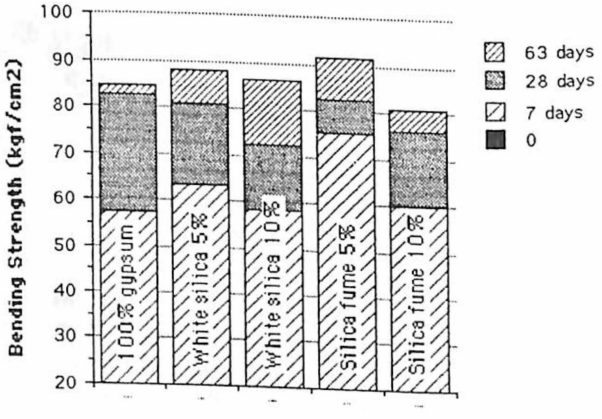

Fig.20(b) Rate of increase of bending strength at 20°C Curing

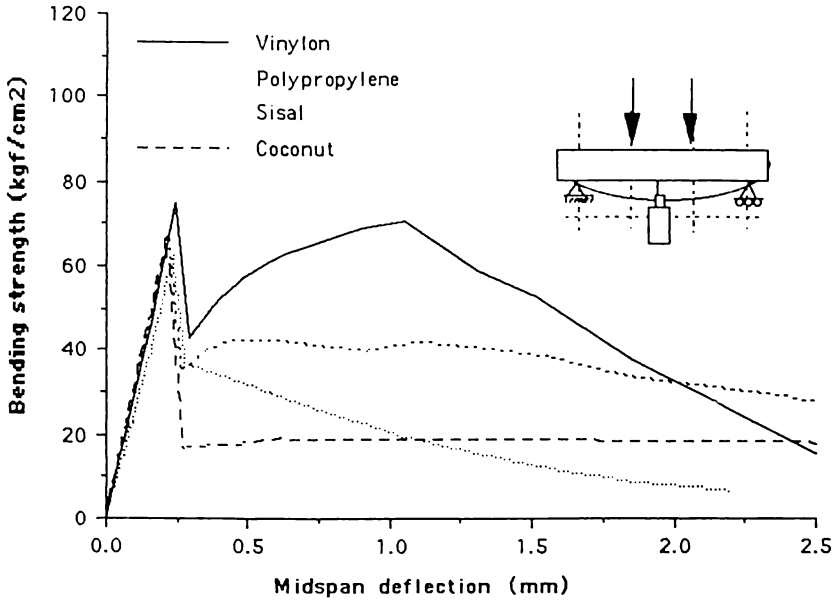

Fig.21(a) Stress-deflection of gypsum based mortar at 7 days with W/G = 45%, pulp = 20% and VF = 1% for 4x4x16

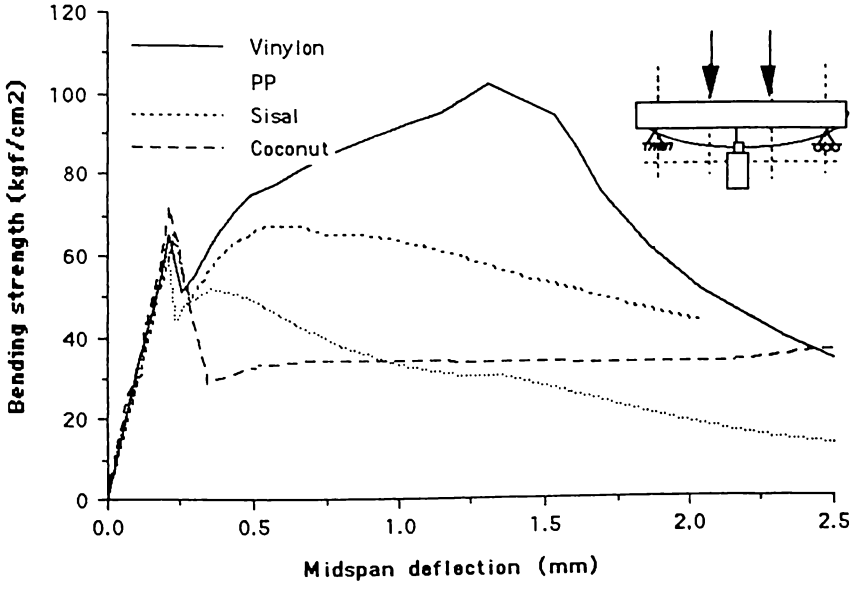

Fig.21(b) Stress-deflection of gypsum based mortar at 7 days with W/G = 40%, pulp = 20% and VF = 2% for 4x4x16

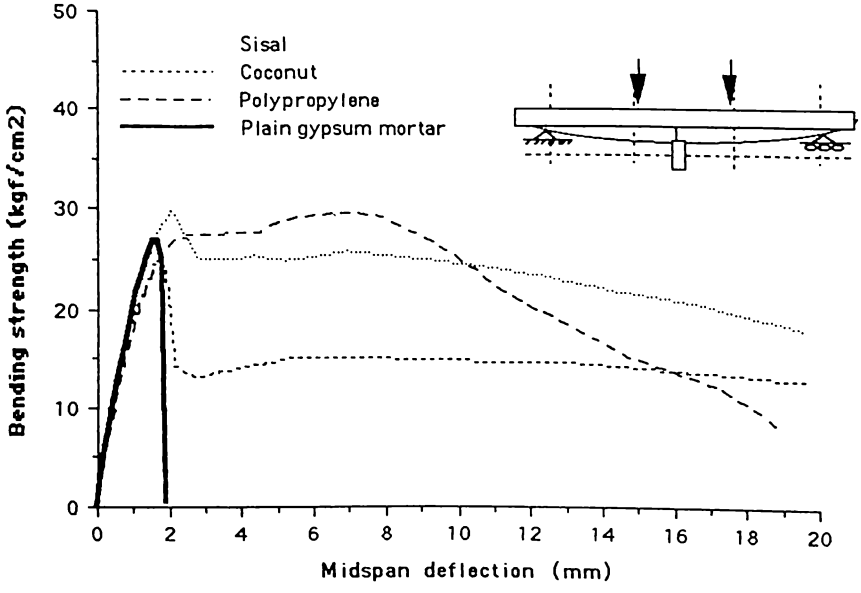

Fig.22(a) Stress-deformation of gypsum fiber composite 60x30x2 board with Vf = 2%, W/G = 45%

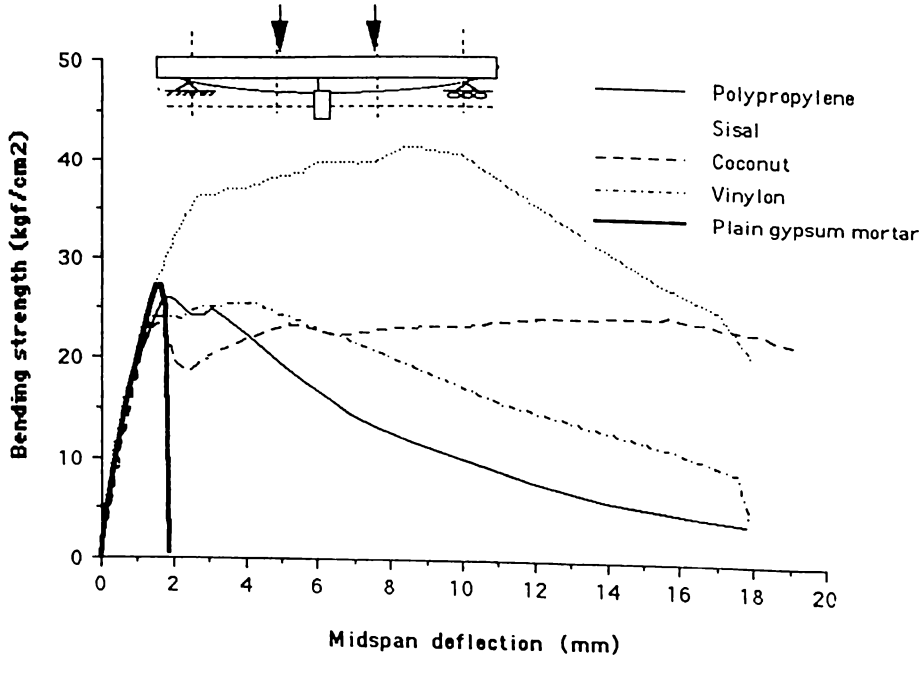

Fig.22(b) Stress-deformation of gypsum sankelite fiber composite 60x30x2 board with Vf = 3%, W/G = 45%

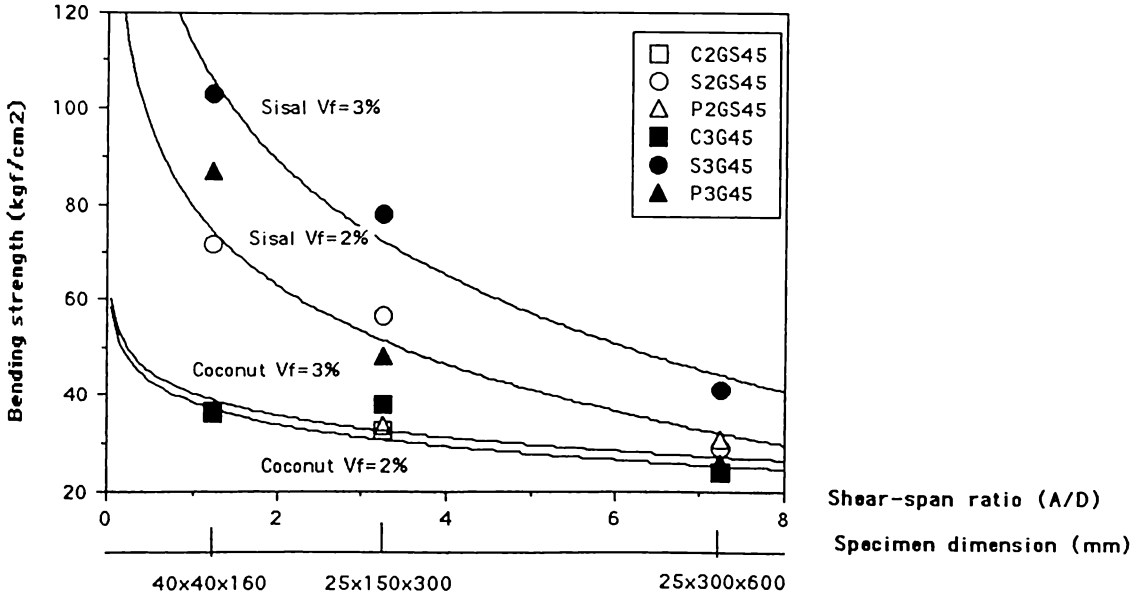

Fig.23 Effect of specimen dimension to the bending strength of gypsum-fiber mortar