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Wood-fibre reinforced plaster

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Gypsum plaster products are widely used in the Australian building industry; however, the cost of reinforcing these products, in the form of glass or sisal, is increasing. This paper describes the use of wood pulp fibres to reinforce the brittle plaster matrix and demonstrates that materials with considerable fracture toughness (greater than 40 times the matrix value) and flexural strength (2 to 3 times matrix value) can be produced.

1. Introduction

Australia has a long history relating to the use of plaster reinforced with natural fibres. The earliest plaster sheets, at the start of the century, were in the form of panels reinforced with hessian and wooden laths; later New Zealand flax was used and finally sisal fibre replaced flax as the reinforcement.

The gypsum industry can be divided into two distinct groups, one manufacturing calcined gypsum and the other using it to cast plaster sheets and other moulded products. Fibrous plaster can be formed by a batch process on inexpensive equipment and in the 1960s there were about 500 small factories operating in this way in Australia [1]. At the start of the 1980s there were less than 70 factories actively manufacturing fibre-reinforced plaster sheeting. The decline in fibrous plaster production was due to the introduction of paper-faced plaster board known world wide as "gypsum board" or "wall board". Two large companies, which manufactured all the calcined gypsum in Australia, captured most of the market in plaster-lining products by making large capital investments in the sophisticated plant needed to produce gypsum board by a continuous process.

Fibre–plaster products have been made with improved mechanical properties by using glass fibres as reinforcement in the plaster matrix [2]. Since glass-fibre reinforced gypsum (GRG) can be manufactured in a variety of moulded shapes having much greater strength and fire resistance than plasterboard, there is widespread interest in its use for internal structural applications [3, 4].

In Australia the current costs of sisal and glass fibres have aroused the need to study alternative reinforcing fibres for use in plaster products. This has resulted in examining wood pulp fibre which is readily available and a cheap source of reinforcement. The use of wood pulp fibre as a replacement for asbestos fibre has been successfully demonstrated in the $200 to 300 M Australian fibre-cement industry [5, 6].

The commercial production of both sisal- and glass-fibre reinforced plaster has not made use of slurry vacuum de-watering techniques. It will be shown that wood pulp fibre plastic composites can be manufactured by such a process with excellent mechanical properties.

2. Experimental details

2.1. Materials

The wood fibre used in this study was *Pinus radiata* kraft lap from Kinleith, New Zealand. The fibre was treated in the laboratory in a Valley beater with a bed-plate load of 5.5 kg and a stock concentration of 360 g oven-dried fibre in 23 litre water. The resulting pulp has a Canadian standard freeness value of approximately 700 ml.

The matrix was prepared from commercially available plaster of Paris (i.e. β-hemihydrate) obtained from Australian Gypsum Ltd.

2.2. Preparative methods

The essential requirements for optimum strength of fibre-reinforced composites are: good bonding between the fibre and matrix material, uniform distribution of the fibres and sufficient compaction to achieve a material with low voidage.

Two methods of fabrication were considered (see Table I). The first, which involved a high calcined gypsum to water ratio (e.g. 100 g calcined gypsum in 100 ml water) used normal dough mixing techniques. This method had proved relatively unsuccessful with sisal and glass fibres [2] as the fibres balled up around the mixer blades. The small wood pulp fibres have an average fibre length of 3 mm and average fibre diameter of 30 μm. These fibres dispersed reasonably well at low fibre loadings although some clumping of the fibres resulted at higher loadings.

The second method of fabrication was slurry/vacuum de-watering, a technique which had proved most successful with wood-pulp fibre cement composites [5]. Use of this method resulted in homogeneous dispersion of high loadings of fibre in a large volume of water (e.g. 100 g calcined gypsum in 600 ml water). However, the excess water had to be removed rapidly before the matrix began to set.

Both methods involved dispersing the required amount of fibre in tap water for about 5 min. Then the calcined gypsum was stirred for 1 min and the mixture poured into a 125 mm × 125 mm evacuable casting box where it was distributed evenly over the screen. An initial vacuum was drawn until the sheet appeared dry on the surface; it was then flattened carefully with

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TABLE I Preliminary study

Sample	Fibre content (% by mass)	G:W*	Conditions of cure (test time)	Flexural strength (MPa)	Fracture toughness ($kJ\,m^{-2}$)	Comments
1	2	1:1	Air cure (3 days)	12.7 ± 2.1	0.43 ± 0.03	
2	2	1:1	60° C/16 h (4 days)	13.6 ± 2.8	0.44 ± 0.09	
3	2	1:1	110° C/5 h (4 days)	2.6 ± 0.3	0.39 ± 0.01	Two samples only, temperature too high
4	2	1:6	Air cure (2 days)	10.6 ± 1.1	0.63 ± 0.06	
5	2	1:6	45–50° C/24 h (7 days)	13.4 ± 1.1	0.55 ± 0.08	
6	8	1:1	Air cure (3 days)	14.7 ± 1.8	1.22 ± 0.34	
7	8	1:1	40° C/24 h (4 days)	14.8 ± 0.9	1.07 ± 0.28	
8	8	1:1	105° C/24 h (6 days)	7.6 ± 1.3	1.10 ± 0.30	Density $1.16\,g\,cm^{-3}$, temperature too high
9	8	1:6	Air cure (7 days)	25.5 ± 3.2	2.68 ± 0.72	
10	8	1:6	45–50° C/24 h (4 days)	25.9 ± 2.6	2.85 ± 0.46	
11	14	1:1.45	Air cure (8 days)	17.9 ± 2.3	1.75 ± 0.36	
12	14	1:1.45	40° C/24 h (6 days)	8.6 ± 1.1	0.91 ± 0.40	Poor mixing of fibre
13	14	1:6	Air cure (6 days)	23.5 ± 1.4	4.07 ± 1.14	
14	14	1:6	45/50° C/24 h (4 days)	23.4 ± 2.1	3.60 ± 0.48	

*G:W gypsum to water radio during mixing.

a tamper. A vacuum of 60 kPa (gauge) was applied for 1 min. The sheet was then removed on the filter screen and pressed for 5 min at a pressure of 3.2 MPa. The load was applied slowly so as not to damage the sheets. After the sheet was pressed, the screen was carefully removed from the sheet and the sheet cured by one of the procedures indicated in Tables I to III.

2.3. Test methods

Specimens were cut with a diamond saw into rectangular strips measuring approximately 125 mm × 40 mm (of varying thicknesses). These test pieces were used for flexural strength and fracture energy tests. The flexural strength was measured in three-point bending as: $3Pl/2bd^2$ where P is the maximum load recorded during the test, l is the specimen span, b is the specimen width and d is the specimen depth. A span of 100 mm and a deflection rate of $0.5\,mm\,min^{-1}$ was used on an Instron testing machine (Model 1114). The results of the flexural tests were obtained using automatic data collecting and processing equipment. The fracture energy was calculated from the area under the load/deflection curve. For the purpose of this paper, the fracture toughness is given by the fracture energy divided by the cross-sectional area of the specimen. Comparisons of fracture energy or fracture toughness are only valid strictly for specimens of the same thickness.

Density values were obtained by weighing samples after drying them for 24 h in an oven at approximately 100° C and then taking measurements of the sample dimensions to determine the volume.

In all cases at least eight samples were tested for flexural strength, fracture toughness and density. Standard deviations are included in the tables.

3. Results and discussion

3.1. Preliminary study

A preliminary examination of the wood-pulp fibre-reinforced plaster (WRFP) system indicated the need to consider curing conditions and fabrication methods (see Table I).

Consideration of composites prepared with different curing regimes and fibre contents showed that at low loadings (2% by mass) the mode of preparation appeared to have little effect on mechanical properties (consider samples 1 and 4 and samples 2 and 5). At a fibre content of 8% (by mass) the slurry vacuum de-watering technique (G:W = 1:6) produced composites with improved properties; consider samples 6 and 9, also 7 and 10. At 14% (by mass) fibre content, samples showed similar improvements in mechanical

TABLE II Effect of fibre content

Fibre content (% by mass)	W:G*	Flexural strength (MPa)	Fracture toughness ($kJ\,m^{-2}$)	Density ($g\,cm^{-3}$)	Comments†
–	0.23	9.0 ± 0.8	0.05 ± 0.01	1.33 ± 0.02	Cured 12 days, pressed 1.6 MPa
2	0.16	14.5 ± 1.1	0.52 ± 0.04	1.49 ± 0.03	Cured 11 days, pressed 3.2 MPa
4	0.23	19.4 ± 2.2	1.22 ± 0.20	1.44 ± 0.03	Cured 11 days, pressed 3.2 MPa
6	0.27	24.8 ± 2.1	1.85 ± 0.23	1.46 ± 0.03	Cured 11 days, pressed 3.2 MPa
8	0.32	27.6 ± 1.4	2.62 ± 0.25	1.40 ± 0.04	Cured 11 days, pressed 3.2 MPa
10	0.37	27.7 ± 1.2	3.02 ± 0.24	1.37 ± 0.04	Cured 11 days, pressed 3.2 MPa
12	0.41	25.3 ± 3.6	3.01 ± 0.36	1.27 ± 0.02	Cured 12 days, pressed 3.2 MPa
14	0.47	23.9 ± 1.5	3.42 ± 0.43	1.24 ± 0.02	Cured 8 days, pressed 3.2 MPa

*After sample vacuum de-watered and pressed, then weighed to obtain water to gypsum ratio (W:G) in formulation.
†Samples cured at 22 ± 2° C in an atmosphere of 50 ± 5% r.h.

TABLE III Effect of curing conditions

Temerature of cure (° C)	Time of cure (h)	Flexural strength (MPa)	Fracture toughness ($kJ\,m^{-2}$)	Comment	W : G*
20	14 days	26.9 ± 1.8	2.49 ± 0.37		–
40	3	10.8 ± 0.9	3.66 ± 0.58	Still moist	–
	6	17.0 ± 2.7	3.40 ± 0.50		0.32
	6	17.0 ± 1.9	3.26 ± 0.66	Repeat	0.33
	15	23.0 ± 1.4	2.71 ± 0.62		0.32
	24	26.4 ± 3.0	2.12 ± 0.50		–
60	3	13.5 ± 1.1	2.93 ± 0.36	Still moist	–
	6	24.7 ± 1.6	2.23 ± 0.26		0.32
	15	26.7 ± 3.6	1.79 ± 0.29		–
	24	27.8 ± 2.9	1.96 ± 0.26		0.35
80	3	19.5 ± 1.5	2.37 ± 0.34		–
	6	25.9 ± 1.1	1.96 ± 0.19		–
	15	19.4 ± 3.9	2.12 ± 0.23		–
	24	15.0 ± 1.0	2.13 ± 0.34		–

*W : G water to gypsum ratio.

performance when slurry/vacuum de-watering techniques were used (see samples 11 and 13; also 12 and 14).

The above findings suggested that when studying the extended range of fibre contents (2 to 14% fibre by mass) the slurry vacuum de-watering technqiue should be used. The data in Table I also indicated that optimization of the relationship between temperature of cure and time of cure should be studied to enable rapid, yet efficient curing of the product. Samples 3 and 8 possess extremely poor mechanical properties due to the high temperature of cure (> 100° C) which may have caused excess water to be expelled forcefully from the composite leaving voids; also particle dehydration of the matrix material takes place at such temperatures.

3.2. Optimum fibre content

Table II lists the mechanical and physical properties of WFRP composites over the fibre content range 2 to 14% (by mass). Included in the table is the ratio of residual water to calcined gypsum (W : G) retained by the sample after pressing. The matrix sample was only pressed to 1.6 MPa as further pressure sometimes caused cracking of the sample; hence the high W : G ratio and low density value reported for this sample.

As the fibre content was increased the flexural strength increased to about 28 MPa when an optimum fibre content was reached at 8 to 10% (by mass) fibre (see Fig. 1). Further increase in fibre content resulted in a decrease in flexural strength. This decrease may be associated with poor fibre packing. Fig. 2 shows the plot of variation of composite density with fibre content. The change is non-linear; density decreases at a greater rate as the fibre content is increased. This supports the hypothesis of less efficient packing of the fibres at high loadings. The low density value of the matrix is due to the relatively low pressure, and hence high W : G ratio, used in its preparation (see Table II).

The property of fracture toughness showed the

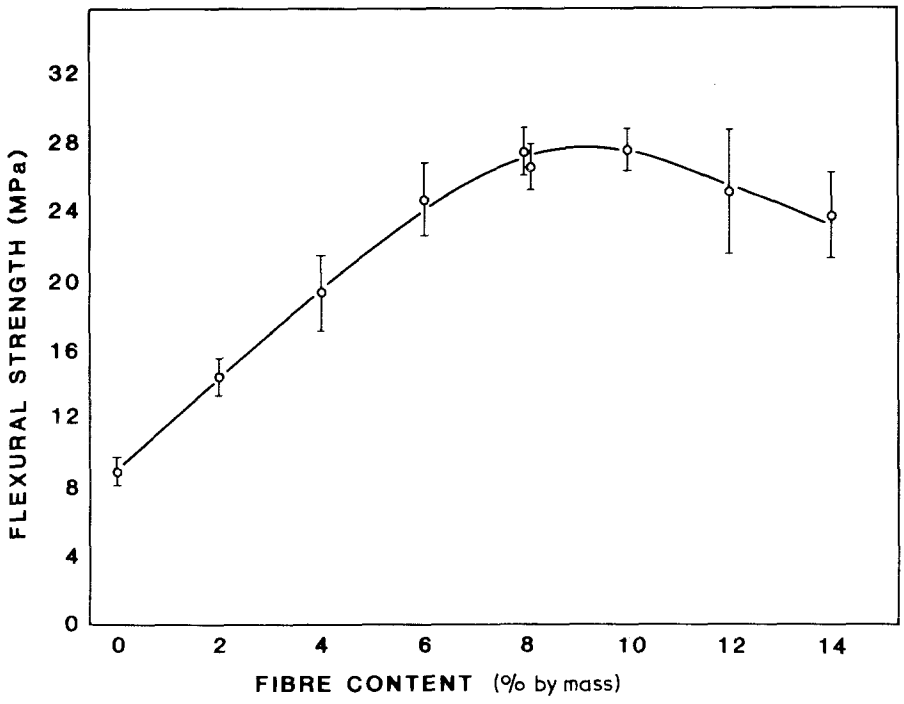

Figure 1 Flexural strength plotted against fibre content.

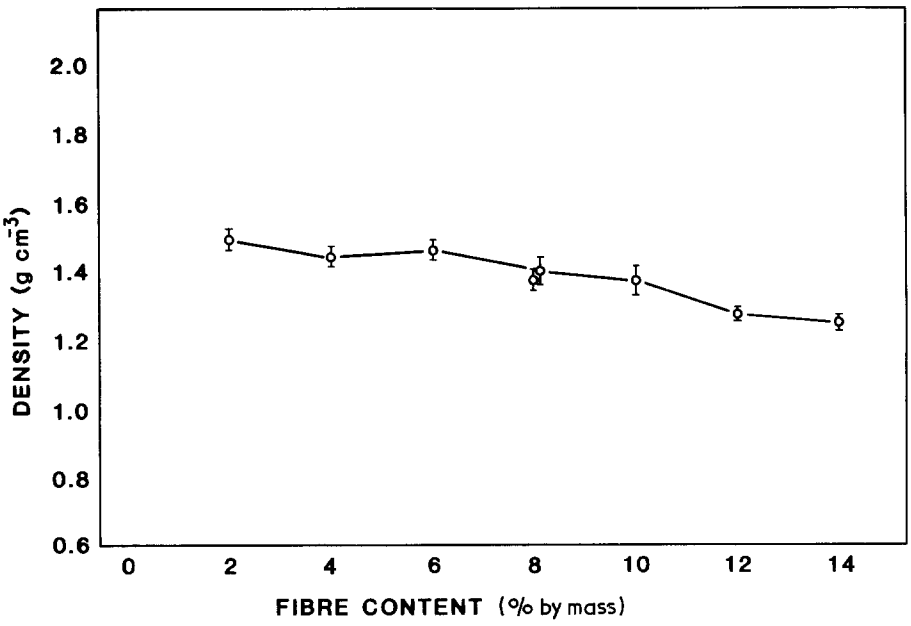

Figure 2 Density plotted against fibre content.

greatest improvement in value with increasing wood fibre content (see Fig. 3). The increase was greater than 40 times that of the plaster matrix when the wood fibre content was in excess of 10% by mass. This increase is due to the crack-arresting mechanism induced in the brittle matrix by the incorporation of reinforcing fibres. Earlier workers, studying glass-fibre reinforcement, had suggested [2] that the cracks which originated in the highly stressed tensile zones of the matrix, on reaching the fibre, travelled along the weak interface of the matrix and fibre. Thus, the energy was dissipated along the fibre–matrix interface and the fibres were pulled out. By contrast we find, with WFRP, that a strong interfacial bond is formed between fibre and matrix and considerable fibre fracture is evident at the fracture surface when examined by scanning electron microscopy [7]. This finding is in keeping with our earlier work, involving the fracture mechanisms [8] and bonding modes [9, 10] of wood-fibre reinforced cement mortars, which showed that strong bonds may form between fibre and matrix by hydrogen bonding or hydroxide bridges and considerable fibre fracture can take place during failure of the sample.

3.3. Optimum curing conditions

Preliminary studies (see Table I) had indicated that both initial temperature of cure and the time of cure could be important in achieving a fast turnover for the product in a commercial process. To study this effect WFRP samples containing 8% fibre (by mass) were prepared and placed in an oven at a controlled temperature (40, 60 or 80° C) for a given period of time (3, 6, 15 or 24 h). The samples were removed from the oven, placed in a desiccator to cool, and then tested (Table III).

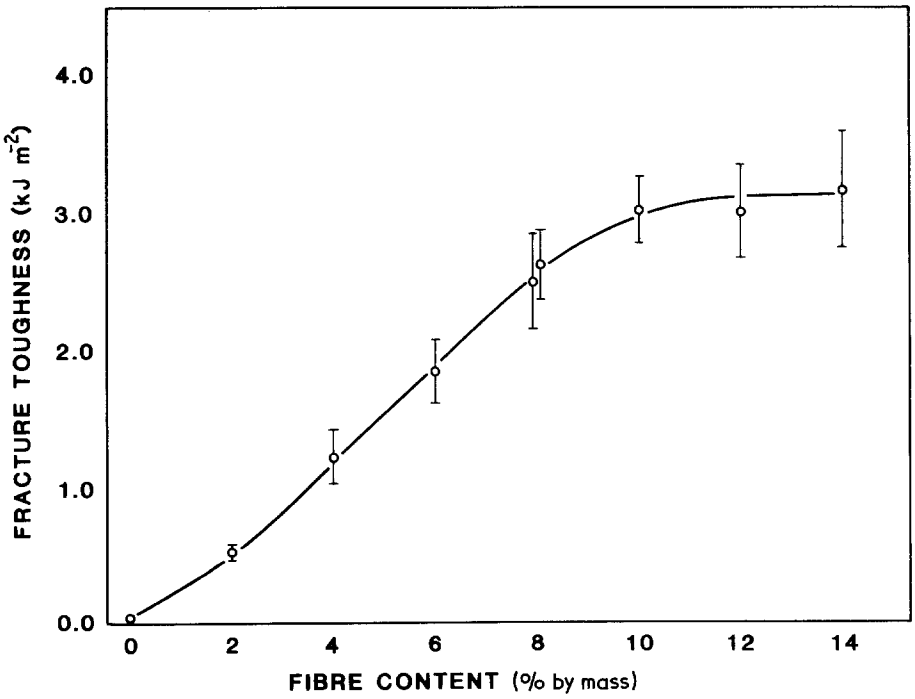

Figure 3 Fracture toughness plotted against fibre content.

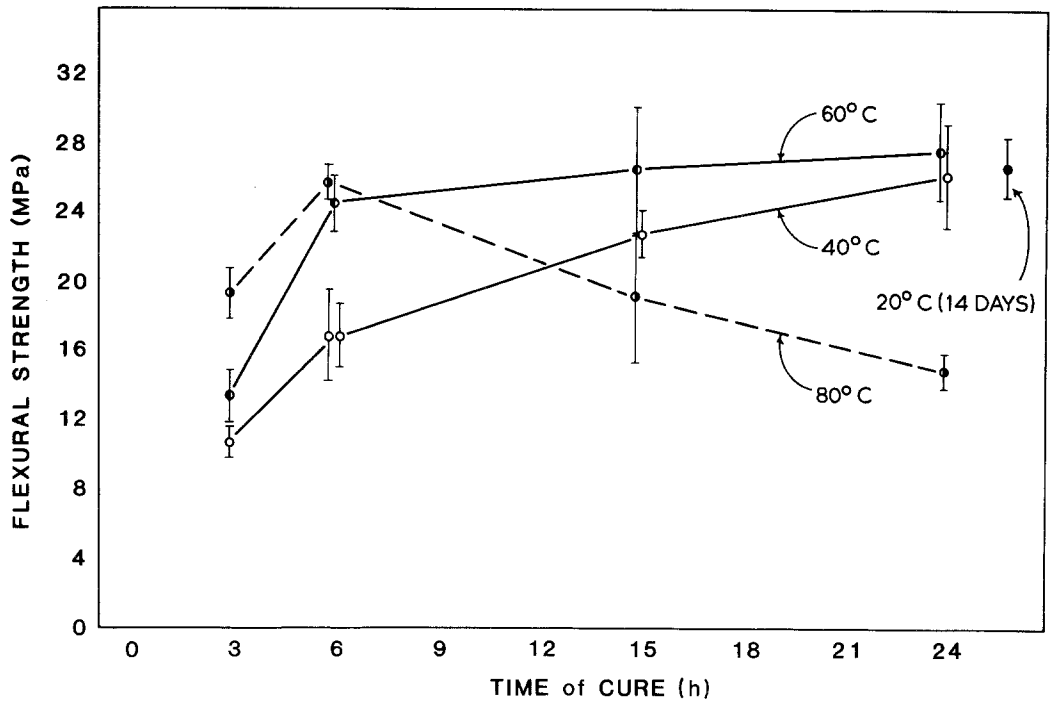

Figure 4 Flexural strength plotted against time of cure (at different temperatures).

A graph of flexural strength against time of cure (see Fig. 4) showed that flexural strength increased with cure time. When the oven temperature was 40° C the rate of strength gain was less than that when the oven temperature was 60° C. If the oven temperature is 80° C initial gain in strength is fast but after 6 h the product starts to lose flexural strength; due possibly to a rapid removal of the excess water vapour, causing voids. The results in Table I showed that at greater than 100° C very weak samples resulted with flexural strength less than the unreinforced matrix (< 10 MPa).

After heating at 60° C for 6 h, a sample (containing 8% by mass of fibre) has a flexural strength which is approximately 90% of the final strength achieved by curing at ambient temperature (20° C) for approximately 14 days (see Table III).

The change in facture toughness, of WFRP samples (containing 8% by mass of fibre) against time of cure at various temperatures is depicted in Fig. 5.

As indicated by the flexural strength data (Table III) the curing process at 40 or 60° C continues for the period of time studied (24 h). With increasing flexural strength we assume an increase in interfacial bond strength between fibre and matrix and hence an increase in the occurrence of fibre fracture when the samples are tested in flexure.

The high values of fracture toughness recorded at short times of cure (3 h) could be attributed to the high

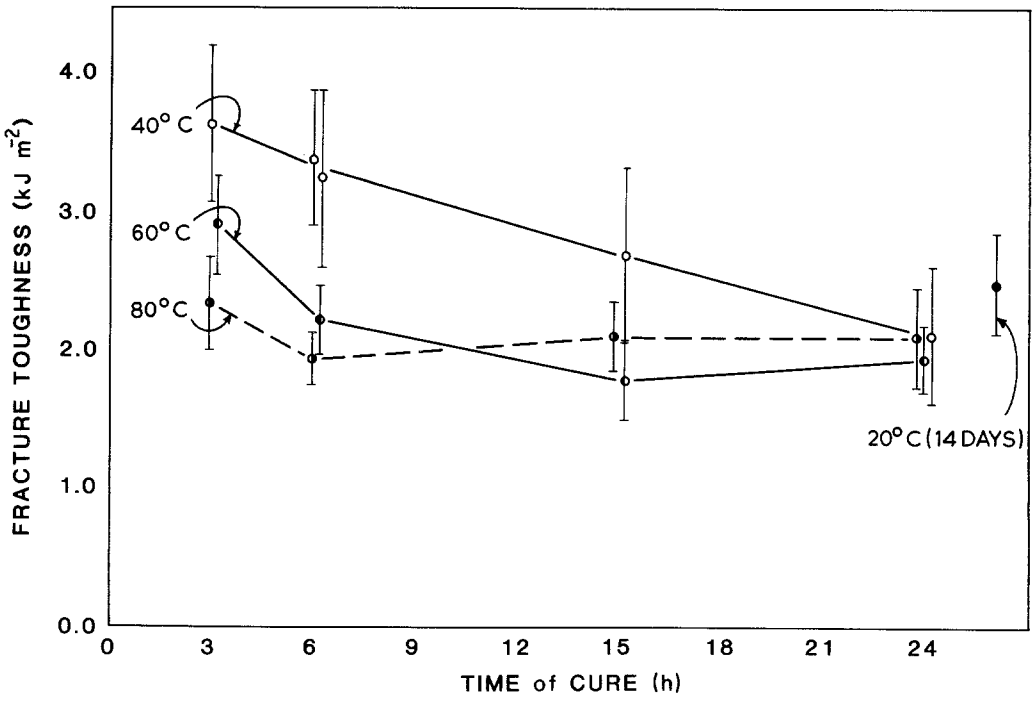

Figure 5 Fracture toughness plotted against time of cure (at different temperatures).

moisture content, incomplete cure, and so weak interfacial bond between reinforcing fibre and matrix. As the temperature of cure is raised or the time of cure increased the fracture toughness values are lowered. This is in keeping with an increase in interfacial bond strength and so a decrease in the occurrence of fibre pull-out instead of fibre failure.

4. Conclusions

1. Wood pulp fibres are effective as reinforcing fibres for plaster of Paris; at a fibre loading of 8 to 10% (by mass) the flexural strength is greater than 27 MPa (three times that of the matrix material).

2. The incorporation of wood pulp fibres into plaster causes the mode of failure to change from a brittle type to that of pseudo-ductile material. The fracture toughness increases with increasing fibre content, over the range studied, and is greater than forty times that of the matrix material (at loadings greater than 8% fibre, by mass).

3. Samples cured at 60° C for 6 h achieve approximately 90% of their final flexural strength which facilitates their handling and transportation.

4. A slurry/vacuum dewatering proces akin to current commercial practice in paper and fibre-cement manufacture could be used to manufacture wood pulp fibre-reinforced plaster products.

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References

1. M. J. RIDGE, ECAFE Seminar of Development of Building Materials (1967).
2. M. A. ALI and F. J. GRIMER, *J. Mater. Sci.* **4** (1969) 389.
3. J. F. RYDER, International Building Exhibition Proceedings Conference on prospects for fibre reinforced materials, London, (Building Research Establishment, Watford, 1971) p. 69.
4. G. A. KING, G. S. WALKER and M. J. RIDGE, *Building materials and equipment* August/September (1972) 40.
5. R. S. P. COUTTS and V. RIDIKAS, *Appita* **35** (1982) 395.
6. Anon, CSIRO Industrial News No. 146 May (1982).
7. R. S. P. COUTTS and J. WARD, unpublished results (1982).
8. R. S. P. COUTTS and P. KIGHTLY, *J. Mater. Sci.* **17** (1982) 1801.
9. *Idem, ibid.* **19** (1984) 3355.
10. F. E. MORRISSEY, R. S. P. COUTTS and P. U. A. GROSSMAN, *Int. J. Cement Composites Lightweight Concrete* **7** (1985) 73.

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