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ACCELERATED DURABILITY TESTING OF AUTOCLAVED WOOD-FIBRE-REINFORCED CEMENT-SHEET COMPOSITES

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Keywords

Panels	Wood	Properties	Mechanical
Cladding	Composite		Physical
	Cement	Mechanisms/causes of failure	Chemical
			Weathering
			Biodegradation
			Moisture cycling
		Testing and performance	Laboratory
			Field
			Accelerated

ABSTRACT

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The paper discusses possible aging mechanisms — corrosion, carbonation, moisture stressing, microbiological attack — and describes the results of tests aimed at accelerating these factors on the mechanical properties of wood-fibre-reinforced cement sheet. The results showed that carbonation appears to be the significant aging mechanism. The implications of the increased moisture movement caused by carbonation are discussed, together with the effects of fungal-cellar exposure on the mechanical properties of carbonated wood-fibre-reinforced cement sheet. It is additionally suggested that the effect of accelerated aging techniques on cellulose-fibre-reinforced cement sheet may depend on the pretreatment of the cellulose fibres.

1. INTRODUCTION

In New Zealand, asbestos-cement sheet cladding has been replaced by wood-fibre- (*Pinus radiata* Kraft pulp) reinforced cement sheet. The commercial production of asbestos-free autoclaved wood-fibre-reinforced cement sheet has been reported from Australia (Anon, 1982), and this material, produced by an identical process, has replaced asbestos cement flat sheet on the New Zealand market since late 1982. The new material is widely used in both domestic and industrial construction in the form of sheets and planks.

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The initial properties of laboratory-produced sheet have been extensively reported (Coutts, 1979, 1984; Andonian et al., 1979; Davis et al., 1981), but the effects of weathering on the long-term properties of the composite are unknown. For cellulose-fibre-reinforced sheet in general, durability estimates range from in excess of 50 years (Cape Boards, undated) to suggestions that the cellulose fibres may be liable to degradation (Cook, 1980; Mansur and Aziz, 1982). An extensive review by Gram (1983) reflects this uncertainty. From the practical viewpoint, changes in sheet properties, such as modulus of rupture, tensile strength, and impact strength on exposure to natural weathering are important to domestic as well as industrial users. Under the current house-building code (Standards Association of New Zealand, 1984), wood-fibre-reinforced cement sheet is considered to provide bracing and thus structural strength (Building Research Association of New Zealand, 1983). All exterior claddings must resist wind loadings.

Four potential aging mechanisms for autoclaved cellulose-fibre-reinforced cement sheet have been described (Sharman, 1983). These are: carbonation; microbiological attack; moisture stressing of the cellulose fibres; increase in the fibre—matrix bond. These may act independently or together.

Carbonation is important in the aging of asbestos cement, causing embrittlement (Jones, 1946; Opoczky and Pentek, 1975) In cellulose-fibre-based composites, carbonation may affect susceptibility to microbiological attack and/or the matrix—cellulose-fibre bond. Although the cement matrix should contain little or no free lime as a result of the autoclaving process, reaction with carbon dioxide still takes place (American Concrete Institute Committee 515, 1965). What is not known, however, is the rate and extent of the occurrence of carbonation. It seems very likely that these will depend on the physical condition of the sheet (e.g. porosity), as well as local climatic effects (relative humidity, temperature).

Microbiological attack on the cellulose fibres is seen by some workers (e.g. Mansur and Aziz, 1982) as a distinct possibility. However, the high alkalinity conferred on the product by the cement (Dinwoodie, 1978) and the requirement of wood-rotting fungi for slightly acidic conditions (Pinion, 1975) appear to make microbiological attack on the cellulose fibres, at least initially, unlikely. The long-term drop in pH of the sheet after weathering and carbonation is important here.

Moisture movement in wood is much greater than temperature movement (Ilston et al., 1979), and hence much more significant when considering changes in properties. In the course of natural weathering, the cellulose-fibre content will be exposed to wetting and drying cycles, causing alternate swelling and shrinking of the fibres. This may cause breakdown of the fibres and/or disruption of the fibre—matrix bond. This mechanism is important in particleboards (Beech et al., 1974).

An increase over time in the bond between the cellulose fibre and the matrix, resulting from crystalline growth into the fibre bundles, has been suggested. Scanning electron microscope studies of fracture surfaces (Davis et al., 1981) showed that the fibres in an unautoclaved cellulose-fibre—cement composite were loosely held after one day. Bonding was slightly increased at age seven days. After 90 days failure had changed from fibre pull-out to fibre fracture, indicating strong bonding between fibre and matrix.

In addition to the mechanisms described above, Cook (1980) considered alkaline degradation of cellulose fibres a possibility. The corrosion of glass fibres by cement-derived alkali has been attributed to the long-term decline in mechanical properties of GRC (Majumdar, 1975). If cellulose fibers are degraded by their alkaline environment, then it seems likely that this could be accelerated by methods similar to those described for GRC (Proctor et al., 1982).

The purpose of the present study was to subject autoclaved wood-fibre-reinforced cement sheet to conditions which would be expected to accelerate the aging mechanisms described above, and measure any subsequent changes in mechanical properties.

2. EXPERIMENTAL

The experimental design is summarised in Table 1.

2.1 Accelerated aging methods

Four different accelerated aging procedures were selected, corresponding to acceleration of the possible aging mechanisms described above. In three cases asbestos-cement sheet was included as a control. Samples were withdrawn after periods of accelerated aging, and were subjected to mechanical testing.

2.1.1 Hot water soak

Hot water soak tests have been used by the Building Research Establishment (1979), and others (e.g. Proctor et al., 1982) to accelerate the corrosion of glass fibres and the consequent loss of strength of glass-fibre-reinforced composites. Whilst it would be expected that any attack on the cellulose fibres by alkali from the cement would occur in autoclaving during manufacture, it was still felt to be of use to carry out long-term hot water soak tests to see if any changes, such as corrosion, or change in nature of fibre bonding, occurred.

The test used in the present study was very similar to that described by Proctor et al. (1982). Both wood-fibre-reinforced cement and asbestos-cement sheet were tested.

Samples were placed in racks in a copper tank 900 × 450 × 450 mm, externally insulated with 50 mm slab polystyrene foam, which also comprised the lid. The tank was filled with tap water, and a heater/stirrer was used to maintain the water at 50°C. The water in the tank was not changed, but made up to the original level with tap water every 2—3 days to counter evaporation losses.

Samples were removed after 20, 70, 200 and 350 days and their mechanical properties compared to those of a set of control samples.

TABLE 1

Summary of experimental design

(a) Summary of accelerated test methods

Test type	Materials tested	Exposure duration before samples removed
Hot water soak	asbestos-cement wood-fibre cement	0, 20, 70, 200, 350 days
V 313	wood-fibre cement	0, 10, 20, 35, 50 cycles
Carbonation	asbestos-cement wood-fibre cement	0, 2, 4, 8, 10% weight increase
Fungal cellar	asbestos-cement wood-fibre cement — both un- and fully carbonated	0, 6 months

Note: All samples withdrawn subjected to mechanical tests as per Table 1(b).

(b) Summary of mechanical tests

Mechanical test	Perpendicular to principal fibre direction[a]	Parallel to principal fibre direction[a]	Number of replicates (each direction)
Modulus of rupture	X	X	3
Tensile strength	X	X	6
Internal bond	not applicable		6
Impact strength	X	X	6
Moisture movement	X	X	3
Modulus of elasticity in bending	X	X	from modulus of rupture data

[a]Direction relative to principal fibre direction in which test load applied.

2.1.2 Moisture cycling (V 313)

This test is widely used for accelerated aging of particleboards (e.g. Beech et al., 1974). For particleboards the cycling between wet, frozen, and drying conditions produces wood-fibre stressing which results in swelling and strength loss in the boards. Normally only 3 cycles are used.

In using this test the intention was to determine whether cyclic moisture stressing affected the wood-fibre content, or the bond between the wood fibres and the cement, in any way.

Only wood-fibre-reinforced cement sheet was tested. The so-called V 313 test (L'Association Francaise de Normalisation, 1972) was used. Sample sets were removed after 10, 20, 35 and 50 cycles and their mechanical properties compared to those of control samples.

2.1.3 Carbonation

Carbonation of the cement matrix by atmospheric carbon dioxide has been implicated in the embrittlement and loss of strength of asbestos cement (Jones, 1946), and in 'corrosion' of the asbestos fibres in asbestos cement (Opoczky and Pentek, 1975). Since wood-fibre cement sheet will also undergo carbonation in everyday use, it was thought desirable to accelerate this process and measure any corresponding changes in properties.

The carbonation method used was a modification of the method used by Jones (1946). Both wood-fibre-reinforced cement sheet and asbestos-cement sheet were tested.

A uPVC tank, $1\,m \times 1\,m \times 1\,m$, had a $1\,m \times 1\,m \times 0.1\,m$ tray, filled with saturated ammonium nitrate solution, placed in the bottom to provide 65% RH at 20°C. One test piece was suspended in a cradle above this tray, the remainder were placed 100 mm apart in a rack standing on a perforated uPVC plate above the tray. Carbon dioxide gas (food grade purity) was introduced to the sealed tank at the rate of $40\,cm^3$/minute. Regular weighing of the suspended sample was used to monitor the progress of carbonation. Full carbonation (approximately 35% $CaCO_3$ by weight) took about two and a half months, with increase being relatively slow over the last month.

A sample set was removed after each weight increase of approximately 2, 4 and 8%, and two sets at the maximum weight gain of 10%. The amount of carbonation was measured as $CaCO_3$ content according to the method of Vogel (1961), modified by Cooke (1983). The mechanical properties of each sample set were compared to those of a control set, with the exception that one of the fully carbonated (10% weight gain) samples was exposed in a fungal cellar, as described below, prior to subsequent examination and mechanical testing.

2.1.4 Fungal cellar exposure

Wood-fibre-reinforced cement sheet and asbestos-cement sheet, both the uncarbonated controls and the fully carbonated specimens as described above, were exposed in a fungal cellar at the New Zealand Forest Research Institute at Rotorua.

The fungal cellar provides a warm humid environment (28°C, 85% RH) in which samples are exposed in non-sterile soil. The soil has not been modified, so that colonisation and decay of test material relies on natural soil mycoflora. Compared to 'graveyard' tests (stakes exposed outside) a six to ten-fold acceleration factor in the decay of wood samples is found (Hedley, 1980).

Samples were buried 60 mm below the surface, with the planar surface of each sample parallel to the surface, for a period of 6 months. Untreated softwood (*Pinus radiata*) stakes were similarly exposed for comparison.

2.2 Material and sample preparation

Commercially produced (Hatschek process) autoclaved wood-fibre-reinforced cement sheet was supplied by the sole New Zealand manufacturer. This had the approximate composition: 8% wood fibre (*Pinus radiata* Kraft pulp), 46% Portland cement, and 46% silica. The sheet was approximately 3 months old at the start of testing.

Commercially produced air-cured asbestos cement sheet was supplied by the same New Zealand manufacturer. This had the composition: 12% asbestos (principally chrysotile) fibre, 75% Portland cement and 13% silica. The sheet was approximately 18 months old at the start of testing.

Both types were supplied as 2400 x 1200 x 6 mm flat sheet, and the cutting patterns were identical for each type. For both the hot water soak and the V 313 test, sample preparation was as follows.

The 2400 x 1200 x 6 mm sheet was reduced to 2300 x 1100 mm by discarding the outer 50 mm of the sheet, and was then cut to give five pieces 1100 x 460 mm. Each of the five pieces was in turn cut to give one set of samples, as follows:

Modulus of Rupture:	3 of 250 x 250 mm;
Moisture movement:	3 of 170 x 170 mm;
Tensile strength:	1 of 200 x 130 mm perpendicular to principal fibre direction;
	1 of 200 x 130 mm parallel to principal fibre direction;
Impact strength:	1 of 200 x 130 mm perpendicular to principal fibre direction;
	1 of 200 x 130 mm parallel to principal fibre direction;
Internal bond strength:	1 of 100 x 130 mm.

The tensile, impact, and internal bond strength samples were further cut into test piece replicates after exposure. Because the material is anisotropic, being stronger parallel to the direction in which most of the fibres lie, mechanical tests were carried out both perpendicular to and parallel to the principal fibre direction.

The samples for carbonation were also prepared by reducing one

2400 x 1200 x 6 mm sheet to 2300 x 1100 mm by discarding the outer 50 mm of the sheet. This was then cut to give six replicates 765 x 550 mm. One piece was retained as a control, and five were placed in the uPVC tank. After exposure these were cut to provide mechanical test pieces as described below.

2.3 Mechanical tests

Both the control (unexposed) sample, and those withdrawn at each stage of each accelerated test were subjected to the mechanical tests described below. All samples were tested after they had been soaked in water for 24 hours at 20°C.

Modulus of rupture (MoR) was determined on samples 250 x 250 mm, in accordance with NZS 3204 (Standards Association of New Zealand, 1979). Three replicates were used for each test. Loading was applied at a crosshead speed of 11.4 mm/min. The Modulus of Elasticity in Bending (MoE) was calculated from the MoR data using the formula of BS 5669 Section A6 (British Standards Institution, 1979). Tensile strength was determined on rectangular samples 150 x 20 x 6 mm, held in wedge grips. The crosshead speed was 1 mm/min. Six replicates perpendicular to, and six parallel to the principal fibre direction were used in each test.

Internal bond strength (tensile strength perpendicular to the plane of the board) was determined in accordance with BS 5669 section A9 (British Standards Institution, 1979). The testing machine crosshead speed was 1 mm/min, and six replicates were used in each test.

Impact strength was determined using an Izod impact-testing machine constructed to ASTM D256-78 Section 4 (American Society for Testing and Materials, 1978). This machine was adapted by slightly reducing the weight of the pendulum to produce a maximum impact energy of 2.52J. Test samples were cut to 75 x 30 mm and tested unnotched. They were clamped in position so that the smooth side of the sheet faced the direction from which the pendulum was released; six replicates perpendicular to, and six parallel to the principal fibre direction were used for each test.

For moisture movement measurements, samples were cut to 170 x 170 mm with sides either parallel to or perpendicular to the principal fibre direction. The corners of a square 150 x 150 mm were marked out on both faces of each sample, centred on the 170 x 170 mm square, and with sides parallel to it. Stainless steel studs 10 mm in diameter by 4 mm high were fixed to each corner of the 150 mm square on the top face. The reverse face of the sample was similarly treated. After curing of the adhesive, the samples were totally immersed on edge in water at 20°C for 24 hours.

Each sample was removed from the water, drained briefly, and the distance between each pair of studs measured to the nearest 0.001 mm using a strain bridge. Four measurements were made on each face. Immediately following measurement the samples were placed on edge in a forced-air oven

TABLE 2

Results of mechanical tests

(a) Wood-fibre cement sheet — V313 test (data for 10, 20 and 35 cycles are not shown because there was no significant difference from 0 and 50 cycles)

No. of cycles	Mechanical test method	Modulus of rupture (MPa)		Tensile strength (MPa)		Internal bond strength (MPa)	Impact strength (kJ/m^2)		Moisture movement (%)		Modulus of elasticity (GPa)	
		perp.	para.	perp.	para.		perp.	para.	perp.	para.	perp.	para.
0	mean	17.9	9.7	4.36	7.44	0.320	3.63	3.06	0.286	0.273	8.20	4.15
	s.d.	0.5	0.5	0.37	0.06	0.109	0.18	0.74	0.007	0.015	0.22	0.22
50	mean	18.2	11.3	4.43	9.17	0.304	3.04	2.97	0.276	0.265	10.3	7.68
	s.d.	1.9	1.0	0.36	0.40	0.053	0.18	1.01	0.005	0.003	1.1	1.13

(b) Wood-fibre cement sheet — 50°C soak test (data for 20, 70 and 200 days are not shown because there was no significant difference from 0 and 350 days)

No. of days immersed	Mechanical test method	Modulus of rupture (MPa)		Tensile strength (MPa)		Internal bond strength (MPa)	Impact strength (kJ/m^2)		Moisture movement (%)		Modulus of elasticity (GPa)	
		perp.	para.	perp.	para.		perp.	para.	perp.	para.	perp.	para.
0	mean	18.6	10.3	4.38	7.98	0.204	3.97	2.46	0.302	0.283	7.92	3.88
	s.d.	0.6	0.2	0.16	0.14	0.056	0.53	0.12	0.008	0.005	0.33	0.70
350	mean	19.2	12.1	5.30	9.06	0.314	3.50	3.45	0.235	0.224	9.79	8.15
	s.d.	0.9	1.2	0.29	0.20	0.140	0.50	0.88	0.009	0.012	0.33	0.35

perp. = test load applied perpendicular to principal fibre direction
para. = test load applied parallel to principal fibre direction
s.d. = standard deviation

TABLE 3

Summary of results showing trends determined by linear regression analysis

Fibre type	Accelerated test method	Mechanical test method	Modulus of rupture	Tensile strength	Internal bond strength	Impact strength	Moisture movement	Modulus of elasticity
wood	V 313	perp.	0	0	0	(−)	0	0
		para.	0	0		0	0	0
	50°C soak	perp.	0	0	0	0	0	0
		para.	0	(+)		0	0	0
	carbonation	perp.	0	(+)	+	(+)	+	(+)
		para.	(+)	(+)		(−)	+	0
asbestos	50°C soak	perp.	0	0	0	0	(−)	0
		para.	0	0		0	(−)	0
	carbonation	perp.	+	+	0	0	−	0
		para.	+	+		0	−	0

0 = no change
+ = increase
− = decrease
( ): significant at 90% level of confidence
no brackets: significant at 95% level of confidence
perp. = test load applied perpendicular to principal fibre direction
para. = test load applied parallel to principal fibre direction

at 105°C for 24 hours, cooled in a dessicator, and the measurements repeated as above.

Three replicates were used in each test; all measurements were carried out in a room conditioned at 20°C, 65% RH.

3. RESULTS AND DISCUSSION

3.1 Analysis of results of hot water soak, V 313, and carbonation tests

The results are given in Table 2. Using linear regression analysis (Ryan et al., 1982), trends are summarised in Table 3. Since it was felt that the aging might well be an exponential process, a logarithmic regression based on the logarithm of the 'time' variable (days soaking, V 313 cycles, or % $CaCO_3$) was also carried out, but yielded results little different from the linear regression and so is not reported further.

3.2 Analysis of results of fungal cellar tests

The mechanical test results for both uncarbonated and fully carbonated asbestos cement and wood-fibre cement exposed in the fungal cellar for a period of six months are shown in Table 4. The results from each exposed sample were compared to the corresponding unexposed control on the basis of a simple 't' test (Ryan et al., 1982). Differences significant at the 95% level are also given in Table 4. Both microscopic and scanning electron microscope examination of exposed material showed no visible sign of fungal attack or colonisation of any of the samples exposed in the fungal cellar.

3.3 Hot water soak test

The only significant change noted in either asbestos- or wood-fibre-reinforced cement sheet was the slow decrease in moisture movement for asbestos cement presumably caused by ongoing cement hydration. There is no direct comparison available with other studies, although Jones (1946) subjected asbestos cement sheet to 480 cycles between water at 20°C and air at 50°C, producing increases in MoR and MoE, and a decrease in moisture movement.

For wood-fibre-reinforced cement sheet, up to 20 days exposure brought about an increase in MoE (bending), but no further change was evident between 20 and 350 days. There was a slight increase in tensile strength (one test direction only).

Harper (1982), in an identical test, found no damage to autoclaved wood-fibre-reinforced cement sheet after 3 weeks. Wells (1982) found a reduction in MoR from 13—15 MPa down to 11 MPa after 84 days for unautoclaved cellulose-fibre-reinforced cement sheet. The results of the present study agree with those of Harper. Degradation of autoclaved wood-

TABLE 4

Summary of fungal cellar exposure results showing trends significant at the 95% confidence level

Fibre type	Comparison between	Mechanical test method	Modulus of rupture	Tensile strength	Internal bond strength	Impact strength	Moisture movement	Modulus of elasticity
wood	uc, ue	perp.	0	0	0	0	—	—
	and	para.	0	0		0	—	—
	uc, e							
	c, ue	perp.	—	—	0	—	0	—
	and	para.	0	—		—	0	—
	c, e							
asbestos	uc, ue	perp.	0	0	0	0	0	—
	and	para.	0	0		0	0	—
	uc, e							
	c, ue	perp.	0	0	0	0	—	—
	and	para.	0	0		0	—	—
	c, e							

uc = not carbonated
c = carbonated
ue = not exposed in fungal cellar
e = exposed in fungal cellar
perp. = test load applied perpendicular to principal fibre direction
para. = test load applied parallel to principal fibre direction
0 = no change
— = decrease

fibre cement sheet by corrosion of the wood fibres by the alkaline cement matrix is therefore unlikely. This is perhaps further reinforced by the realisation that the Kraft process by which the wood-fibre pulp is prepared has, as a major processing parameter, the removal of lignin and hemicelluloses under the action of NaOH, Na_2S, heat, and pressure (Packer, 1978). The lignin and hemicellulose content of sisal fibre has been implicated in the breakdown under alkaline conditions of sisal-fibre cement composites (Gram, 1983). Susceptibility of cellulose fibres to alkaline degradation thus appears to depend on their pretreatment.

The fact that the mechanical properties of the wood-fibre-reinforced cement sheet remained much the same throughout exposure leads to the inference that there was no radical change in the nature of the fibre/cement bond. Failure in mechanical testing was predominantly by fibre pull-out.

3.4 V 313 test

Only the wood-fibre cement sheet was tested. In a similar manner to the hot water soak test, MoE (bending) increased somewhat between 0 and 10 cycles, with no further change between 10 and 50 cycles. There is an indication of a slight fall-off in impact resistance (one test direction only). The lack of effect of freeze/thaw cycles or V 313 cycles on autoclaved wood-fibre-reinforced cement sheet is verified by the research literature; Harper (1982) used both the freeze/thaw test from BS 690 (25 cycles alternating between $-20°$ and $+20°C$) and the V 313 test. In neither was the sheet affected. Similar claims are made in the corresponding manufacturer's literature (Cape Boards, undated). These results supported the present findings, and it thus appears that, unlike particleboards, moisture stressing (cycling) of the wood fibres has little effect on the strength of autoclaved wood-fibre-reinforced cement sheet, or on the fibre—cement bond. Failure was predominantly by fibre pull-out.

3.5 Carbonation

In theory, all of the cementing compounds can be converted to calcium carbonate and hydrated silica, aluminium or iron oxides by long-term exposure to air (Lea, 1970). In the present experiments the maximum amount of carbonation obtained was of the order of 35% $CaCO_3$ by weight for both the asbestos and the wood-fibre-reinforced cement sheet. At this level, absorption of further CO_2 was extremely slow. The calcium carbonate content of some naturally exposed fibre cement sheets is given in Table 5. In artificial carbonation of asbestos cement products, $CaCO_3$ contents ranging from 11—41% were achieved (Jones, 1946) — mainly in the range 36—41%. At this level absorption of CO_2 was stated to have virtually ceased. The value of 35% achieved here is thus felt to provide a realistic upper limit for naturally weathered fibre-cement sheet, and is comparable with levels of artificial carbonation achieved in other studies.

TABLE 5

Calcium carbonate content of naturally weathered fibre cement sheet as a function of age

Fibre type	Exposure location	Exposure orientation	Age (y)	$CaCO_3$ (wt. %.)	Reference
asbestos or asbestos + wood fibre	Camellia, Australia	not known	'new'	2.5—5	Cooke, 1983
asbestos + wood fibre	Australia	not known	'old'	12.5—17	Cooke, 1983
asbestos + wood fibre	Australia	not known	'heavily weathered'	25	Cooke, 1983
asbestos + wood fibre	Auckland, N.Z.	vertical	13	11	Milestone, 1982
asbestos + wood fibre	Porirua, N.Z.	N, vertical	9	14	Milestone, 1982
	Porirua, N.Z.	N, vertical	3	3	Milestone, 1982
	Porirua, N.Z.	unweathered	2 months	1	Milestone, 1982

The major significant changes in mechanical properties occurred for both the asbestos- and wood-fibre cement sheet after carbonation. The asbestos-cement sheet showed increases in the modulus of rupture and tensile strength, and decreased moisture movement (see Fig. 1). The corresponding MoR and tensile strength changes have previously been reported for artificially carbonated asbestos cement by Jones (1946). An increase in MoR after 17 years natural weathering has been reported for asbestos cement (Anon, 1958), and Neville (1981) has noted that carbonation of unautoclaved cement products is recognised as reducing their moisture movement. Jones also reported that artificial carbonation of asbestos cement reduced its impact resistance. He attributed the reduction in impact resistance of asbestos-cement sheet with natural exposure to ongoing atmospheric carbonation. The reduction in impact resistance was not reproduced in the present study. An examination of Jones's results shows that of the six products carbonated, only four in fact lost impact strength. The two which remained unchanged had $CaCO_3$ contents of 18% and 39%. In a study of the 'corrosion' of asbestos fibres by cement, Opoczky and Pentek (1975) note

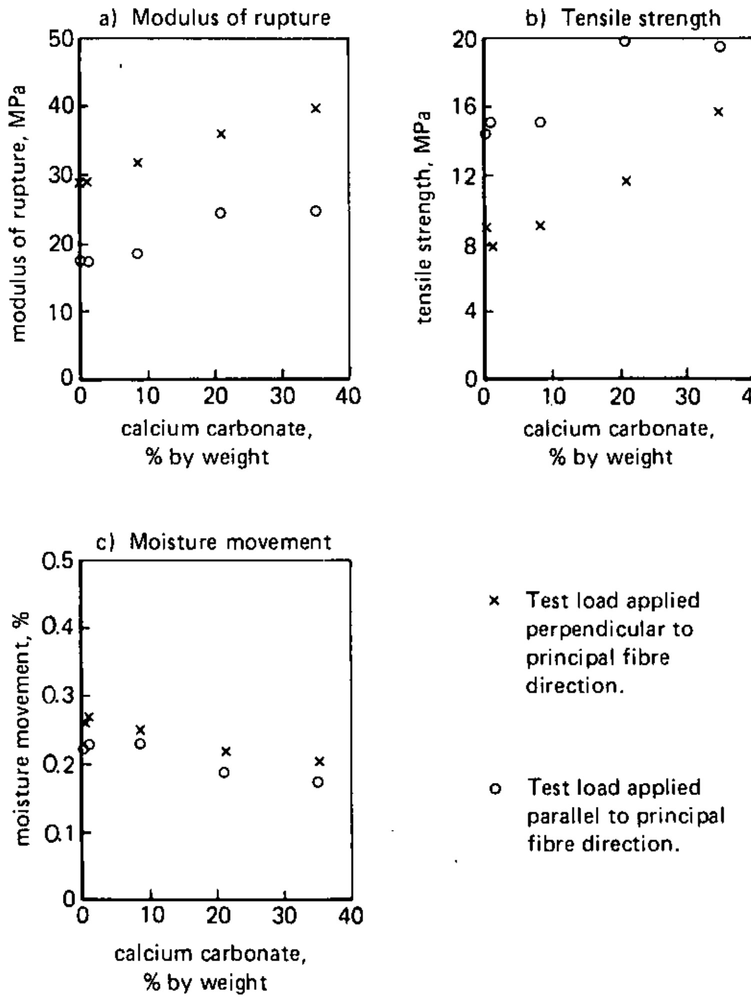

Fig. 1. Effect of carbonation on mechanical properties of asbestos-cement sheet.

two stages in the weathering of asbestos cement. The first (up to 16 years) is partial carbonation of the asbestos fibres. Following this, crystallisation of 'corrosion product' on and between fibres is seen. It may be possible that, when different asbestos-cement products are subjected to accelerated carbonation, different stages in these reactions are reached, with consequent variations in the effect on mechanical properties.

The significant changes noted in the properties of carbonated wood-fibre-reinforced cement sheet were increases in tensile strength, internal bond, and moisture movement (see Fig. 2). An increase in the modulus of rupture (one test direction only) was seen, and modulus of elasticity in bending showed a similar increase.

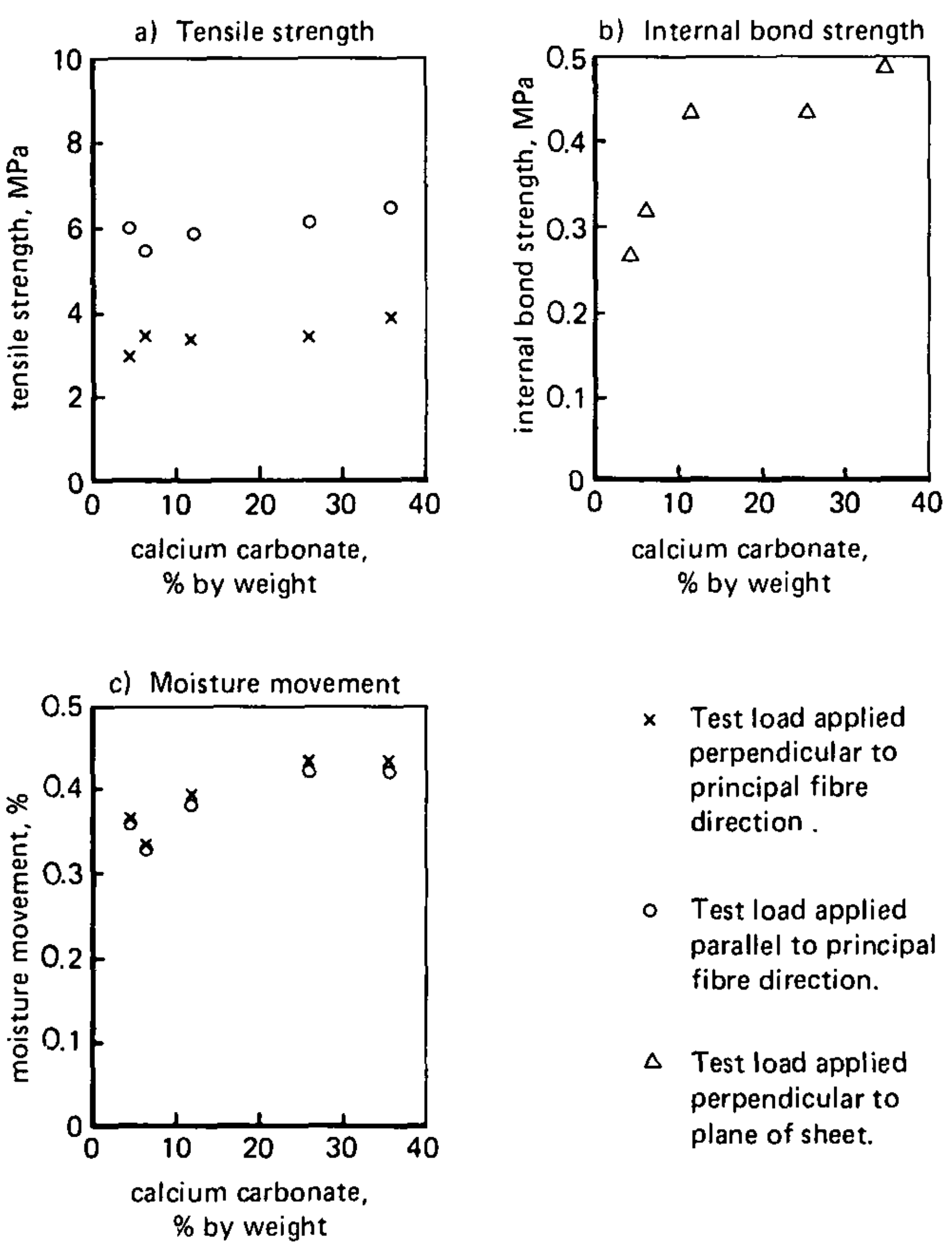

Fig. 2. Effect of carbonation on mechanical properties of wood-fibre cement sheet.

An increase in moisture movement as a consequence of carbonating autoclaved cement products has been noted elsewhere (American Concrete Institute Committee 515, 1965). The effect of this increase is difficult to gauge. Reports on the effects of natural weathering on the mechanical properties of wood-fibre-reinforced cement (Harper, 1982) and closely related products (Sinha et al., 1975) make reference only to 'no marked change' in mechanical properties for periods of up to 4 years, without stating which properties were measured. Moisture movement was reported (Gram, 1983) as being a problem in cellulose cement roofing sheet based on paper pulp in Scandinavia, but no moisture movement problems have been reported from the use of wood-fibre cement flat sheet as an exterior wall cladding in New Zealand over the past two years.

The current preference (Building Research Association of New Zealand, 1983) is that the material should be painted for exterior exposure. It is expected that this will increase the rate of carbonation since, if the entry of liquid water into the sheet is prevented, the internal relative humidity of the sheet is likely to remain in the range most favouring carbonation (Ho and Lewis, 1981; Weber, 1983). Conversely, the magnitude of moisture-content change, and hence subsequent movement, will be reduced. It is not known which effect will predominate, but this question forms part of an investigation into changes in mechanical properties due to natural weathering which is currently in progress.

Although wood-fibre cement-sheet products are not often used as an interior wall lining in New Zealand, in Australia the use of ceramic-tile-faced fibre-cement sheet is common in wet internal areas such as bathrooms. It has already been noted (Martin, 1984) that wood-fibre-cement sheet has a higher moisture movement than asbestos cement, and that this is a potential cause of problems for ceramic-tile-faced sheet. On the basis of the increase in moisture movement of carbonated wood-fibre cement sheet, and the potential for more rapid carbonation under the more favourable indoor humidity levels (Jungermann, 1982), the potential for problems with ceramic-tile-faced sheet may increase as the sheet ages.

3.6 Fungal cellar tests

For other wood/cement composites such as wood-wool cement slabs, or wood cement particleboard, the high pH of the cement matrix is stated to provide resistance against microbiological attack (Pinion, 1975; Dinwoodie, 1978). Fungal cellar tests on freshly manufactured wood-fibre cement (Harper, 1982) and cotton- or bamboo-pulp-reinforced cement (Sinha et al., 1975) have supported this viewpoint. On long exposure and consequent carbonation, however, the matrix pH is lowered from around 12 to around 8 (Pihlajaavara, 1982). Although most wood-destroying fungi prefer an acid environment, it has been noted that soft-rot organisms may thrive in slightly alkaline conditions (Parameswaren and Broker, 1979), and there is the potential risk of microbiological attack on carbonated wood-fibre cement sheet.

Although one generation of *Pinus radiata* stakes, exposed simultaneously with the cement sheet samples, was completely consumed, and a second set exposed after the decay of the first was heavily attacked, both the micro-

TABLE 6

Summary of comparison between carbonated, fungal cellar-exposed and uncarbonated, unexposed wood-fibre cement sheet (differences significant at the 95% confidence level)

Comparison between	Mechanical test method	Modulus of rupture	Tensile strength	Internal bond strength	Impact strength	Moisture movement	Modulus of elasticity
uc, ue and c, e	perp.	—	0	0	—	+	0
	para.	0	—		0	+	—

uc = not carbonated
c = carbonated
ue = not exposed in fungal cellar
e = exposed in fungal cellar
perp. = test load applied perpendicular to principal fibre direction
para. = test load applied parallel to principal fibre direction
0 = no change
— = decrease

scopic and S.E.M. inspection of uncarbonated and carbonated wood-fibre cement sheet exposed in the fungal cellar support the conclusion of Parameswaran and Broker (1970), who found no, or very little, decay in 25—30-year-old wood—cement composites in contact with soil. However, there were significant decreases in the tensile strength, modulus of elasticity, and modulus of rupture and impact strength (one direction only) in the carbonated, exposed wood-fibre cement sheet compared to the carbonated, unexposed control (see Table 4). These effects are difficult to explain in the absence of any fungal infestation or evidence of gross damage to the wood fibres, although colonisation and damage to the fibres by soil bacteria has not been eliminated as a causative agent. The change in matrix pH appears implicated in the reduction of modulus of rupture, tensile and impact strengths compared to uncarbonated wood-fibre cement sheet. The changes in mechanical properties from uncarbonated, unexposed wood-fibre cement sheet used as the original control and those of the carbonated, fungal cellar-exposed samples were also calculated and are summarised in Table 6. Apart from moisture movement, which is carbonation-dominated, the remaining changes can best be interpreted as a moderate decline in mechanical properties for the exposed material compared to the control.

Fungal cellar exposure of carbonated wood-fibre cement sheet is an extreme case of likely exposure conditions, thus the changes observed represent the 'bottom line' in likely behaviour in practice. In general, wood-fibre-reinforced cement sheet can be considered resistant to microbiological attack.

No explanation is offered for the reduction in modulus of elasticity of all the exposed samples compared to their controls, nor for the reduction in moisture movement of the uncarbonated wood-fibre cement sheet and the carbonated asbestos-cement sheet.

4. CONCLUSIONS

When subjected to accelerated aging by the hot water soak test, V 313 test, or carbonation, only carbonation had any significant effects on the mechanical properties of wood-fibre-reinforced cement sheet. Of the three types of changes induced, namely increases in the tensile strength, internal bond, and moisture movement, only the increase in moisture movement is seen as potentially deleterious. The likely level of effect is uncertain. With the present New Zealand preference that the sheet be painted for exterior use, the degree of moisture cycling should be considerably reduced and the increase in moisture movement due to carbonation may not be significant. This point is undergoing further investigation in the course of natural weathering trials. Where wood-fibre cement sheet is used as a substrate for ceramic tiles, a few problems have arisen with new wood-fibre cement sheet and the increased moisture movement following carbonation may exacerbate this.

Exposure of fully carbonated wood-fibre cement sheet in a fungal cellar generally confirmed literature projections of fungal resistance, although a moderate decline in mechanical properties was observed.

In asbestos-cement, which was used as a control, carbonation produced changes in mechanical properties (such as an increase in modulus of rupture) which have been observed elsewhere, but no decrease in impact resistance which has been stated as a consequence of carbonation. Close examination of the original research showed that this effect had been observed there also. A possible explanation lies in a difference in the reaction rates of the aging processes caused by carbonation in various asbestos-cement types.

The susceptibility of cellulose fibres, in cellulose-fibre-reinforced cement sheet composites, to degradation by alkali from the cement binder appears to be dependent on pretreatment of the cellulose fibre prior to inclusion in the composite.

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