Concrete reinforced with up to 0.2 vol% of short carbon fibres

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The use of short pitch-based carbon fibres (0.5% by weight of cement, 0.189 volume % (vol%) of concrete), together with a dispersant, chemical agents and silica fume, in concrete with fine and coarse aggregates resulted in a flexural strength increase of 85%, a flexural toughness increase of 205%, a compressive strength increase of 22%, and a material price increase of 39%. The slump was 102 mm (4 in) at the optimum water/cement ratio of 0.50. The air content was 6%, so the freeze-thaw durability was increased, even in the absence of an air entrainer. The aggregate size had little effect on the above properties. The minimum carbon fibre content for flexural strength increase was 0.1 vol%, although the flexural toughness was still increased below this fibre volume fraction. The optimum fibre length was such that the mean fibre length decreased from 12 mm before mixing to 7 mm after mixing, which used a Hobart mixer. The drying shrinkage was decreased by up to 90%. The electrical resistivity was decreased by up to 83%.

Key words: *composite materials; fibre-reinforced concrete; mechanical properties; mix formulation; aggregate size; air content; fibre volume fraction; short carbon fibres*

Like brittle materials in general, concrete is strong under compression and weak under tension or flexure. This problem may be alleviated by the addition of short carbon fibres (typically ~10 μm in diameter)[1–7]. The majority of the previous work on carbon fibre-reinforced concrete was conducted in Japan and it showed that the use of carbon fibres in the amount of 2 volume% (vol%) approximately doubled the flexural strength[1–4]. Work performed in the USA by Zheng and Chung[6] showed the approximate doubling of the flexural strength with only 0.3 vol% of carbon fibres—an improvement resulting from the use of chemical agents. Recent work performed in the USA by Larson *et al.*[7] showed a flexural strength increase of 500 ± 150% with 3 vol% of carbon fibres; this high fractional increase was because the flexural strength of their case without fibres was unusually low.

All previous work on short carbon fibre-reinforced concrete used isotropic pitch-based carbon fibres, which are the least expensive form of commercially available carbon fibres. Their tensile strength and modulus are much lower than those of continuous pitch-based or polyacrylonitrile (PAN) based carbon fibres that are used for aircraft. The price of short pitch-based carbon fibres has been steadily decreasing. In the USA, the price was $12/lb in 1985, $9/lb in 1990, and is expected to drop to below $5/lb (1 lb = 0.454 kg)[8]. This price decrease is giving much impetus to the use of carbon fibres in concrete. Nevertheless, it is desirable for economic reasons to keep the amount of carbon fibres in concrete to a minimum. Therefore, this paper is focused on concrete containing carbon fibres in the amount of ~0.2 vol%, i.e., an extension of the work of Zheng and Chung[6].

Almost all of the previous work in both Japan and the USA on carbon fibre-reinforced concrete used only fine aggregate[1,2,4–7], so that the material was really mortar rather than concrete. Table 1 compares the results of various workers on pitch-based carbon fibre-reinforced mortars. All previous workers (except Zheng and Chung[6]) used fibres in the amount of ⩾1 vol%, but this work used fibres in the amount of only 0.2 vol%. In spite of the low carbon fibre content of this work, the resulting effect on the flexural strength is comparable to the previous work. Table 2 compares the results of various workers on pitch-based carbon fibre-reinforced concretes. Akihama *et al.*[3] used microballoons as the aggregate, so the resulting concrete is not directly comparable to conventional concrete. Therefore, an objective of this paper is to extend the technology of carbon fibre-reinforced concrete to concrete of common mix proportions. This extension deserves investigation, as the length of the carbon fibres relative to the aggregate size decreases as the aggregate size increases, so that the effectiveness of the carbon fibres in improving the flexural strength of concrete may decrease as the aggregate size increases. In this paper, we found that this aggregate size effect is quite minor, so that the technology of carbon fibre-reinforced

Table 1. Comparing this work to previous work on carbon fibre-reinforced mortar*

Reference	Fibre vol%	Flexural strength† increase (%)	Fibre length (mm)	Water/ cement ratio	Sand/ cement ratio	Silica fume/ cement ratio	Methylcellulose/ cement (%)	Water reducing agent/cement (%)	Admixtures
1	1	10	6	0.32	0.504	0.4	–	–	Superplasticizer/ cement = 6%
	1	32	6	0.40	1	0.4	–	–	Superplasticizer/ cement = 6%
2	1.72	46	10	0.42	–	–	1	–	–
	1.72	25	10	0.473	0.25	–	1	–	–
	1.72	97	10	0.527	0.50	–	1	–	–
3	2.1	150	3	0.473	0.25	–	1	–	–
4	1	56	6	0.3	–	0.4	–	6	–
5	1	16	3	0.3	–	0.4	–	–	Superplasticizer/ cement = 6%
	1	20	10	0.3	–	0.4	–	–	Superplasticizer/ cement = 6%
7	3	500 ± 150**	1.7	0.42	–	0.34	–	–	Superplasticizer/ cement = 4.3%
This work	0.244	105	5	0.45	1.5	–	0.4	2	Dis
	0.244	50	5	0.45	1.5	0.15	0.4	2	Dis + chem + silica fume A

*Pitch-based carbon fibres
†7 days of curing in air or water, 20–25°C, 60–100% relative humidity; the increase is relative to the same mortar without carbon fibres
**The flexural strength without fibres is only 1.4 MPa

Table 2. Comparing this work to previous work on carbon fibre-reinforced concrete*

Reference	Fibre vol%	Flexural strength (MPa)	Water/ cement ratio	Aggreg/ cement ratio	Fine aggreg/ cement ratio	Coarse aggreg/ cement ratio	Water reducing agent/ cement (%)	Admixtures	Curing conditions
3	0	4.5	0.44	0.45	2.57	2.01	–	Not disclosed (1%)	
	2.5 (3 mm)	7.6	0.737	0.295†	–	–	1.2	–	Cured with moisture at 40°C for 7 h, then auto-claved at 180°C and 10 atm for 5 h
This work	0	5.00	0.5	–	1.5	2.49	–	–	Cured in moist room for 28 days
	0	7.86	0.5	–	1.5	2.49	2	Chem + silica fume A	
	0.189 (5 mm)	7.95	0.5	–	1.5	2.49	2	Dis	
	0.189 (5 mm)	9.23	0.5	–	1.5	2.49	2	Dis + chem + silica fume A	

*Pitch-based carbon fibres
†Aggregate = microballoons + silica fume + silica powder

concrete is indeed viable for concrete with coarse aggregates, such as concrete that is typically used for highway pavements.

The technique of dispersing carbon fibres randomly in the concrete mix is critical to the success of carbon fibre-reinforced concrete technology. Two options are possible. One is to mix the fibres with cement and fine aggregate in the dry state (referred to as 'dry mix' in this paper). The other option is to first disperse the fibres in water and then pour the dispersion into the slurry with cement and fine aggregate (referred to as 'wet mix' in this paper). The second option is much more practical. Almost all published papers[1–5,7] on short carbon fibre-reinforced concrete did not reveal the method of dispersing the carbon fibres. Zheng and Chung[6] did and they used dry mix. An objective of this paper is to develop a practical and effective method for dispersing the fibres

Table 3. Properties of carbon fibers

Filament diameter	10 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	3.0×10^{-3} Ω cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt%

Table 4. List of aggregates used

Label	Description
Aggregate A	#2 silica sand
Aggregate B	Standard aggregate for Masonry Mortar ASTM C114–81 100% passed #4 standard sieve
Aggregate C	#7 aggregate ASTM C33–84 100% passed 19 mm (¾ in) standard sieve
Aggregate D	#57 aggregate ASTM C33–84 100% passed 25 mm (1 in) standard sieve Commonly used for highway pavements

Table 5. Aggregates in mortars and concretes

Label	Aggregate(s) used
Mortar A	Aggregate A
Mortar B	Aggregate B
Concrete C	Aggregates B + C
Concrete D	Aggregates B + D

and to compare the effect of dry mix and wet mix. We found that wet mix is an effective method only if a dispersant (methylcellulose in this work) and a defoamer (Colloids 1010 in this work) are used.

The freeze-thaw durability of carbon fibre-reinforced concrete had not been previously studied. We found that carbon fibres increase the freeze-thaw durability of concrete.

EXPERIMENTAL

Raw materials

The short carbon fibres were pitch-based and unsized. Various nominal fibre lengths (provided by the fibre manufacturer) from 3.0 to 12.7 mm were used. Unless stated otherwise, fibres of nominal length 5.1 mm were used. The fibre properties are shown in Table 3.

Table 4 lists the aggregates used; Fig. 1 shows the particle size analysis of each aggregate. Table 5 describes the two types of mortar and two types of concrete used. Because aggregate D is most commonly used for highway pavements, concrete D was given most attention in this work. Table 6 describes the various raw materials used. Unless stated otherwise, carbon fibres in the amount of 0.5% by weight of the cement were used.

Mixing procedures

Two mixing procedures were used. They are referred to as 'dry mix' and 'wet mix', and are described in Tables 7 and 8. Both procedures were used for concrete D for the sake of comparison. Only dry mix was used for mortar B. Only wet mix was used for mortar A and concrete C. For both procedures, a Hobart mixer with a flat beater as well as a stone concrete mixer were used. The Hobart mixer was necessary for mixing the fibres.

After pouring the mix into oiled moulds, a vibrator was used to decrease the amount of air bubbles.

Fig. 2 shows the effect of wet mix (involving a Hobart mixer and then a stone concrete mixer) on the length distribution of the carbon fibres in concrete D, as obtained by separately measuring the lengths of 200 fibres before and after wet mix. Mixing decreased the mean fibre length from 12 to 7 mm. Similar measurement done after the Hobart mixer stage and before the stone concrete mixer stage of wet mix showed a fibre length distribution essentially the same as Fig. 2(b). Thus, most of the fibre damage occurred during the Hobart mixer stage of wet mix.

Curing procedure

The specimens were demoulded after 1 day and then allowed to cure in a moist room for various lengths of time.

Mechanical testing

Flexural testing was performed on all specimens by three-point bending (ASTM C348-80), with a span of 241 mm (9.5 in). The specimen size was 40 × 40 × 160 mm for mortars and was 76.2 × 76.2 × 279 mm (3 × 3 × 11 in) for concretes. For compressive testing the specimen size was 50.8 × 50.8 × 50.8 mm (2 × 2 × 2 in) (ASTM C109-80) for mortar B and 102 mm (4 in) diameter × 203 mm (8 in) length (ASTM C39–83b) for concrete D. Six specimens of each type were used for each type of test. The flexural toughness was calculated from the area under the load/deflection curve obtained in flexural testing, such that three specimens of each type of specimen were used.

RESULTS

In the reporting of results the following abbreviations are used:

Chem	chemical agents, consisting of water reducing agent and accelerating agents;
M	methylcellulose;
1010	Colloids 1010;
Dis	dispersant, consisting of methylcellulose and Colloids 1010.

Mortar B

The raw materials for Mortar B are listed in Table 9.

Table 6. List of raw materials

Material	Source
Portland cement Type I	Lafarge Corporation (Southfield, MI)
Silica sand, #2 crystalline 99.91% SiO_2	Pennsylvania Glass Sand Corporation (Berkeley Springs, WV)
TAMOL SN Sodium salt of a condensed naphthalenesulphonic acid, 93–96% Water, 4–7% Tan, free-flowing powder	Rohm and Haas Company (Philadelphia, PA)
TAMOL L Sodium salt of a condensed naphthalenesulphonic acid, 46–49% Water, 51–54% Dark brown, mobile liquid	Rohm and Haas Company (Philadelphia, PA)
Methocel, A15–LV Methylcellulose	Dow Chemical (Midland, MI)
Daravair Air-entraining admixture ASTM C-260	W.R. Grace & Co (Cambridge, MA)
Carboflex Carbon fibres	Ashland Petroleum Company (Ashland, KY)
Colloids 1010 Defoamer	Colloids Inc (Marietta, GA)
Aluminium potassium sulphate	Fisher Scientific (Fair Lawn, NJ)
Sodium sulphate	Riverside Chemical Co (Buffalo, NY)
Triethanolamine 85%	Riverside Chemical Co (Buffalo, NY)
Silica fume A	Elkem Materials Inc (Pittsburgh, PA)
Silica fume B	TAM Ceramics (Niagara Falls, NY)

Table 10 shows the effect of carbon fibres and chemical agents on the flexural strength and compressive strength after 7, 14 and 28 days of curing. The use of both fibres (3.0 mm long) and chemical agents increased the flexural strength by 37%, 33% and 21% respectively after 7, 14 and 28 days, and increased the compressive strength by 40%, 22% and 17% respectively after 7, 14 and 28 days, as shown by comparing rows 1 and 4. The chemical agents alone are more effective than the fibres alone in increasing the flexural or compressive strength, as shown by comparing rows 2 and 3. Nevertheless, it is significant that the fibres increased the compressive strength as well as the flexural strength of the mortar, as shown by comparing rows 1 and 3. The effect of the fibres on the flexural and compressive strengths of the mortar containing chemical agents was small, as shown by comparing rows 2 and 4.

Table 11 shows the effect of carbon fibre length on the flexural and compressive strengths at 14 days of curing. The flexural strength increased monotonically with increasing nominal fibre length, but the difference in flexural strength between fibre lengths of 5.1 and 12.7 mm was small. The compressive strength was highest for an intermediate fibre length of 5.1 mm when no chemical agents were used; it decreased monotonically with increasing fibre length when chemical agents were used. Thus, for high flexural and compressive strengths, the optimum fibre length is 5.1 mm.

Table 12 shows the effect of carbon fibre content (3.0 mm long fibres) on the flexural and compressive strengths at 14 days of curing. The flexural strength increased monotonically with increasing fibre content, though the difference in flexural strength between fibre contents of 1.0% and 2.0% (by weight of the cement) is small. The compressive strength was highest for the intermediate fibre content of 1.0% by weight of the cement. Thus, for

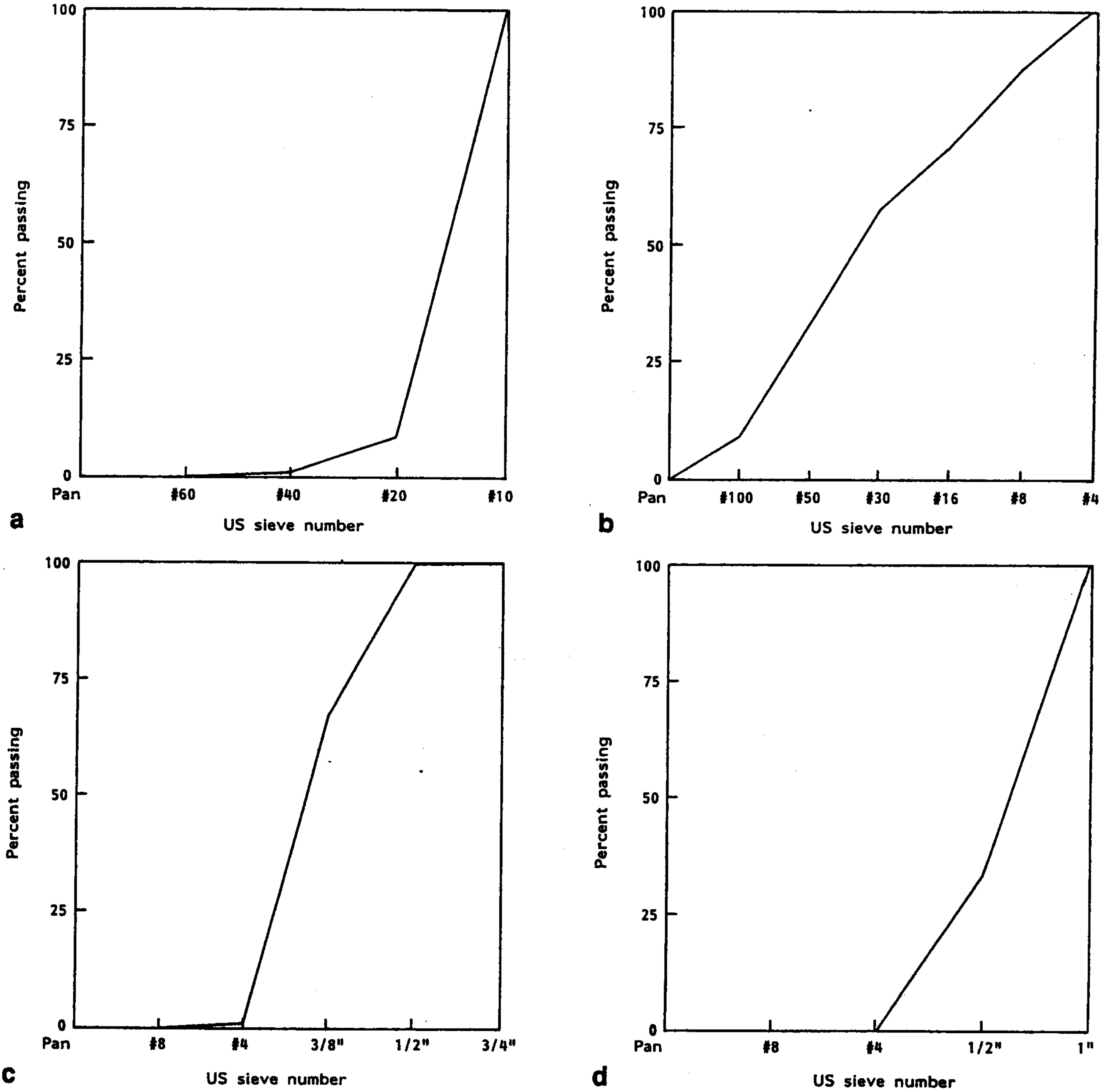

Fig. 1 Aggregate size distributions: (a) aggregate A; (b) aggregate B; (c) aggregate C; and (d) aggregate D

economy and high strengths, the optimum fibre content is 1.0% by weight of the cement.

The effect of each accelerating agent and various combinations of accelerating agents on the fluidity of the mortax mix was investigated by performing the slump test, and measuring the flexural strength after 3 days of curing. It was found that sodium sulphate (with or without other accelerating agents) decreased the slump. Table 13 shows the effect of the sodium sulphate content on the slump and flexural strength. The slump decreased with increasing sodium sulphate content, with an abrupt decrease between sodium sulphate contents of 0.3 and 0.4% by weight of the cement. The flexural strength increased with increasing sodium sulphate content from 0.2 to 0.5% by weight of the cement. Thus, for good fluidity and high flexural strength, the optimum sodium sulphate content is 0.3% by weight of the cement.

Concrete D with low fluidity

The raw materials for concrete D are listed in Table 14. Dry mix was applied when methylcellulose and Colloids 1010 were not used, and wet mix was applied when methylcellulose and Colloids 1010 were used, unless stated otherwise. This formulation resulted in a mix with low fluidity compared with another one (to be described in a following section) involving wet mix only. Concrete D of Table 14 is referred to as 'concrete D of low fluidity', whereas concrete D involving wet mix only (to be described in a following section) is referred to as 'concrete D of normal fluidity'. Note from Table 14 that

Table 7. Dry mix: mixing procedure for mortar B and for concrete D*

1)	Mix carbon fibres with aggregate B by hand (by roughly putting a layer of fibres, a layer of aggregate B, a layer of fibres, a layer of aggregate B, etc.)
2)	Start the Hobart mixer and then add (1) and cement (and silica fume, if applicable)
3)	Add the water reducing agent
4)	Stir with the Hobart mixer for ~5 min
5)	Dissolve accelerating agents in water
6)	Add accelerating agents in the Hobart mixer and stir for ~3 min
7)†	Pour into the stone concrete mixer
8)†	Add aggregate D
9)†	Mix for ~3 min

*With low fluidity
†For concrete D, not for mortar B

Table 8. Wet mix: mixing procedure for mortar A and concretes C and D*

1)	Dissolve dispersant in water
2)	Add fibres and stir
3)	Add aggregate A, cement and silica fume A (for mortar A only) or add aggregate B, cement and silica fume A (for concretes C and D* only)
4)	Add water reducing agent
5)	Stir with the Hobart mixer for ~5 min
6)	Add chemical agents in the Hobart mixer and stir for ~3 min
7)†	Pour into the stone concrete mixer
8)†	Add aggregate D (for concrete D* only) or add aggregate C (for concrete C only)
9)†	Mix for ~3 min

*Of normal fluidity
†For concretes C and D, not for mortar A

the sodium sulphate content was the optimum amount of 0.3% by weight of the cement.

Table 15 shows the effect of chemical agents and silica fume B on the flexural strength. Note that Table 15 involves no fibres. The use of both chemical agents and silica fume B increased the flexural strength by 68%, 49% and 58% respectively for 7, 14 and 28 days of curing, as shown by comparing rows 1 and 4 of Table 15. Silica fume B alone was more effective than chemical agents in increasing the flexural strength at 14 days, but was comparable to the chemical agents in the effect on the flexural strength at 7 and 28 days.

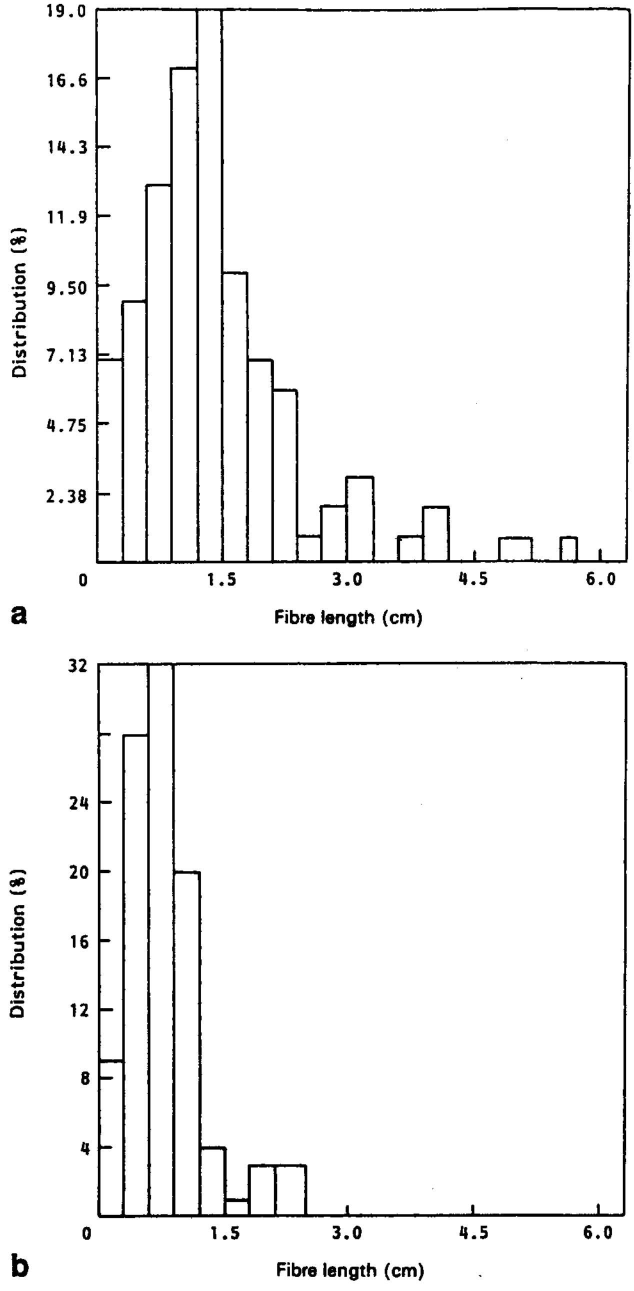

Fig. 2 Fibre length distributions (a) before and (b) after mixing

Table 9. Raw materials for mortar B

Water/cement = 0.6
Aggregate B/cement = 5.48
Fibres/cement = 0.5%
Water reducing agent (TAMOL L)/cement = 1%
Acclerating agents:
Triethanolamine/cement = 0.06%
Potassium aluminium sulphate/cement = 0.5%
Sodium sulphate/cement = 0.5%

Table 10. Effect of carbon fibres* and chemical agents on strength for mortar B

	Flexural strength (MPa) 28 days	14 days	7 days
1 Plain mortar	5.82 (±9%)	4.80 (±2%)	4.32 (±4.5%)
2 +Chem	6.95 (±10%)	5.95 (±1%)	5.10 (±3%)
3 +Fibres	6.42 (±6%)	5.28 (±7.6%)	4.76 (±1.4%)
4 +Fibres+chem	7.03 (±2.9%)	6.37 (±7.6%)	5.92 (±9.2%)
	Compressive strength (MPa) 28 days	**14 days**	**7 days**
1 Plain mortar	31.38 (±9%)	26.02 (±2%)	18.37 (±1%)
2 +Chem	35.93 (±9%)	32.84 (±6%)	26.14 (±4%)
3 +Fibres	34.65 (±12.5%)	30.70 (±3%)	24.73 (±1%)
4 +Fibres+chem	36.87 (±5.5%)	31.63 (±5%)	25.76 (±8%)

*0.5% by weight of cement; 3.0 mm long fibres

Table 11. Effect of carbon fibre* length on strength at 14 days for mortar B

Fibre length (mm)	Strength (MPa) Flexural	Compressive
Without chemical agents		
–	4.80 (±2.3%)	26.02 (±2%)
3.0	5.28 (±7.6%)	30.70 (±3%)
5.1	6.66 (±5.4%)	34.26 (±10%)
12.7	6.69 (±1.7%)	20.66 (±10%)
With chemical agents		
–	5.95 (±1%)	32.84 (±6%)
3.0	6.37 (±7.6%)	31.63 (±5%)
5.1	6.93 (±4.2%)	27.99 (±3%)
12.7	6.94 (±8.6%)	20.19 (±20%)

*0.5% by weight of cement
Conclusion: The optimum fibre length is 5.1 mm

Table 12. Effect of carbon fibre* content on strength at 14 days for mortar B

Fibre content (% by weight of cement)	Strength (MPa) Flexural	Compressive
Without chemical agents		
–	4.80 (±2.3%)	26.02 (±2%)
0.5	5.28 (±7.6%)	30.70 (±3%)
1.0	6.41 (±5.3%)	31.84 (±5.2%)
2.0	6.45 (±8.9%)	29.23 (±8%)
With chemical agents		
–	5.95 (±1.0%)	32.84 (±6%)
0.5	6.37 (±7.6%)	31.63 (±5%)
1.0	6.92 (±3.7%)	34.11 (±4%)
2.0	7.03 (±9.7%)	25.88 (±4.7%)

*3.0 mm long carbon fibres
Conclusion: The optimum fibre content is 1% by weight of cement

Table 16 shows the effect of carbon fibres, methylcellulose and Colloids 1010 on the flexural strength. Comparison between rows 1 and 2 of Table 16 shows that, for identical formulations, dry mix gave slightly higher flexural strength than wet mix. Comparison between rows 2 and 3 shows that, for wet mix with fibres and chemical agents, methylcellulose increased the flexural strength. Comparison between rows 3 and 4 shows that, for wet mix with fibres, chemical agents and methylcellulose, silica fume B increased the flexural strength. Comparison between rows 3 and 5 shows that, for wet mix with fibres, chemical agents and methylcellulose, Colloids 1010 increased the flexural strength. Comparison between rows 4 and 5 shows that Colloids 1010 was more effective than silica fume B in increasing the flexural strength. Comparison between rows 1 and 5 shows that wet mix gave higher flexural strength than dry mix if both methylcellulose and Colloids 1010 were used. Row 5 of Table 16 corresponds to the formulation for the highest flexural strength for concrete D of low fluidity. Comparison of row 5 of Table 16 with row 1 of Table 15 shows that the use of fibres, chemical agents, methylcellulose and Colloids 1010 increased the flexural strength by 105% and 79% respectively for 7 and 14 days of curing.

Table 17 gives the freeze-thaw durability test (ASTM C666) results. Temperature cycling was carried out between −40 and 10°C, with a temperature accuracy of ±3°C, at a rate of 1 cycle per day. Cycling started after 7 days of curing. Thirty cycles (30 days) were conducted. After that, the flexural strength was measured and compared with that of the same kind of concrete that had undergone no cycling (just 7+30=37 days of curing). For plain concrete D, the cycling decreased the flexural strength by 27%. For concrete D containing fibres, methylcellulose, chemical agents and silica fume B, the cycling decreased the flexural strength by 15%.

Table 13. Effect of sodium sulphate on slump and flexural strength at 3 days of curing for mortar B*

Sodium sulphate/ cement (%)	Slump (mm)[†]	Flexural strength (MPa)
0.5	77	5.88 (±5.8%)
0.4	77	5.81 (±3.2%)
0.3	110	5.75 (±2.4%)
0.2	135	5.48 (±4.7%)
0	180	5.71 (±5.8%)

*Mix design as in Table 9 except water/cement = 0.35, aggregate B/ cement = 1.5, and sodium sulphate/cement ratio was varied from 0 to 0.5%

[†]Mould for slump test: cylinder, D_0 = 77 mm, H_0 = 58 mm. The slump was determined by measuring the outer surface of the horizontal displaced mortar

Table 14. Raw materials for concrete D of low fluidity

Water/cement = 0.45
Cement/aggregate B/aggregate D = 1:1.5:2.49 (by weight)
Fibres/cement = 0.5%, 5.1 mm long
Methylcellulose/cement = 0.8%
Colloids 1010 = 0.13 vol% (if applicable)
Silica fume B = 15% replacement of cement
Water reducing agent (TAMOL SN)/cement = 0.7%
Accelerating agents:
  Triethanolamine/cement = 0.06%
  Potassium aluminium sulphate/cement = 0.5%
  Sodium sulphate/cement = 0.3%
Air entrainer/cement = 3% (if applicable)

Note: The raw materials were the same for concrete C except that aggregate C was used instead of aggregate D

Mortar A

Table 18 shows the effect of silica fume A vs. silica fume B on the flexural strength at 3 days of curing. Comparison between rows 1 and 3 and between rows 2 and 4 show that fibres and methylcellulose are effective in increasing the flexural strength. Comparison between rows 1 and 2 and between rows 3 and 4 show that silica fume A gave higher flexural strength than silica fume B. Table 19 lists the properties of silica fume A and silica fume B. The lower SiO_2 content in silica fume B compared with silica fume A leads to less pozzalanic reaction with silica fume B, so that silica fume B gave lower flexural strength than silica fume A. In addition, the higher surface area of silica fume A contributed to the higher flexural strength.

Table 20 lists the raw materials for mortar A in the following investigation. Note that silica fume A rather than silica fume B was used. Table 21 gives the effect of fibres, dis, chem and microsilica on the flexural strength of mortar A. The use of fibres + dis + chem + silica fume A increased the flexural strength by 130% and 110% respectively after 7 and 14 days of curing. The effectiveness of fibres + dis in increasing the flexural strength is comparable to or higher than that of chem + silica fume A, as shown by comparing rows 2 and 3 of Table 21. The use of just fibres + dis (without chem or silica fume A) increased the flexural strength by 100% and 60% respectively after 7 and 14 days of curing, as shown by comparing rows 1 and 2.

Table 22 gives the effect of fibres, dis, chem and silica fume A on the flexural toughness of mortar A. The use of fibres + dis + chem + silica fume A increased the flexural toughness by 130% and 380% respectively after 7 and 14 days of curing. The effectiveness of fibres + dis in increasing the flexural toughness is higher than that of chem + silica fume A for both 7 and 14 days of curing, as shown by comparing rows 2 and 3. The use of just fibres + dis (without chem or silica fume A) increased the flexural toughness by 190% and 430% respectively after 7 and 14 days of curing, as shown by comparing rows 1 and 2. The flexural toughness of mortar A containing fibres + dis is even higher than that of mortar A containing fibres + dis + chem + silica fume A, as shown by comparing rows 2 and 4. Fig. 3 shows the plots of flexural stress vs. displacement during flexural testing of the four types of mortar A (labelled 1, 2, 3 and 4 in Table 22 and Fig. 3) after 7 and 14 days of curing. These plots indicate that the high flexural toughness of 2 (i.e., mortar A with fibres + dis) is due to its high flexural strength and exceptionally high ductility.

Concrete D of normal fluidity

The raw materials for concrete D of normal fluidity are listed in Table 23. Wet mix was applied.

Comparison between Tables 23 and 14 shows that the water/cement ratio was higher for concrete D of normal fluidity than for concrete D of low fluidity. Moreover, the amounts of water reducing agent and sodium sul-

Table 15. Effect of chemical agents and silica fume B on flexural strength for concrete D of low fluidity

		Flexural strength (MPa)		
		28 days	14 days	7 days
1	Plain	4.76 (±4.5%)	4.39 (±6.0%)	3.40 (±2.1%)
2	+ Chem	7.29 (±6.0%)	5.14 (±4.0%)	4.76 (±5.0%)
3	+ Silica fume B	7.40 (±9.6%)	6.31 (±2.2%)	4.40 (±9.7%)
4	+ Chem + silica fume B	7.52 (±2.7%)	6.54 (±15%)	5.70 (±4.6%)

Table 16. Effect of carbon fibres, methylcellulose and Colloids 1010 on flexural strength for concrete D of low fluidity

	Flexural strength (MPa)		
	28 days	14 days	7 days
1 [a]Fibres + chem	7.46 (±9.0%)	6.71 (±9.6%)	5.62 (±8.7%)
2 [b]Fibres + chem	–	6.42 (±11%)	5.46 (±9.2%)
3 [b]Fibres + chem + M	7.83 (±4.5%)	6.69 (±5.6%)	6.56 (±6.4%)
4 [b]Fibres + chem + M + silica fume B	8.07 (±2.7%)	6.84 (±3.2%)	6.66 (±2.3%)
5 [b]Fibres + chem + M + 1010	–	7.86 (±7%)	6.96 (±5%)

[a]Dry mix; [b]wet mix

Table 17. Freeze-thaw durability test for concrete D of low fluidity

	Flexural strength (MPa)		
	37 days	7 days, then 30 cycles at 1 cycle per day	Freeze-thaw durability* (%)
Plain	6.64 (±7%)	4.87 (±3%)	73
+ Fibres + M + chem + silica fume B	8.84 (±3%)	7.52 (±4.6%)	85

*Fractional retention of flexural strength after thermal cycling

Table 18. Effect of silica fume A vs. silica fume B on the flexural strength at 3 days for mortar A*

	Flexural strength (MPa)
1 Plain + silica fume A	4.68 (±2.0%)
2 Plain + silica fume B	4.09 (±3.0%)
3 Fibres + M + silica fume A	6.42 (±5.0%)
4 Fibres + M + silica fume B	5.26 (±5.0%)

*Raw materials: water/cement = 0.45; aggregate A/cement = 1.5; TAMOL SN/cement = 2%; methycellulose/cement = 0.4%; silica fume A/cement = 0.15; silica fume B/cement = 0.15; fibres/cement = 1.0%, 5.1 mm long

phate were higher for concrete D of normal fluidity than for concrete D of low fluidity whereas the amount of methylcellulose was lower for concrete D of normal fluidity than for concrete D of low fluidity.

Comparison between Tables 23 and 20 shows that the amounts of methylcellulose, water reducing agent and accelerating agents are the same for concrete D of normal fluidity and mortar A. The difference between the two sets of raw materials lies only in the water/cement ratio and in the aggregate, as required by the fact that mortar A is a mortar whereas concrete D is a concrete.

Table 24 shows the effect of fibres + dis + chem + silica fume A on the flexural strength of concrete D of normal fluidity. The use of fibres + dis + chem + silica fume A increased the flexural strength by 90%, 83% and 85% respectively after 7, 14 and 28 days of curing, as shown by comparing rows 1 and 5. The effectiveness of just fibres + dis in increasing the flexural strength is comparable to that of just chem + silica fume A, as shown by comparing rows 2 and 3. The use of just fibres + dis increased the flexural strength by 56%, 58% and 59% respectively after 7, 14 and 28 days of curing, as shown by comparing rows 1 and 2. Comparison between rows 2 and 4 shows that chem is useful for increasing the flexural strength. Comparison between rows 4 and 5 shows that silica fume A is useful for increasing the flexural strength.

Table 25 shows the effect of fibres, dis, chem and silica fume A on the flexural toughness of concrete D of normal fluidity. The use of fibres + dis + chem + silica fume A increased the flexural toughness by 80%, 160% and 205% respectively after 7, 14 and 28 days of curing, as shown by comparing rows 1 and 4. The effectiveness of just fibres + dis in increasing the flexural toughness is superior to that of just chem + silica fume A or that of fibres + dis + chem + silica fume A, as shown by comparing rows 2, 3 and 4. The use of just fibres + dis increased the flexural toughness by 160%, 170% and 170% respectively after 7, 14 and 28 days of curing, as shown by comparing rows 1 and 2.

Fig. 4 shows the plots of flexural stress vs. displacement during flexural testing of the four types of concrete D (labelled 1, 2, 3 and 4 in Table 25 and Fig. 4) after 7, 14 and 28 days of curing. These plots indicate that the high flexural toughness of type 4 (i.e., concrete D with fibres + dis + chem + silica fume A) after 14 days of curing is due to its high flexural strength as well as its high ductility. Comparison between types 2, 3 and 4 at 28 days

Table 19. Comparison of properties of silica fume A and silica fume B

	Silica fume A	Silica fume B
Manufacturer	Elkem Materials Inc (EMS 960)	Tam Ceramics
Particle size	100%<1 mm 0.15 μm (ave) Range 0.03–0.5 μm 20%, 0.04 μm	>10 μm, 19% >1 μm, 44% >0.3 μm, 76%
Bulk density (g cm³)	0.16–0.45	0.48
Specific gravity	2.2	2.3
SiO_2	94%	90.2%
Surface area ($m^2 g^{-1}$)	22 (spherical)	12.5 (spherical)
Mohs hardness	6.5	–
Colour	Grey	Light grey
Chemical composition	C 3% FeO 0.1% Al_2O_3 0.36% CaO 0.27% MgO 0.2% 3.6% ion on ignition Na_2O, K_2O<0.5%	Much less C ZrO_2

Table 20. Raw materials for mortar A

Water/cement=0.45
Aggregate A/cement=1.5
Fibres/cement=0.5%, 5.1 mm long
Methylcellulose/cement=0.4%
Silica fume A/cement=0.15
Colloids 1010=0.13 vol%
Water reducing agent (TAMOL SN)/cement=2%
Accelerating agents:
Triethanolamine/cement=0.06%
Potassium aluminium sulphate/cement=0.5%
Sodium sulphate/cement=0.5%

Table 21. Flexural strength of mortar A at different curing ages

	Flexural strength (MPa)	
	14 days	7 days
1 Plain	4.75 (±5%)	3.36 (±4%)
2 +Fibres+dis	7.61 (±5%)	6.87 (±8%)
3 +Chem+silica fume A	7.60 (±4%)	5.11 (±3%)
4 +Fibres+dis+chem+silica fume A	9.81 (±7%)	7.68 (±5%)

Table 22. Flexural toughness of mortar A at different curing ages

	Flexural toughness (MPa cm)	
	14 days	7 days
1 Plain	0.036 (±5%)	0.020 (±4%)
2 +Fibres+dis	0.192 (±5%)	0.058 (±8%)
3 +Chem+silica fume A	0.081 (±4%)	0.056 (±3%)
4 +Fibres+dis+chem+silica fume A	0.176 (±7%)	0.046 (±5%)

of curing shows that the relatively high flexural toughness of type 2 is due to its high ductility.

Table 26 shows the compressive strength of concrete D of normal fluidity. Comparison between rows 1 and 4 of this table shows that the use of fibres+dis+chem+silica fume A gave a compressive strength that was quite close to that of plain concrete. However, comparison between rows 3 and 4 shows that the use of just chem +silica fume A gave much higher compressive strength than the use of fibres+dis+chem+silica fume A.

Fig. 5 shows the plot of compressive stress vs. axial strain and that of compressive stress vs. lateral strain for the samples corresponding to rows 1–4 of Table 26 after 90 days of curing. Although types 3 and 4 are comparably brittle in the axial direction, 4 is more ductile than 3 in the lateral direction.

Table 27 gives the freeze-thaw durability test (ASTM C666) results of concrete D of normal fluidity. Tempera-

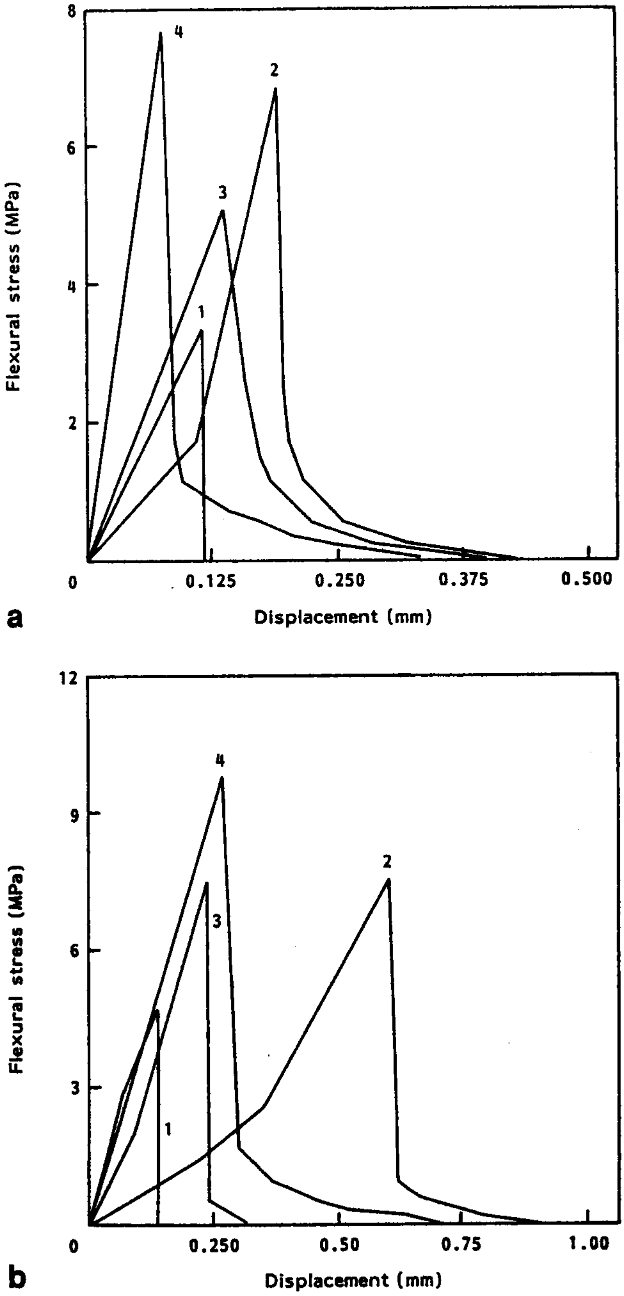

Fig. 3 Flexural stress vs. displacement for mortar A after (a) 7 days and (b) 14 days of curing. 1, 2, 3 and 4 are as defined in Table 22

Table 23. Raw materials for concrete D of normal fluidity

Water/cement = 0.50
Cement/aggregate B/aggregate D = 1:1.5:2.49 (by weight)
Fibres/cement = 0.5%, 5.1 mm long
Methylcellulose/cement = 0.4%
Silica fume A/cement = 0.15
Colloids 1010 = 0.13 vol%
Water reducing agent (TAMOL SN)/cement = 2%
Accelerating agents:
  Triethanolamine/cement = 0.06%
  Potassium aluminium sulphate/cement = 0.5%
  Sodium sulphate/cement = 0.5%

ture cycling was carried out between −40 and 10°C, with a temperature accuracy of ±3°C, at a rate of 1 cycle per day. Cycling started after 14 days of curing. Thirty cycles (30 days) were conducted. After that, the flexural strength was measured and compared with that of the same kind of concrete that had not undergone cycling (just 14 + 30 = 44 days of curing). For plain concrete D, cycling decreased the flexural strength by 12%. For concrete D containing fibres + dis, cycling decreased the flexural strength by 6.9%. For concrete D containing chem + silica fume A, cycling decreased the flexural strength by 10%. For concrete D containing fibres + dis + chem + silica fume A, cycling decreased the flexural strength by 5.1%. Hence, fibres + dis are more effective than chem + silica fume A in improving the freeze-thaw durability. Moreover, fibres + dis + chem + silica fume A are most effective in improving the freeze-thaw durability.

Air-entrained concrete D of normal fluidity

Air-entrained concrete D of normal fluidity used the same raw materials as in Table 23, except that water/cement = 0.45 (instead of 0.50) and air entrainer/cement = 1% (instead of 0%). The air entrainer used was Daravair (Table 6). The air content is given later in this paper. Tables 28 and 29 give the flexural strength and flexural toughness, respectively. Comparison of rows 1 and 4 of Table 28 shows that the use of fibres + dis + chem + silica fume A increased the flexural strength of air-entrained concrete D by 83%, 95% and 79% respectively after 7, 14 and 28 days of curing. Comparison of rows 1 and 4 of Table 29 shows that the use of fibres + dis + chem + silica fume A increased the flexural toughness by 49%, 43% and 53% respectively after 7, 14 and 28 days of curing.

Fig. 6 shows the plots of flexural stress vs. displacement during flexural testing of the four types of air-entrained concrete D (labelled 1, 2, 3 and 4 in Table 29 and Fig. 6) after 7, 14 and 28 days of curing. These plots indicate that the high flexural toughness of type 4 (i.e., concrete D with fibres + dis + chem + silica fume A) after 28 days of curing is due to its high flexural strength as well as its high ductility.

Comparison of Tables 29 and 25 shows that the use of fibres + dis + chem + silica fume A is much more effective for enhancing the flexural toughness of concrete without air entrainment than concrete with air entrainment. However, comparison of Tables 28 and 24 shows that the use of fibres + dis + chem + silica fume A is comparably effective for enhancing the flexural strength of concrete without air entrainment and that with air entrainment.

Table 30 shows the compressive strength of air-entrained concrete D of normal fluidity. Comparison between Table 26 (without air entrainer) and Table 30 (with air entrainer) shows that the air entrainer greatly decreased the compressive strength. Comparison between rows 1 and 2, and between rows 3 and 4 of Table 30 shows that the fibres decreased the compressive strength slightly, whether or not chem and silica fume A were present. Nevertheless, comparison between rows 1 and 4 of Table 30 shows that the use of fibres + dis + chem + silica fume A increased the compressive strength by 95% and 120% at 28 and 7 days respectively, relative to the values of plain concrete.

Table 24. Flexural strength of concrete D (of normal fluidity) at different curing ages

	Flexural strength (MPa)		
	28 days	14 days	7 days
1 Plain	5.00 (±5%)	4.22 (±4%)	3.10 (±4%)
2 + Fibres + dis	7.95 (±6%)	6.65 (±3%)	4.84 (±2%)
3 + Chem + silica fume A	7.86 (±3%)	5.89 (±2%)	5.03 (±4%)
4 + Fibres + dis + chem	–	7.15 (±7%)	5.22 (±6%)
5 + Fibres + dis + chem + silica fume A	9.23 (±9%)	7.74 (±9%)	5.90 (±7%)

Table 25. Flexural toughness of concrete D (of normal fluidity) at different curing ages

	Flexural toughness (MPa cm)		
	28 days	14 days	7 days
1 Plain	0.083 (±5%)	0.077 (±4%)	0.047 (±4%)
2 + Fibres + dis	0.221 (±6%)	0.210 (±3%)	0.123 (±2%)
3 + Chem + silica fume A	0.187 (±3%)	0.095 (±2%)	0.107 (±4%)
4 + Fibres + dis + chem + silica fume A	0.253 (±9%)	0.198 (±9%)	0.085 (±7%)

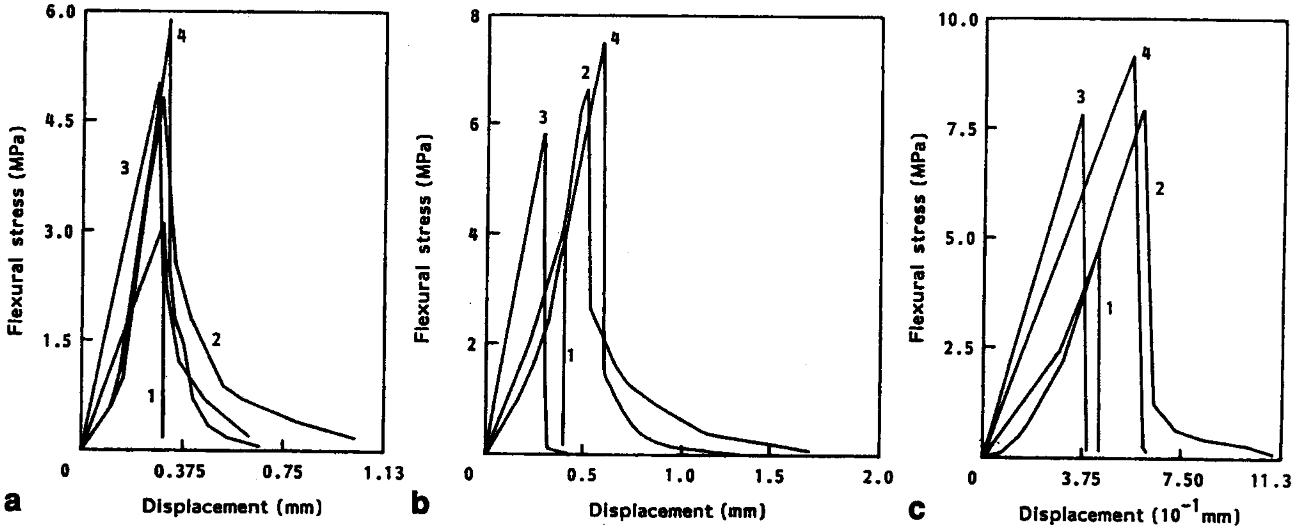

Fig. 4 Flexural stress vs. displacement for concrete D of normal fluidity (without air entrainment) after (a) 7 days, (b) 14 days and (c) 28 days of curing. 1, 2, 3 and 4 are as defined in Table 25

Table 26. Compressive strength of concrete D of normal fluidity at different curing ages

	Compressive strength (MPa)		
	90 days	28 days	7 days
1 Plain	30.35 (±3%)	29.20 (±2%)	27.23 (±4%)
2 + Fibres + dis	25.48 (±6%)	24.71 (±5%)	23.39 (±9%)
3 + Chem + silica fume A	56.67 (±5%)	52.56 (±3%)	35.09 (±3%)
4 + Fibres + dis + chem + silica fume A	36.90 (±8%)	35.69 (±7%)	26.90 (±8%)

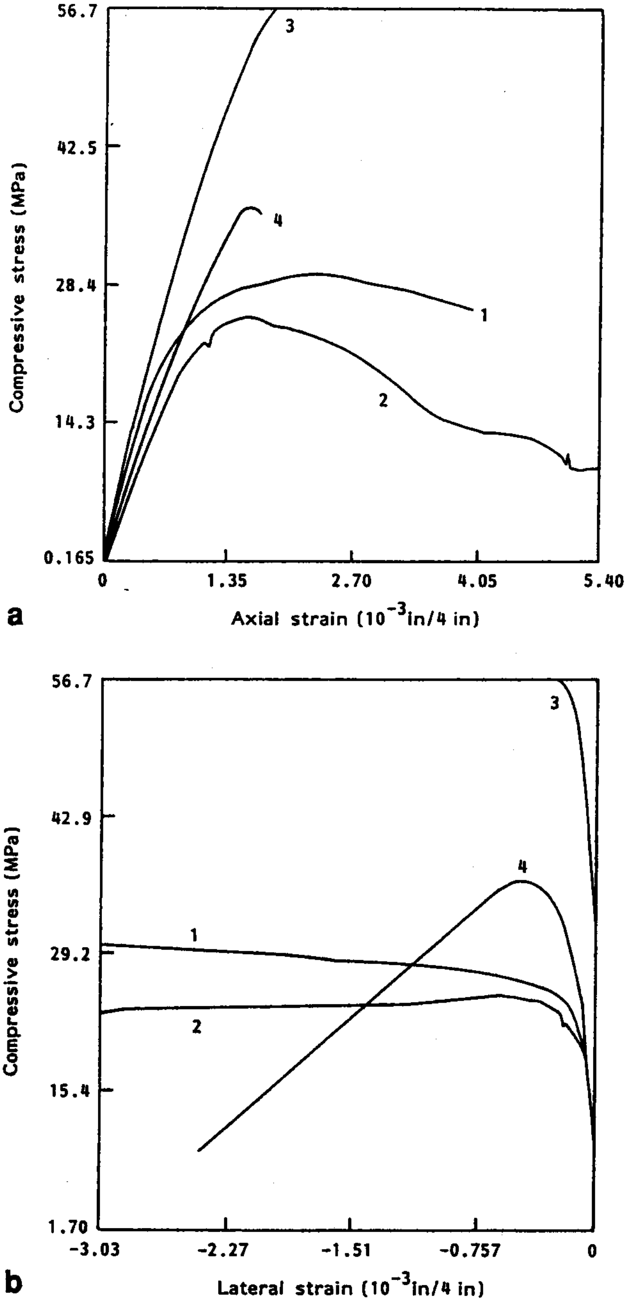

Fig 5 Compressive stress vs. compressive strain for concrete D of normal fluidity after 90 days of curing: (a) axial strain; and (b) lateral strain. 1, 2, 3 and 4 are as defined in Table 26

Table 31 gives the freeze-thaw durability test (ASTM C666) results of air-entrained concrete D of normal fluidity. Comparison between Table 27 (without air entrainer) and Table 31 (with air entrainer) shows that the fractional decrease in the flexural strength due to the temperature cycling was about the same, whether or not an air entrainer was used.

Concrete C

The raw materials for concrete C were the same as those for concrete D of normal fluidity (Table 23) except that aggregate C was used instead of aggregate D. Thus, comparison between concrete C and concrete D with normal fluidity provides a study of the effect of aggregate size.

Table 32 gives the effect of fibres, dis, chem and silica fume A on the flexural strength of concrete C after 7 and 14 days of curing. The use of fibres + dis + chem + silica fume A increased the flexural strength by 100% and 73% respectively after curing for 7 and 14 days. The effect of just fibres + dis on the flexural strength is comparable to that of just chem + silica fume A. The use of just fibres + dis increased the flexural strength by 49% and 54% respectively after 7 and 14 days of curing.

Table 33 gives the effect of fibres, dis, chem and silica fume A on the flexural toughness after 7 and 14 days of curing. The use of fibres + dis + chem + silica fume A increased the flexural toughness by 160% and 200% respectively after 7 and 14 days of curing. The effect of just fibres + dis on the flexural toughness was comparable to or slightly larger than that of just chem + silica fume A. The use of just fibres + dis increased the flexural toughness by 100% after either 7 or 14 days of curing.

Slump and effect of water/cement ratio

The water/cement ratio was 0.50 in concrete D of normal fluidity. Keeping all other ingredients the same, the water/cement ratio was varied from 0.50 to 0.40 and the effect of this variation on the flexural strength and slump (ASTM C143–78) was investigated. The decrease in the water/cement ratio increased the flexural strength but decreased the slump, as shown in Table 34 for concrete D without air entrainer. For case 4 with fibres + chem + silica fume A, a decrease of the water/cement ratio from 0.50 to 0.45 decreased the slump from 102 to 25.4 mm (4 to 1 in), so that a ratio of 0.50 is optimum.

For a water/cement ratio of 0.45, Table 34 also shows that the use of an air entrainer increases the slump.

Effect of fibre content on flexural strength and toughness

The fibre content was 0.500% by weight of the cement (or 0.189 vol%) in concrete D of normal fluidity. Keeping all other ingredients the same (no air entrainer), the fibre content was reduced to 0.249% by weight of the cement (or 0.094 vol%) and the effect of this change on the flexural strength and flexural toughness was investigated. This reduction of the fibre content caused the fibres to be ineffective in increasing the flexural strength although still effective in increasing the flexural toughness, as shown in Table 35.

Air content

The air content was measured using ASTM C231–82. Table 36 shows the air content of concrete D of normal fluidity without and with the air entrainer. Comparison of rows 1 and 2 and of rows 3 and 4 shows that the use of fibres significantly increased the air content. Even without the air entrainer, the air content was 6% for concrete D with fibres + dis + chem + silica fume A. With the air entrainer, the air content was further increased.

Dry shrinkage

The dry shrinkage was investigated by measuring the length change of mortar A and concrete D of normal fluidity in accordance with ASTM C490–83a. The speci-

Table 27. Freeze-thaw durability testing of concrete D of normal fluidity

	Flexural strength (MPa)		
	44 days	14 days, then 30 cycles at 1 cycle per day	Freeze-thaw durability* (%)
1 Plain	5.28 (±2.3%)	4.65 (±2%)	88
2 + Fibres + dis	8.10 (±7%)	7.54 (±6%)	93
3 + Chem + silica fume A	8.14 (±4%)	7.33 (±5.4%)	90
4 + Fibres + dis + chem + silica fume A	9.70 (±8%)	9.21 (±9%)	95

*Fractional retention of flexural strength after thermal cycling

Table 28. Flexural strength of air-entrained concrete D of normal fluidity* at different curing ages

	Flexural strength (MPa)		
	28 days	14 days	7 days
1 Air-entrained concrete D	5.04 (±8%)	4.04 (±6%)	3.84 (±9%)
2 + Fibres + dis	5.84 (±3%)	5.33 (±8%)	4.42 (±9%)
3 + Chem + silica fume A	7.42 (±10%)	7.24 (±9%)	6.05 (±8%)
4 + Fibres + dis + chem + silica fume A	9.00 (±5%)	7.86 (±10%)	7.03 (±9%)

*Raw materials as described in Table 23, except that water/cement = 0.45 and air entrainer/cement = 1%

Table 29. Flexural toughness of air-entrained concrete D of normal fluidity* at different curing ages

	Flexural toughness (MPa cm)		
	28 days	14 days	7 days
1 Air-entrained concrete D	0.179 (±8%)	0.185 (±6%)	0.141 (±9%)
2 + Fibres + dis	0.189 (±3%)	0.278 (±8%)	0.206 (±9%)
3 + Chem + silica fume A	0.199 (±10%)	0.154 (±9%)	0.215 (±8%)
4 + Fibres + dis + chem + silica fume A	0.274 (±5%)	0.265 (±10%)	0.210 (±9%)

*Raw materials as described in Table 23, except that water/cement = 0.45 and air entrainer/cement = 1%

men size was 25.4 × 25.4 × 286 mm (1 × 1 × 11.25 in) for mortar A and 76.2 × 76.2 × 286 mm (3 × 3 × 11.25 in) for concrete D. The accuracy in the length change measurement was ± 0.0025 mm (0.0001 in). Fig. 7 shows the plots of drying shrinkage strain vs. curing time for mortar A curing in air and curing in water. For all samples, curing in water resulted in much less shrinkage than curing in air. However, for each case, the use of fibres decreased the shrinkage, irrespective of the presence of chem + silica fume A. Fig. 8 shows the plot of drying shrinkage strain vs. curing time for concrete D curing in a moist room. The use of fibres + dis + chem + silica fume A (case 4 in Fig. 8) lowered the drying shrinkage at 14 days by 90%, compared with that of plain concrete (case 1 in Fig. 8).

Fibre volume fraction

The fibre content of 0.5% by weight of the cement corresponds to the volume fractions shown in Table 37. Note that the volume fractions are all less than 0.25%. The volume fraction for mortar B is particularly low.

Effectiveness of the fibres

The mix designs for mortar A, concrete D of normal fluidity and concrete C were all similar, as all involved wet mix with dis. In contrast, mortar B involved dry mix, without dis. Therefore, comparison among mortar A, concrete C and concrete D of normal fluidity provides a study of the effect of aggregate size. Both concrete C and concrete D contained 0.189 vol% fibres, whereas mortar

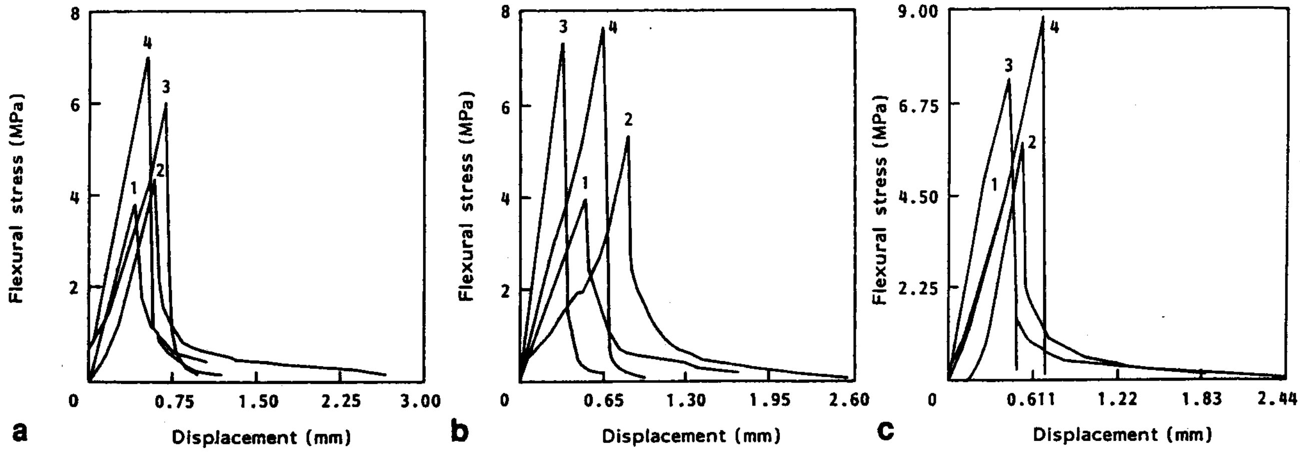

Fig. 6 Flexural stress vs. displacement for air-entrained concrete D of normal fluidity after (a) 7 days, (b) 14 days and (c) 28 days of curing. 1, 2, 3 and 4 are as defined in Table 29

Table 30. Compressive strength of air-entrained concrete D of normal fluidity at different curing ages

	Compressive strength (MPa)	
	28 days	7 days
1 Air-entrained concrete D	16.02 (±3%)	11.85 (±2%)
2 +Fibres+dis	15.74 (±7%)	11.12 (±4%)
3 +Chem+silica fume A	33.49 (±5%)	27.27 (±3%)
4 +Fibres+dis+chem+silica fume A	31.30 (±4%)	25.73 (±5%)

A contained 0.244 vol% of fibres. Therefore, comparison between concrete C and concrete D is most appropriate for studying the effect of aggregate size.

Table 38 shows that the effect of aggregate size on the effectiveness of fibres+dis+chem+silica fume A for increasing the flexural strength and flexural toughness is not large. An increase in aggregate size (from that of concrete C to that of concrete D) did not degrade the effectiveness of fibres+dis+chem+silica fume A.

Table 39 shows that the effect of aggregate size on the effectiveness of fibres+dis (without chem or silica fume A) for increasing the flexural strength and flexural toughness is not large. An increase in aggregate size (from that of concrete C to that of concrete D) increased the effectiveness of fibres+dis slightly.

The combination of Tables 38 and 39 shows that the fibres (5 mm long) are similarly effective for aggregate size ranging to 19 mm (3/4 in, aggregate C) and for aggregate size ranging to 25 mm (1 in, aggregate D), as well as for aggregate size ranging to 2 mm (aggregate A), even though the aggregate size is smaller than the fibre length in the case of aggregate A and is larger than the fibre length in the case of aggregates C and D.

Table 40 shows the effect of aggregate size on the effectiveness of fibres+chem (dry mix) for increasing the flexural strength. Because of the difference in fibre volume fraction between mortar B and concrete D of low fluidity, the flexural strength increases cannot be directly compared with one another. Since the fibre volume fraction in concrete D of low fluidity is about twice that in mortar B, it can probably be concluded that the effect of aggregate size is small.

Comparison between Tables 39 and 40 shows that mortar B is particularly poor in the effectiveness of the fibres in increasing the flexural strength. This is attributed to the particularly low volume fraction of fibres in mortar B. Hence, the minimum fibre volume fraction for the fibres to be effective for increasing the flexural strength is around 0.10%.

Comparison between Tables 39 and 40 with regard to

Table 31. Freeze-thaw durability testing of air-entrained concrete D of normal fluidity

	Flexural strength (MPa)		
	44 days	14 days, then 30 cycles at 1 cycle per day	Freeze-thaw durability* (%)
1 Air-entrained concrete D	5.33 (±3%)	4.42 (±5%)	83
2 +Fibres+dis	6.12 (±6%)	5.60 (±4%)	92
3 +Chem+silica fume A	7.69 (±4%)	6.65 (±5%)	86
4 +Fibres+dis+chem+silica fume A	9.45 (±3%)	8.79 (±5%)	93

*Fractional retention of flexural strength after thermal cycling

Table 32. Flexural strength of concrete C* at different curing ages

		Flexural strength (MPa)	
		14 days	7 days
1	Plain	4.15 (±3%)	3.32 (±3%)
2	+ Fibres + dis	6.39 (±5%)	4.94 (±5%)
3	+ Chem + silica fume A	6.12 (±3%)	4.96 (±4%)
4	+ Fibres + dis + chem + silica fume A	7.18 (±8%)	6.64 (±7%)

*Same as concrete D with normal fluidity except using aggregate C instead of aggregate D

Table 33. Flexural toughness of concrete C* at different curing ages

		Flexural toughness (MPa cm)	
		14 days	7 days
1	Plain	0.052 (±3%)	0.048 (±3%)
2	+ Fibres + dis	0.104 (±5%)	0.098 (±5%)
3	+ Chem + silica fume A	0.087 (±3%)	0.093 (±4%)
4	+ Fibres + dis + chem + silica fume A	0.156 (±8%)	0.124 (±7%)

*Same as concrete D with normal fluidity except using aggregate C instead of aggregate D

concrete D shows that wet mix (with dis) and dry mix (with chem) gave comparable effectiveness of the fibres for increasing the flexural strength. For a more direct comparison between wet mix (with chem) and dry mix (with chem), refer to Table 16.

Electrical resistivity

The electrical resistivity was measured by the four-probe method, using silver paint for electrical contacts. Table 41 shows the resistivity (at 14 days of curing) of concrete D of normal fluidity and mortar A. The presence of fibres + M decreased the resistivity by 73% and 83% respectively for concrete D and mortar A. The presence of chem + silica fume A (without fibres) decreased the resistivity by 13% and 35% respectively for concrete D and mortar A. The presence of fibres + M + chem + silica fume A decreased the resistivity by 83% and 84% respectively for concrete D and mortar A. Hence, fibres + M are much more effective than chem + silica fume A for decreasing the electrical resistivity.

Increasing the fibre content beyond 0.5% by weight of the cement is expected to greatly increase the effectiveness of the fibres for decreasing the electrical resistivity.

Microscopy

Scanning electron microscopy (SEM) was performed on the fracture surfaces after flexural testing. It revealed some fibre pull-out, which furthermore showed that the individual fibres were quite uniformly distributed. No fibre clustering was observed and nor was fibre damage.

PRICE

Table 42 shows the percentage material price increase per cubic yard (1 yd^3 = 0.765 m^3) of the various mortars and concretes due to the addition of various additives. The fibres are the most expensive type of additive, although the price increase due to fibres (0.5%) + M + 1010 is not much greater than that due to chem + silica fume A. The best concrete studied in this work corresponds to row 10 of Table 42—a price increase of 39%.

The use of fibres in the amount of 1.0% by weight of the cement was not investigated in this work, but it is expected to further increase the flexural strength and flexural toughness. The best such concrete corresponds to row 14—a price increase of 56%.

The processing price increase is associated with the use of both a Hobart mixer and a stone concrete mixer.

COMPETITION

The carbon fibre-reinforced concrete of best performance in this work is concrete D (of normal fluidity) with fibres (0.5% by weight of the cement) + dis + chem + silica fume A. Its properties and price relative to plain concrete D are summarized in Table 43 in the column labelled concrete α.

A competitive concrete is concrete D (of normal fluidity) with chem + silica fume A (no fibres). Its properties and price relative to plain concrete D are summarized in Table 43 in the column labelled concrete β.

Concrete α is superior to concrete β in its higher flexural strength, higher flexural toughness, higher freeze-thaw durability, lower drying shrinkage and lower electrical resistivity, but it is inferior to concrete β in its lower compressive strength and higher price. Although the thermal conductivity was not measured, it is clear that concrete α is superior to concrete β in its higher thermal conductivity, which is attractive for heated bridges.

Other competitive concretes are those containing carbon fibres in excess of about 1 vol%[1–5,7]. Although these concretes tend to be superior to concrete α in flexural strength and toughness, they are much more costly. Moreover, the high fibre content makes the mixing more difficult.

Competitive fibres include organic and steel fibres. Acrylic fibres in the amount of 2.5 vol% increase the flexural strength by 28% and the flexural toughness by 240%[9], whereas steel fibres in the amount of 1.2 vol% increase the flexural strength by 41% and the flexural toughness by 1500%[10]. In spite of the large fibre volume fractions, acrylic and steel fibres yield fractional increases in the flexural strength that are lower than that of the carbon fibres of this work (0.2 vol%). However, acrylic and steel fibres of such large volume fractions yield fractional increases in the flexural toughness that are higher than that of 0.2 vol% carbon fibres. In addition to the better

Table 34. Effects of the water/cement ratio (W/C) on the flexural strength and slump of concrete D of normal fluidity

Material	W/C	Flexural strength (MPa)			Slump (mm)*	
		28 days	14 days	7 days	Without air entrainer	With air entrainer
1 Plain	0.50	5.00 (±5%)	4.22 (±4%)	3.10 (±4%)	152 (6)	–
	0.45	–	5.25 (±9%)	4.01 (±8%)	127 (5)	152 (6)
	0.40	–	6.05 (±8%)	5.38 (±7%)	102 (4)	–
2 + Fibres + dis	0.50	7.95 (±6%)	6.65 (±3%)	4.84 (±2%)	102 (4)	–
	0.45	–	6.91 (±5%)	5.59 (±8%)	50.8 (2)	76.2 (3)
	0.40	–	7.13 (±8%)	6.02 (±3%)	45.7 (1.8)	–
3 + Chem + silica fume A	0.50	7.86 (±3%)	5.89 (±2%)	5.03 (±4%)	102 (4)	–
	0.45	–	9.97 (±1%)	–	76.2 (3)	102 (4)
	0.40	–	12.82 (±3%)	–	25.4 (1)	–
4 + Fibres + dis + chem + silica fume A	0.50	9.23 (±9%)	7.74 (±9%)	5.90 (±7%)	102 (4)	–
	0.45	–	11.82 (±5%)	–	25.4 (1)	50.8 (2)
	0.40	–	–	–	–	–

*Figures in brackets refer to slump in inches

Table 35. Effect of fibre volume fraction on the flexural properties of concrete

Fibre (vol%)	Flexural strength (MPa)			Flexural toughness (MPa cm)		
	28 days	14 days	7 days	28 days	14 days	7 days
Fibre + dis						
0.000*	5.00 (±5%)	4.22 (±4%)	3.10 (±4%)	0.083 (±5%)	0.077 (±4%)	0.047 (±4%)
0.094†	4.93 (±4%)	4.36 (±4%)	3.29 (±3%)	0.165 (±4%)	0.116 (±4%)	0.108 (±3%)
0.189	7.95 (±6%)	6.65 (±3%)	4.84 (±2%)	0.221 (±6%)	0.210 (±3%)	0.123 (±2%)
Fibres + dis + chem + silica fume A						
0.000*	7.86 (±3%)	5.89 (±2%)	5.03 (±4%)	0.187 (±3%)	0.095 (±2%)	0.107 (±4%)
0.094†	7.50 (±8%)	5.91 (±7%)	5.10 (±6%)	0.240 (±8%)	0.151 (±7%)	0.140 (±6%)
0.189	9.23 (±9%)	7.74 (±9%)	5.90 (±7%)	0.253 (±9%)	0.198 (±9%)	0.085 (±7%)

*Dis was not used in the absence of the fibres
†Same as the fibre volume fraction of mortar B

Table 36. Air content of concrete D of normal fluidity

	Air content (%)	
	Without air entrainer*	With air entrainer†
1 Plain	1	6
2 + Fibres + dis	7	10
3 + Chem + silica fume A	3	7
4 + Fibres + dis + chem + silica fume A	6	9

*Water/cement = 0.50; †water/cement = 0.45

effectiveness in increasing the flexural strength, carbon fibres are attractive in their chemical stability.

CONCLUSIONS

A formulation for carbon fibre-reinforced concrete has been developed. This formulation uses short pitch-based carbon fibres in the amount of 0.5% by weight of the cement. In addition, it uses dis + chem + silica fume A. In the case of concrete D, which uses #57 aggregate, the carbon fibres amount to 0.189 vol% of the concrete. Compared with plain concrete, this formulation costs 39% more in materials and yields a flexural strength increase of 85%, a flexural toughness increase of 205% and a compressive strength increase of 22% at 28 days of curing. When an air entrainer is used, this formulation, compared with plain air-entrained concrete, yields a flexural strength increase of 79%, a flexural toughness

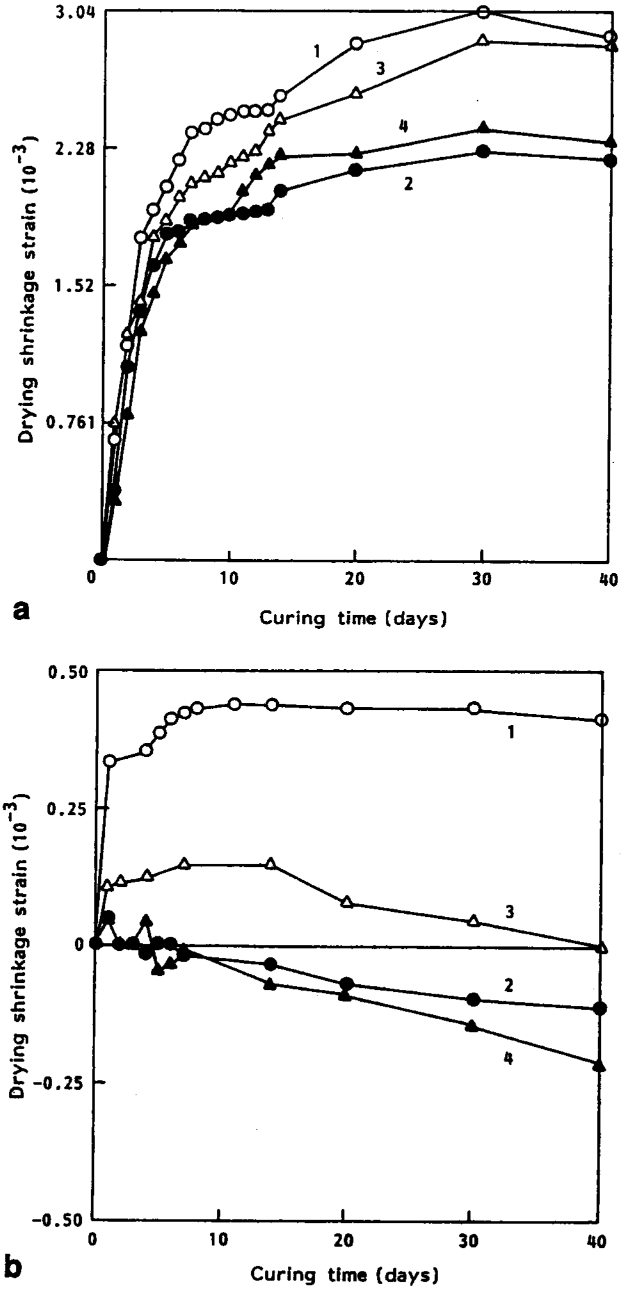

Fig. 7 Drying shrinkage strain vs. curing time for mortar A: (a) curing in air; and (b) curing in water. 1, 2, 3 and 4 are as defined in Table 22

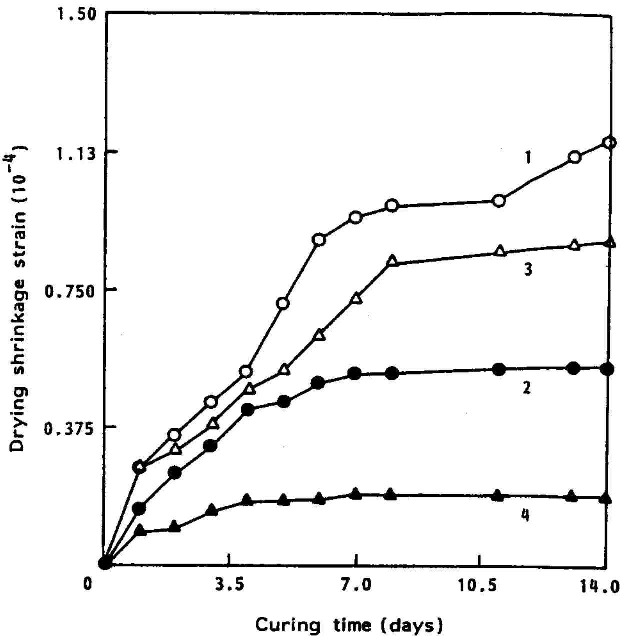

Fig. 8 Drying shrinkage strain vs. curing time for concrete D of normal fluidity curing in a moist room. 1, 2, 3 and 4 are as defined in Table 26

increase of 53% and a compressive strength increase of 95% at 28 days of curing. Hence, the formulation works well for increasing the flexural strength, whether or not an air entrainer is used, but is is much more effective for increasing the flexural toughness when an air entrainer is not used. The increase in flexural toughness is due to the increase in both the flexural strength and the ductility.

The aggregate size has little effect on the effectiveness of the abovementioned formulation.

The minimum carbon fibre volume fraction for the fibres to be effective for increasing the flexural strength is 0.1% for both mortar and concrete. Below this fibre volume fraction, the fibres are still effective for increasing the flexural toughness.

Table 37. Volume fraction of fibres in mortars and concretes with fibres in the amount of 0.5% by weight of the cement

	Vol fraction fibres (%)
Concrete C or D	0.189
Mortar B	0.094
Mortar A	0.244

The optimum fibre length is such that the mean fibre length decreases from 12 mm before mixing to 7 mm after mixing. The fibre length decrease occurs in the Hobart mixer stage of the mixing procedure.

The optimum water/cement ratio is 0.50 (slump = 102 mm (4 in)) when an air entrainer is not used, and is 0.45 (slump = 50.8 mm (2 in)) when an air entrainer is used. The slump of the corresponding plain concrete of the same water/cement ratio is 152 mm (6 in).

The use of dis (methylcellulose plus a defoamer) refers to a wet mixing (in water) procedure. Dispersing the fibres by dry mixing (without dis) gives similar results, but it is tedious compared with dispersing the fibres in water.

The air content is significantly increased by the fibre addition, whether or not an air entrainer is used. As a consequence, the compressive strength is decreased by the fibre addition, unless chem and silica fume A are also used. As another consequence, the freeze-thaw durability is increased by the fibre addition, even in the absence of an air entrainer. The further use of an air entrainer does not further improve the freeze-thaw durability.

The drying shrinkage is decreased by the addition of

Table 38. Effectiveness of fibres + dis + chem + silica fume A (wet mix) in increasing the flexural strength and flexural toughness

	Increase due to fibres + dis + chem + microsilica (%)		
	28 days	14 days	7 days
Flexural strength			
*Concrete D of normal fluidity			
Without air entrainment	85	83	90
With air entrainment	79	95	83
*Concrete C (without air entrainment)		73	100
†Mortar A (without air entrainment)		110	130
Flexural toughness			
*Concrete D of normal fluidity			
Without air entrainment	205	160	80
With air entrainment	53	43	49
*Concrete C (without air entrainment)		200	160
†Mortar A (without air entrainment)		390	132

*0.189 vol% of fibres; †0.244 vol% of fibres

Table 39. Effectiveness of fibres + dis (wet mix) in increasing the flexural strength and flexural toughness

	Increase due to fibres + dis (%)		
	28 days	14 days	7 days
Flexural strength			
*Concrete D of normal fluidity			
Without air entrainment	59	58	56
With air entrainment	16	32	15
*Concrete C (without air entrainment)		54	49
†Mortar A (without air entrainment)		60	100
Flexural toughness			
*Concrete D of normal fluidity			
Without air entrainment	170	170	160
With air entrainment	6	50	46
*Concrete C (without air entrainment)		100	100
†Mortar A (without air entrainment)		430	190

*0.189 vol% of fibres; †0.244 vol% of fibres

Table 40. Effectiveness of fibres + chem (dry mix) in increasing the flexural strength

	Increase due to fibres + chem (%)		
	28 days	14 days	7 days
*Mortar B	21	33	37
†Concrete D of low fluidity	57	53	65

*0.094 vol% of fibres; †0.189 vol% of fibres

fibres + dis + chem + silica fume A by 90% at 14 days of curing.

The electrical resistivity is decreased by the fibre addition.

This work differs from previous carbon fibre work in that it uses much less carbon fibres to achieve a similar fractional increase in the flexural strength and that previous work is essentially all on mortar only (not concrete).

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Table 41. Electrical resistivity of concrete D of normal fluidity and mortar A

		Electrical resistivity (Ω cm)	
		Concrete D	Mortar A
1	Plain	1.36×10^7	1.46×10^5
2	+ Fibres + M	3.70×10^6	2.53×10^4
3	+ Chem + silica fume A	1.19×10^7	9.53×10^4
4	+ Fibres + M + chem + silica fume A	2.32×10^6	2.31×10^4

Table 42. Price increase (%) per cubic yard

		Mortar A, concretes C and D	Mortar B
1	Plain	–	–
2	+ Fibres*	17.5	15.4
3	+ Chem	7	6
4	+ M	5	5
5	+ 1010	0.25	0.25
6	+ Silica fume A	9	9
7	+ Fibres* + chem	24.5	21.4
8	+ Fibres* + M + 1010	22.75	20.65
9	+ Chem + silica fume A	16	15
10	+ Fibres* + M + 1010 + chem + silica fume A	38.75	35.65
11	+ Fibres**	35	30.8
12	+ Fibres** + chem	42	36.8
13	+ Fibres** + M + 1010	40.25	36.05
14	+ Fibres** + M + 1010 + chem + silica fume A	56.25	51.05

*0.5% fibres by weight of cement; ** 1% fibres by weight of cement

Table 43. Properties and price relative to those of plain concrete D

	Increase (%)	
	Concrete α*	Concrete β†
Flexural strength (28 days)	85	57
Flexural toughness (28 days)	205	125
Compressive strength (28 days)	22	80
Freeze-thaw durability	8.0	2.3
Drying shrinkage (14 days)	−84	−23
Electrical resistivity (14 days)	−83	−13
Price	39	16

*Concrete of best performance (i.e., concrete D with fibres (0.5% by weight of cement) + dis + chem + silica fume A)
†Competitive concrete (i.e., concrete D with chem + silica fume A)

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