Freeze/thaw durability in concrete with fibre additions

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Abstract

From recent laboratory research monofilament and fibrillated polypropylene fibres were used in structural concrete and have been tested against 150 freeze/thaw cycles. The findings show monofilament fibres to play a significant role in protecting the concrete matrix against the forces encountered. External cube integrity was shown to be a poor indicator of structural condition. A significant aspect of the work is the range of tests applied to the freeze/thaw concrete cubes against the control sample. Strong evidence of condition was obtained from ultrasonic, compressive strength and weight loss. Surface scaling was not a satisfactory indication of the structural condition of the concrete.

Introduction

The significance of this work on freeze/thaw testing, is such that if polypropylene fibres are universally adopted as a concrete additive, there will be a reduction in maintenance and remedial work to concrete, due to freeze/thaw damage.

In addition, "with the world pouring around 5 billion tonnes of concrete a year – nearly one tonne per person per year – concrete is probably the most common material in modern construction" (Kernan, 2003) and if this concrete can have low life cycle costs due to freeze/thaw resistance and enhanced durability, this will have a lower environmental impact upon our world, with subsequent benefits. Long *et al.* (2001, p. 65) state, "It has been estimated that the value of the infrastructure and built environment represents 50 per cent of the national wealth within most European countries, because of the degree and rate of degradation of the built environment in Europe, it is of enormous economic and technical importance". Mulheron (2001, p. 1) also comments, "The need to improve our ability to both understand the mechanisms by which deterioration occurs, and the impact that methods of preventing deterioration have on subsequent material performance, is driven by the high cost of maintaining an ageing infrastructure". The marine environment will benefit from extensive use of polypropylene fibres, because of the fibres' ability to provide increased resistance to freeze/thaw conditions, where the environment can be classed as severe, without the use of secondary steel to provide resistance to fine cracking, as polypropylene will not rust. Examples of work that could be carried out are: piers, harbour walls, revetments and piles.

The testing programme has been undertaken over 12 months, with regular inspection as to the progressive condition of the concrete cubes under test. The range of tests as undertaken are complimentary to one another and all provide corroborative information that lead towards a conclusive and compelling case for the use of monofilament fibres in concrete where aggressive conditions may be experienced. It is shown that the use of polypropylene fibres will achieve a significant saving on maintenance costs in most climates, where regular and severe freeze/thaw cycles occur.

Test procedure

Concrete cubes were cast in 150mm moulds, the water cement ratio was 0.5 and the cement content $350kg/m^3$. Four types of concrete were batched; referenced A, B, C and D. The specimens were weighed and measured prior to the start of testing and the cube types were: plain (A); 19mm long polypropylene monofilament fibre addition at $0.91kg/m^3$ (B); 38mm fibrillated fibre addition at $0.91kg/m^3$ (C); and 6.5mm long polypropylene monofilament fibre addition at $0.91kg/m^3$ (D).

The procedure involved immersing the concrete specimens in a temperature controlled curing tank at 20°C for 28 days and leaving them to air dry over a convector heater for seven days before starting the freeze/thaw cycles. The average temperature of the freezer used was approximately − 18°C and when the cubes were removed from the freezer and the cube temperature was allowed to reach 4°C. The average freeze/thaw cycle was of three hours duration and the steps followed are as shown below:

- specimens placed into freezer and left for three hours;
- specimens removed from freezer and tap water was sprayed over the cube surface to simulate *in situ* conditions;
- time was given for water to turn into ice, then 3 grams of de-icing salt were applied to the surface of the cube;
- the ice thawed; (approximately ten minutes) clean the specimen and return specimen to the freezer;
- the process was repeated until 35 cycles have been completed, with interim measurements taken to monitor progress;
- the remaining cycles to be carried out with saturated concrete samples.

The purpose of this testing regime was to test earlier theories that 91 per cent saturation has to take place before a physical breakdown of the concrete can take place and to see what effect polypropylene fibres would have on the absorption qualities of the concrete under test. In addition, the Arrhenius equation[1] was considered with regard to absorption and the effects of temperature. The cubes were sprayed when their temperature was below freezing and this proved to be a problem with regard to water diffusion, as can be seen from the freeze/thaw results, as none of the concrete had started to breakdown after 35 freeze/thaw cycles.

This statement is further corroborated by the Arrhenius equation as shown below:

$$\text{Arrhenius equation extract} \\ - \text{Reaction rate constant} \\ = k = Ae^{-Ea/RT}, \tag{1}$$

where:

K = reaction rate constant;
A = frequency of collisions;
Ea = activation energy (kJ/mol);
R = gas constant (8.314J/mol-K);
T = temperature (Kelvin).

There is clear empirical evidence, that lowering the water and concrete temperature, affects the ability of the liquid to pass through the concrete matrix. This will have a freeze/thaw damage resistance in its own right, as water has to enter the concrete before damage can occur. This is not withstanding the effect of Fickean temperature dependence (Chatterji, 1995).

The problem is further complicated, with the consideration of viscosity of water, because as water tends towards freezing point, the density increases, this can be defined using Reynolds numbers from the equation:

$$Re = VL/\gamma, \tag{2}$$

where:

V = velocity;
L = characteristic length;
γ = kinematic velocity.

It was considered prudent to wait until 35 cycles had elapsed to determine the next phase of testing.

As suggested by Hobbs (2002), "The deterioration associated with expansion can result in major reductions in compressive strength and tensile strength". Options were available for comparing the final weight against the original weight, observe surface scaling, examine the cubes for microscopic D line cracking and testing for structural integrity.

It was considered that a final compression test would be appropriate if the cubes still retained their structural integrity, however a form of non destructive test would enable results to be predicted and corroborated prior to crushing, hence building a picture of the structural and freeze/thaw performance of concrete with and without fibres.

Test observations

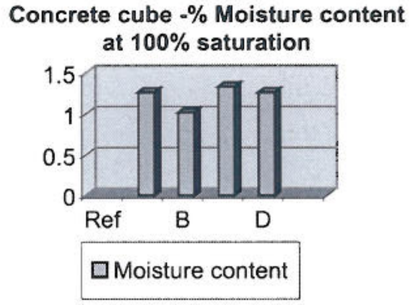
During the testing period, weight measurements were taken when visual weight loss occurred, with photographic records taken at 0, 70 and 150 cycles (see Plate 1).

At 35 cycles the cubes were thawed and soaked for 9 days in a curing tank to simulate seasonal changes in the weather and place the concrete under a severe test with regard to hydraulic pressure build up and percentage water content required to cause structural damage. It was noted that little or no damage had occurred to the cubes at 35 cycles.

After 35 cycles the test cubes were air dried for 48 hours in compliance with BS 1881 – 208:1996 (8.1.3.1) (BSI, 1996) for non oven dried specimens, then soaked for nine days and removed from the tank, the absorption results are shown in Table I and Figure 1.

It is clear from the results that the overall absorption is relatively low and this may be due to the size of the concrete sample being tested and the phreatic surface.
The distance water has to travel through the cube is also a key factor as the section length is double that of standard BS core tests, therefore the lower figures are predictable. A further consideration is that 19 mm monofilament polypropylene fibres in concrete hinder the absorption of water ingress at a significant rate compared to plain concrete and other types of polypropylene fibres and this is corroborated by the author (Richardson, 2002, 2003a, b). After 70 cycles slight scaling was observed on the plain sample, whereas the samples with polypropylene fibre additions showed no signs of damage to the external laitance (see Plates 2-4).

Figure 1 Cube moisture content after 35 cycles



Observations at 150 freeze/thaw cycles

Scaling was measured in terms of a visual rating of the surface condition, according to the ASTM C 672 (ASTM International, n.d.a) procedure (see Table II), the standard

Plate 1 Cube A – plain concrete prior to freeze thaw testing

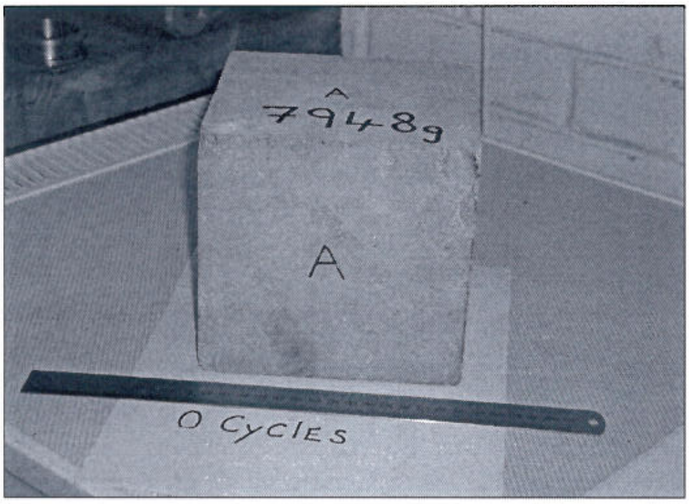


Plate 2 Cubes during freeze/thaw tests at 70 freeze/thaw cycles

Table I Water absorption of concrete cubes

Reference	Dry weight (grams)	Wet weight (grams)	Water gain (grams)	Percentage moisture content at "100 per cent" saturation
A	7,948	8,048	100	1.26
B	7,977	8,058	81	1.02
C	7,959	8,065	106	1.33
D	7,915	8,015	100	1.26

Plate 3 Cubes A and B during freeze/thaw tests at 70 freeze/thaw cycles

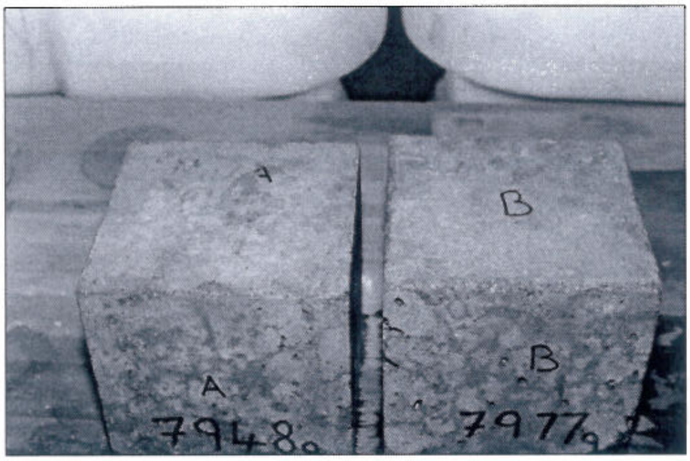


Plate 4 Cubes C and D during freeze/thaw tests at 70 freeze/thaw cycles

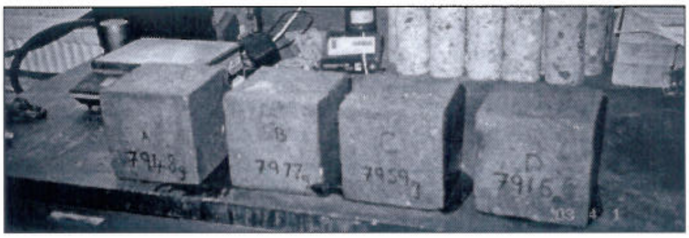
Table II ASTM C 672 (ASTM International, n.d.a) – visual grading of surface scaling

Rating	Condition of surface
0	No scaling
1	Very slight scaling (3mm depth, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

test method subjects the concrete samples to 50 freezing and thawing cycles and evaluates the concrete based upon a visual inspection. The current series of freeze/thaw tests have subjected the concrete samples to 150 cycles (see Plate 5).

The observations taken upon removal of the cubes from the curing tank, following a period of thawing of 12 hours, were as follows.

Plate 5 Cubes following 150 freeze/thaw cycles



Surface scaling of cubes C and D had a surface condition rated as 1 as in Table II. Cube A was rated as a grade 2, whereas cube B showed no significant signs of scaling and was classified as a grade 0. Cube D had one aggregate pop out failure and a corner missing surrounding a large spherical aggregate that may have been caused due to handling. These two factors may have slightly influenced the final results.

Weight loss was considered to be another factor in determining the durability of concrete and in this regard Table III shows weight loss and moisture absorbed after one year of freeze/thaw cycles. It was expected the water content would increase when the dynamic modulus broke down due to the freeze/thaw cycle.

From examination of Table III and Figure 2, there is clear evidence that the inclusion of any polypropylene fibres into concrete has a positive effect in reducing the water ingress. Monofilament fibres as cubes B and D show an improved performance when compared to fibrillated fibres. Failure due to weight loss has not occurred when comparing the weight loss against ASTM C 666A (ASTM International, n.d.b), which demands a 5 per cent loss before failure has occurred. If the results are extrapolated failure would occur at 209 cycles for cube A, 341 cycles for cube B, 326 cycles for cube C and 288 cycles for cube D (see Figure 3).

The 5 per cent water content for cube A is mainly thought to be due to lack of polypropylene fibres, however there may be internal cracking due to the freeze/thaw action. The ultrasonic testing will address this problematical area.

Portable ultrasonic non destructive digital tests

Test procedure

Concrete with various fibre additives was examined, measuring the results in micro

Table III Weight loss and moisture content after 150 cycles

Ref.	New dry weight (grams)	Original dry weight (grams)	Weight loss (grams and per cent)	Wet weight (grams)	Water gain (grams)	per cent Moisture content at "100 per cent" saturation
A	7,674	7,948	274/3.6 per cent	8,060	386	5
B	7,806	7,977	171/2.2 per cent	8,056	250	3.2
C	7,781	7,959	178/2.3 per cent	8,060	279	3.6
D	7,717	7,915	198/2.6 per cent	7,987	270	3.5

Figure 2 Percentage moisture content and weight loss following freeze/thaw tests

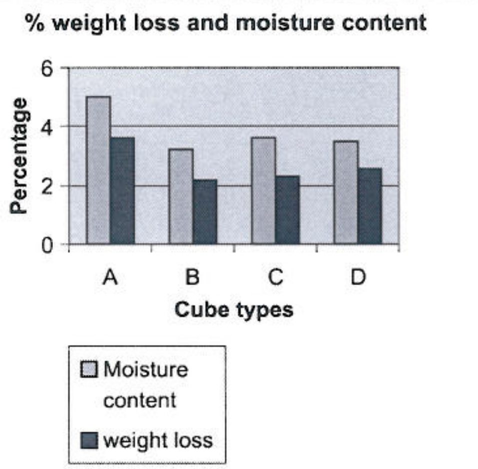
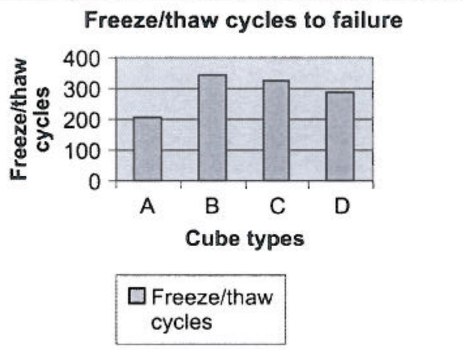


Figure 3 Extrapolated freeze/thaw cycles to failure

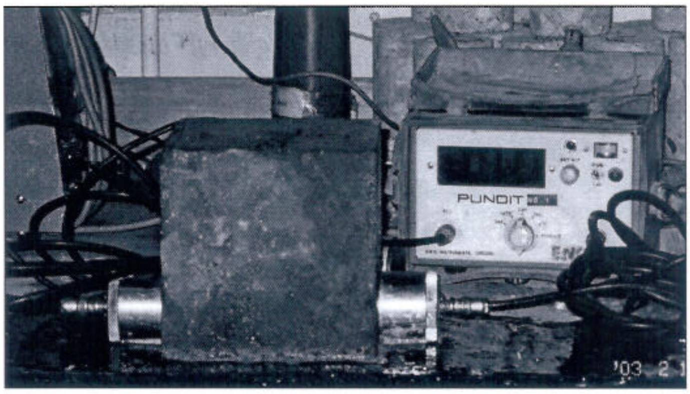


seconds at 50kHz. A coupling gel was used on the relatively smooth faces of the concrete cubes, the cubes were taken from the curing tank, wiped to remove surface moisture and tested immediately.

One year old; control sample concrete cubes (A to D) were examined with a PUNDIT (portable ultrasonic non destructive digital indicating tester) to determine whether or not polypropylene fibres had an effect upon the wave transmission through concrete with regard to subsequent integrity and density (see Plate 6).

The reference sample results are shown in Table IV.

Plate 6 Ultrasonic measurement on concrete cube



No correction was required with regards to the temperature and pulse transmission as the air and cube temperature was 20°C, controlled by a dedicated thermostat.

Correction with regard to concrete strength and subsequent density was also considered unnecessary as the cubes were made to the same design mix and subject to the same curing regime throughout the year. The pulse velocity was relatively constant throughout all of the cubes as tested, whether or not they contained polypropylene fibres. It can be concluded from these readings that the concrete was manufactured consistently and polypropylene fibres have little effect on the internal structure, normally indicated by compressive or tensile strength (see Tables V and VI).

Observations

The surface of each cube was generally smooth and free from major defects such as missing aggregate, with the exception of sample D3 which showed signs of missing laitance, this could be a reason for the − 11.3 per cent change compared to the lower results from the other cubes. This condition is discussed in the 150-cycle freeze/thaw section of the paper.

Discussion

A significant change was discovered between the pulse velocities of the concrete cubes

Table IV PUNDIT pulse velocity measurements – reference samples

Cube reference	Length of transmission (mm)	Recorded value in micro seconds	Pulse velocity = length/time km/s
A plain	149	33.5	4.4478
A	149.5	33.9	4.4100
A	150	33.7	4.4510
B mono	149	33.6	4.4345
B	150	33.4	4.4910
B	150	33.5	4.4776
C crimped	149	33.2	4.4879
C	149	33.5	4.4477
C	149	33.6	4.4345
D 6.5 mono	149	33.3	4.4745
D	149.5	33.0	4.5303
D	150	32.8	4.5732

Table V PUNDIT pulse velocity measurements – freeze/thaw samples

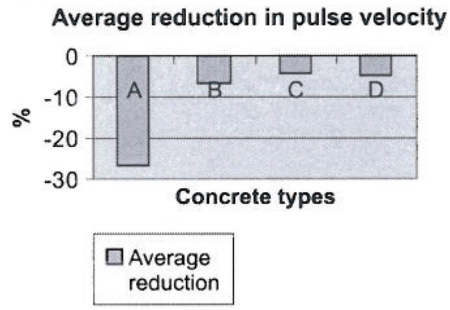
Cube reference	Length of transmission (mm)	Recorded value in micro seconds	Pulse velocity = length/time km/s
A plain	149	48.0	3.1042
A	148.5	44.5	3.3371
A	148	44.5	3.3258
B mono	149	36.0	4.1388
B	149	36.7	4.0599
B	148	34.2	4.3275
C crimped	148	34.6	4.2775
C	148	34.4	4.3023
C	148	35.2	4.2045
D 6.5 mono	148	33.9	4.3658
D	148.5	33.4	4.4461
D	148	36.5	4.0547

Table VI PUNDIT pulse velocity measurements – percentage change between control and freeze/thaw samples

Cube reference	Pulse velocity (control sample)	Pulse velocity (freeze/thaw)	Percentage change on control sample
A 1 plain	4.4478	3.1042	−30.2
A 2	4.4100	3.3371	−24.3
A 3	4.4510	3.3258	−25.2
B 1 mono	4.4345	4.1388	−6.7
B 2	4.4910	4.0599	−9.6
B 3	4.4776	4.3275	−3.4
C 1 crimped	4.4879	4.2775	−4.7
C 2	4.4477	4.3023	−3.3
C 3	4.4345	4.2045	−5.2
D 1 6.5 mono	4.4745	4.3658	−2.4
D 2	4.5303	4.4461	−0.4
D 3	4.5732	4.0547	−11.3

without polypropylene fibres following the freeze/thaw tests (see Figure 4). When the control samples were tested, no significant change in pulse velocity could be detected, however following 150 freeze/thaw cycles a significant change in sample A was detected. The readings as obtained were due to the internal pathway being disturbed from internal micro cracking. The results show a clear association between the effects of polypropylene fibres in concrete and enhanced durability. The reasons for this may be from qualities of physical micro reinforcement, pressure relief due to different densities of materials and reduced water absorption.

Figure 4 Comparison of pulse velocity performance



Compressive strength and strain results from 150 cycle freeze/thaw tests

The purpose of the compressive strength and strain tests was to compare plain concrete, against concrete with polypropylene fibre additions to evaluate any differences in strain that would indicate a different internal structure, brought about from freeze/thaw damage. The series of tests were carried out using the control sample, which had not been subjected to 150 freeze/thaw cycles. A high strain value would indicate loss of internal structural integrity.

Procedure

The Dennison compressive testing machine was used at a loading rate of 200kN/minute. Samples were cleaned and the flattest and most perfect face was applied to the platen. Readings of compressive movement were taken using a dial gauge calibrated at increments of 0.02mm at loading intervals of 100kN. Compressive strengths were calculated as was the strain value being compression divided by original depth.

Results of compression/strain tests

Table VII shows the relationship between load and strain for plain and concrete with monofilament fibre additions.

Table VIII shows the relationship between load and strain for concrete with fibrillated and short monofilament fibre additions.

It is apparent from Figure 5 that monofilament fibres achieve the lowest strain values and the highest compressive strength when compared to the other freeze/thaw samples.

Table VII Compressive deflection for cubes A and B

Sample A1				Sample B1			
Control		Freeze/thaw		Control		Freeze/thaw	
Load	mm σ	Load	mm σ	Load	mm σ	Load	mm σ
0	0	0	0	0	0	0	0
101	0.150	100	0.17	101	0.04	101	0.078
201	0.208	200	0.264	200	0.102	201	0.136
302	0.254	301	0.332	301	0.198	302	0.184
400	0.298	400	0.398	400	0.202	400	0.226
500	0.344	500	0.456	500	0.224	500	0.268
600	0.380	600	0.518	600	0.268	600	0.312
700	0.424	700	0.592	700	0.314	700	0.362
800	0.468	800	0.674	800	0.352	800	0.404
900	0.512	900	0.810	900	0.391	900	0.444
1,000	0.564	952	Failure	1000	0.427	1000	0.486
1,100	0.610			1,100	0.472	1,100	0.538
1,200	0.672			1,200	0.520	1,200	0.598
1,300	0.744			1,300	0.550	1,300	0.615
1,400	0.824			1,400	0.584	1,333	Failure
1,470	Failure			1,500	0.616		
				1,560	Failure		

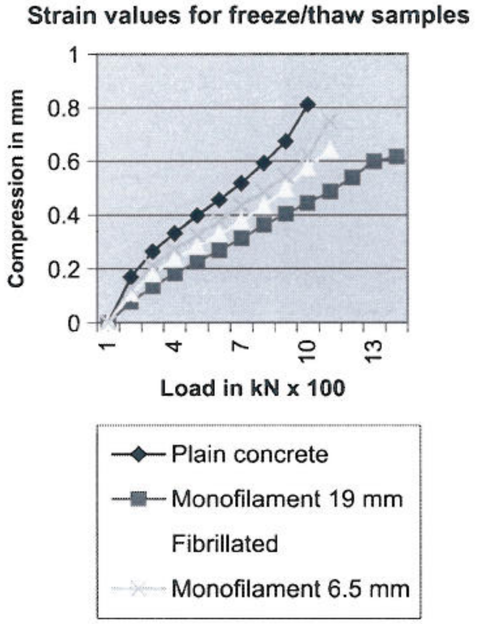
Table VIII Compressive deflection for cubes C and D

Sample C1				Sample D1			
Control		Freeze/thaw		Control		Freeze/thaw	
Load	mm σ	Load	mm σ	Load	mm σ	Load	mm σ
0	0	0	0	0	0	0	0
100	0.080	100	0.108	100	0.066	100	0.130
200	0.134	200	0.182	200	0.120	200	0.210
300	0.178	300	0.236	301	0.168	300	0.270
400	0.216	400	0.282	400	0.210	400	0.324
500	0.250	500	0.328	500	0.254	500	0.376
600	0.282	600	0.376	600	0.296	600	0.435
700	0.318	700	0.432	700	0.338	702	0.486
800	0.352	800	0.496	800	0.378	800	0.544
900	0.390	900	0.576	900	0.412	900	0.620
1,000	0.428	1,000	0.640	1,000	0.450	1,000	0.750
1,100	0.464	1,073	Failure	1,100	0.488	1,081	Failure
1,200	0.502			1,200	0.530		
1,300	0.548			1,300	0.562		
1,400	0.602			1,400	0.598		
1,502	Failure			1,500	0.630		
				1,550	Failure		

Observations

It was recorded that the reading taken prior to failure was showing signs of creep and if the apparatus was left on once it had been stopped for taking readings slight loading took place and compressive force values crept up by a value of 1kN. Intermediate readings were taken at 50kN increments prior to failure; these have been omitted due to the difficulty

Figure 5 Strain values for freeze/thaw samples



in obtaining precise readings due to the creep experienced. No significant change in strain was detected within the control sample, therefore it can be concluded that fibres play very little part in the compressive performance of concrete, which concurs with previous findings.

Analysis

The final recorded strain for the freeze/thaw cubes was taken as the lowest obtained value, being 900kN, this allowed for direct comparison between all of the samples (see Table IX).

Analysis of the fully cured samples show that, monofilament fibre additions to concrete, outperform the plain concrete samples by 20.8 per cent. Fibrillated and 6.5mm monofilament fibres outperform plain concrete by approximately 6 per cent.

Monofilament fibres added to concrete are shown to have the lowest strain value; hence they have the greatest structural integrity, when providing freeze/thaw protection.

The lowest difference as shown in Figure 6 between the control sample and the freeze/thaw sample was that of concrete with monofilament fibre additions, therefore there has been shown another association of the use of monofilament fibres in concrete and enhanced durability.

It is apparent from Figure 7 that monofilament fibres retain the structural integrity of concrete when subjected to freeze/thaw cycles as the strain values before and after freeze/thaw cycles are the closest of all the samples.

Figure 6 Final compressive strength analysis

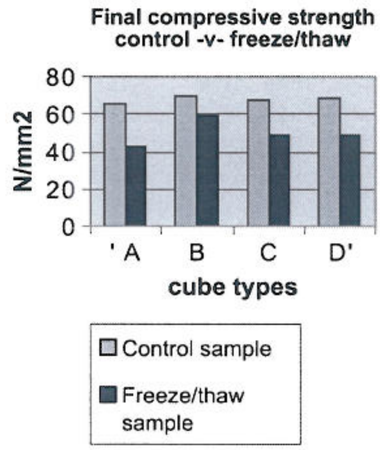


Figure 7 Comparison of final strain values

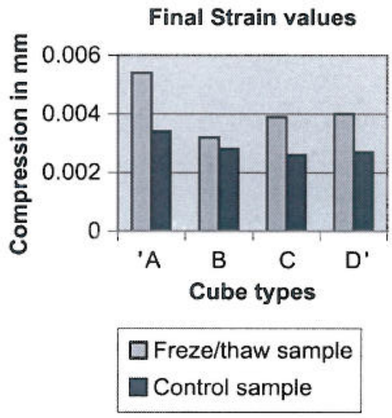


Table IX Compressive deflection analysis for cubes

Sample	Final compressive strength Control	Final compressive strength Freeze/thaw	Percentage loss of strength	Final f/thaw strain recorded	Strain of control at 900kN	Increase in strain (percentage change)
A1	65.33	42.31	35.20	0.0054	0.0034	59
B1	69.33	58.85	15.12	0.0032	0.0028	14
C1	67.65	48.33	28.56	0.0039	0.0026	50
D1	68.88	49.35	28.33	0.0040	0.0027	48

Conclusion

The 150mm fully-cured concrete cubes showed little surface erosion due to the freeze/thaw cycle and little visual loss of structural integrity. The compressive strength and strain measurements show a clear association between the use of monofilament polypropylene fibres in concrete and freeze/thaw protection, hence enhanced durability. The values obtained are significant, therefore the benefits will be tangible and worthwhile from the addition of polypropylene fibres to concrete where it is anticipated freeze/thaw cycles will occur. When all tests as described herein are considered, there is a clear association between the use of polypropylene fibres in concrete and freeze/thaw protection leading to subsequent enhanced durability.

Note

1 Arrhenius equation: www.shodor.org/UNChem/advanced/kin/arrhenius.html

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