FREEZE/THAW PERFORMANCE OF CONCRETE USING GRANULATED RUBBER CRUMB

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ABSTRACT

This paper evaluates the properties and use of recycled rubber tyres in the form of rubber crumb as a freeze/thaw protection agent when used in concrete. Reusing scrap tyres in the form of rubber crumb in concrete could benefit the environment by contributing to the percentage of tyres used for a variety of recycling processes such as carpet underlay or tyre derived fuel, thus reducing disposal of tyres to landfill sites and the chemical usage of air entraining agents as a means of achieving freeze/thaw protection.

Concrete cubes of 100mm were produced from design mixes which have been classified as plain, air entrained and rubber crumb and subjected to freeze/thaw cycles at 5 days of age.

Thawing was conducted in water to ensure full saturation of pores and maximum stress on the concrete samples. The rubber crumb and plain concrete mixes were compared against the freeze/thaw performance of that entrained with air. Air entrainment is known to protect against freeze/thaw action.

Rubber crumb when used at a 0.5% addition by volume provided the optimum freeze/thaw protection whilst maintaining the maximum compressive strength. The research shows that rubber crumb was effective at providing freeze/thaw protection albeit with a reduced compressive strength when compared to air entrained concrete. The practical constraints of the test program were time and freezer space so the test was limited to 50 freeze/thaw cycles, which was sufficient for conclusions to be drawn.

This paper contributes to the understanding of the effects of varying doses of rubber crumb in concrete when used as a freeze/thaw protection additive. The final compressive strength of the concrete mixes tested at freeze/thaw and non freeze/thaw conditions are determined. The compaction of concrete is raised as an area of concern with regard to rubber particle separation within the plastic phase of the concrete's life.

KEYWORDS

rubber crumb, concrete freeze/thaw protection, sustainability, recycled tyres

1.0 INTRODUCTION

To understand the scale of the problem of tyre disposal, over one billion tyres are manufactured annually, world wide, using approximately ten million tonnes of elastomeric materials, including most of the natural rubber produced (Watson Brown, 2009). On disposal, these tyres produce hazardous waste materials that accumulate and must be processed in large quantities. Re-use of these non-decaying materials by incorporating them into concrete mixes (Batayeh et al, 2008), will avoid the environmental problems associated with disposal.

Producing a typical car tyre uses about 40% natural rubber and 60% synthetic rubber (Wasteonline 2009) that needs to be separated from the tyre's steel casing before it can be used as a rubber crumb. The products obtained from scrap tyres are classified as whole scrap tyres, slit tyres, shredded/chipped, ground and rubber crumb. Rubber crumb particle sizes range between 4.75mm to less than 0.075 mm and are irregularly shaped, torn particles due to the micro-mill process they are subjected to during the manufacturing process (Siddique and Naik 2004).

Benazzouk and Queneudec (2002) and Paine et al (2002) investigated the efficacy of rubber crumb at providing freeze/thaw resistance in concrete and they surmised that rubber crumb provides freeze/thaw protection when added to plain

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concrete. Concrete can be affected by freeze/thaw damage from the point of placing to being fully cured. This work examines the effects of successive freeze/thaw cycles on concrete, starting at 5 days of curing.

The scarcity of test data identifying the early life performance of concrete with rubber crumb at varying additions was a key factor justifying this research. Guneyisi et al (2004) suggest further work be carried out with regard to the durability of rubber concrete and this paper acts upon this suggestion. This paper will examine rubber crumb use at 0.5% and 1.0% addition, by volume, and compare to contemporary measures for protecting concrete from freeze/thaw damage.

Sustainable material development is a key philosophy in this investigation and therefore a CEM 11 cement binder was used to ensure the final concrete product had a lower embodied energy than that produced using CEM 1and therefore, higher sustainability credentials. The CEM 11 manufacture was carried out in accordance with BS EN 197-1:2000 and further defined for use in BS 8500 Part 208 as part of a composite concrete mix.

2.0 FREEZE THAW PROTECTION FROM RUBBER CRUMB

Air entrainment is currently the most widely adopted method of providing freeze/thaw protection. If it can be shown that rubber crumb in concrete would be as effective as air entrainment in providing freeze/thaw protection, then discarded rubber waste could be utilised in the construction industry as a freeze/thaw protection method with subsequent sustainability credentials. Paine et al (2002) investigated the use of rubber crumb as an alternative to air entrainment using three sizes of crumb from 0.5 to 25 mm and their tests showed that there is potential for using rubber crumb as a freeze thaw resisting agent in concrete.

Recycled particles of sustainable rubber crumb have a low modulus of elasticity (Khaloo et al. 2008). Due to this it is postulated that its inclusion as a constituent of concrete production introduces pressure relief chambers. These chambers are believed by the authors to alleviate hydrostatic pressure, via a mechanism akin to that afforded by air entrainment, thus promoting freeze/thaw protection. If the rubber crumb does entrain air further concrete protection is afforded. Skripkiunas et al (2007:85) state that, "rubber waste has no influence on capillary porosity of hardened concrete but it does increase the air content . . . and has a positive effect upon freeze and thawing resistance of concrete." Yilmaz and Degrirmenci (2009), suggest that concrete made with rubber crumb exhibits a lower water absorption capacity and it is postulated that this may be a contributing factor in providing freeze/thaw protection.

The method of freeze/thaw protection has been identified by Khaloo et al, (2008: 5-6) who stated that, "due to the non-polar nature of rubber particles and their tendency to entrap air in their rough surfaces, tyre-rubber concrete specimens contain higher air contents than plain concrete." Furthermore, rubber particles tend to repel water (Khaloo et al, 2008). When tyre particles are substituted for mineral aggregates in the control mixture, the tyre particles attract air; the amount of attraction is dependent on the internal pressure within the mixture (Khaloo et al, 2008).

According to Chatterji (2003), an entrained air bubble system of between 5% and 7% by volume of concrete is required to improve the freeze/thaw performance of concrete. This value is confirmed in BS EN 206 – 1. US Patent 669509 (2004) suggests that a rubber crumb addition rate of 5.3 to 9.8 kg/m^3 achieves a 5% entrained air content. This has informed the dosages used for the purpose of this study as detailed in Section 4.1.3 of this paper.

3.0 THE MECHANICAL RESPONSE OF RUBBER CRUMB CONCRETE

Air entrainment, when used as a freeze/thaw defence mechanism within concrete, produces a compressive strength reduction (Khorami & Ganjian 2007). According to Khorami & Ganjian (2007: 274) "rubber filled concrete showed a systematic reduction in strength, while its toughness was enhanced." In exploring the potential for rubber crumb concrete to meet durability requirements a further study will also attempt to assess the respective compressive strength reduction that occurs when freeze/thaw protection is provided by rubber crumb or air entrainment.

The properties of concrete with added rubber were outlined by Khorami & Ganjian (2007:274) who state that:

> a concrete mixture with tyre chip and crumb rubber aggregates exhibited lower compressive and splitting tensile strengths than regular Portland cement plain concrete. There was approximately 85% reduction in compressive strength and 50% reduction in splitting tensile strength when coarse aggregate was fully replaced by coarse crumb rubber chips. However, a reduction of about 65% in compressive strength and up to 50% in splitting tensile strength was observed when fine aggregates were fully replaced by fine crumb rubber. Both of these mixtures demonstrated a ductile failure and had the ability to absorb a large amount of energy under compressive and tensile loads,

which may determine the application of rubber concrete use.

4.0 THE LABORATORY INVESTIGATION

This study has incorporated recycled tyre rubber into concrete in the form of rubber crumb. Considering US Patent 669509 (2004) additions of 0.5% and 1.0% of rubber crumb by volume of concrete are proposed to replicate levels of air entrainment in concrete that will provide freeze/thaw durability. Concrete entrained with 5% air is known to offer a degree of freeze/thaw protection. The addition of 1.0% of rubber crumb by volume of concrete was selected to observe freeze/thaw performance at an upper limit of protection.

The test program presented was developed to compare the compressive strength and weight loss of concrete cubes manufactured from plain and rubber crumb mixes (see section 4.1.3) subjected to freeze/thaw cycles, against a similar set of cubes which were not.

4.1 Materials

The materials used were primarily ground rubber crumb from vehicle tyres and virgin aggregates bound with a cement binder containing pulverised fuel ash (PFA) as a Portland cement replacement.

4.1.1 Physical properties of rubber crumb

This section offers a rigorous illustration of the properties of the rubber crumb used in this research including its physical properties and density. The rubber crumb sourced from vehicle tyres was sieved to determine particle grading in accordance with BS 812: Part 103 : 1985. The results are shown in Table 1., and Figure 1. These results confirm that 94.9% of the sourced rubber crumb particle sizes were between 1.16 and 2.36 mm, with 5% being finer than 1.16 mm and no material passing the 0.43 mm sieve.

Following the sieve test, the rubber crumb was subjected to particle size analysis using ASTM D 412 and the average particle size from an average of ten samples was 1.41mm as shown in Table 2.

Figure 1 and Table 2 illustrate that no sample particle is less than 0.43 mm thus avoiding the potential for cement paste disturbance as identified by Neville (1995).

Determination of the mechanical properties of the rubber crumb to be adopted in the freeze/thaw program was obtained by formation of the material into test slabs in accordance with ASTM D – 2084. The results are presented for completeness and transparency but are not referred to hereafter. Further tests (IS 7490:1997and ASTM D – 412) were carried out to determine a range of rubber characteristics using three different test standards, which has built up a profile of the material. These tests identify the physical and chemical properties of the rubber crumb.

To determine some of the physical properties of the rubber crumb, the material was formed into rubber test slabs in accordance with ASTM D – 2084. The physical properties of the rubber crumb were obtained and are shown in Table 3.

TABLE 1. Results of rubber crumb sieve test.

Sieve size (mm)	Sieve weight (g)	Sieve and crumb weight (g)	Rubber crumb - weight retained (g)	Percentage of sample passing (%)
2.36	482.0	482.0	0.0	100
1.16	443.0	443.0	473.5	5.1
0.43	381.5	855.0	25.5	0
Base Pan	248.0	273.5	0	0
Total	**1554.5**	**2053.5**	**499.0**	—

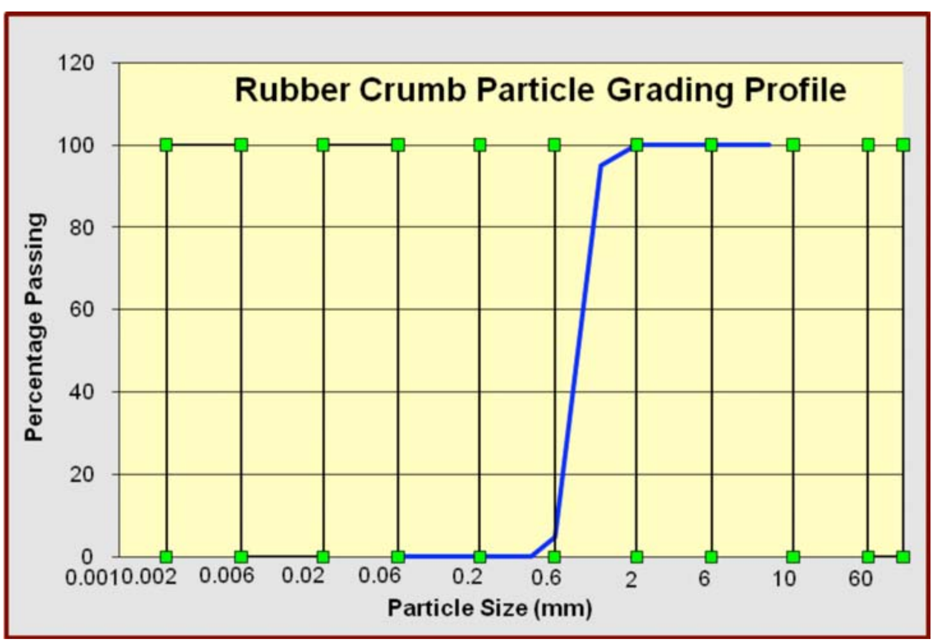


FIGURE 1. Rubber crumb grading profile.

TABLE 2. Particle size analysis (ASTM D 412).

Sample	Mean sample particle size (mm)	Mean
01	1.6111	1.41 mm
02	1.7444	
03	1.2222	
04	1.4333	
05	1.4111	
06	1.3222	
07	1.6889	
08	0.8556	
09	1.2667	
10	1.5444	

TABLE 3. Physical properties of rubber crumb (ASTM D-2084)(RPA 2000 Study at 150°C).

Sample	Test	Observed values
1	Maximum Torque MH (dNm)	87.04
2	Minimum Torque ML (dNm)	26.75
3	Optimum cure time Tc90 (min)	17
4	Induction time (min)	0.43
5	Scorch time (min)	0.55

Further mechanical properties of the material are illustrated in Table 4 from methods specified in ASTM D – 412. The results provide details of rubber properties that assist in the freeze/thaw protection of concrete. It is suggested that elongation as measured in Table 4 provides an indication of the elastic properties of the rubber crumb material. When the free water in concrete freezes and expands, hydrostatic pressure is induced within the concrete matrix and the rubber crumb will assist in providing pressure relief due to its elastic nature, in addition to the entrained and natural air within the concrete.

An accurate assessment of rubber density was required to allow the determination of the mass (kg) required to be added to the concrete at 0.5% and 1.0% volume. A solid density nominal value of 1522 kg/m^3 (BS 648:1964 and SI Metric 2010) was used to determine the rubber crumb additions. Normal concrete mix design uses quantities of mass for batching purposes, hence the need to convert percentage volume into mass. The density test results as derived are shown in Table 5.

4.1.2 Chemical properties of rubber crumb

Table 6 presents the chemical composition of the rubber crumb which was determined in accordance with IS 7490:1997. The mercaptobenzothiazol (MBT) value is 0.5

TABLE 4. Physical properties of rubber crumb.

Sample	Test	Direction "A" (Observed values)	Direction "B" (Observed values)
1	Tensile Strength (kg/cm^2)	82,78,79,75	72,93,66,77
2	Elongation at break (%)	100,110,110,100	100,120,100,110
3	Hardness (Shore A)	77,78,77,78	77,78,77,78

TABLE 5. Rubber crumb density (ASTM D 412).

Samples	Density (gm/cm^3)	Mean
1	0.448	0.4686 (gm/cm^3)
2	0.494	
3	0.466	
4	0.476	
5	0.459	

TABLE 6. Analysis of rubber crumb (IS 7490:1997).

Sample	Ingredients	Parts per hundred—Rubber
1	Rubber Crumb	100 (as rubber hydrocarbon)
2	Zinc Oxide	5.0
3	Stearic acid	2.0
4	MBT	0.50
5	Sulphur	3.0

and this is a concern with regard to health and safety. Correct procedures such as gloves, overalls, dust masks and adequate ventilation should be considered when operatives are exposed to this chemical. The stearic acid was not thought to pose a significant problem when used in the alkaline environment of concrete.

4.1.3 Design mix

Four concrete mix designs were utilized in this test program. These were classified as plain, air entrained, 0.5% rubber crumb and 1.0% rubber crumb concrete. The basic mix design used for the plain concrete samples (batch group 1) is shown in Table 7. The mix was designed in accordance with the use of design of normal concrete mixes (Teychenné et al. 1997) to achieve a C20 characteristic design strength at 28 days. A C20 mix is adopted to determine the minimum strength of commercially produced concrete with rubber crumb addition, subjected to freeze/thaw action.

TABLE 7. Constituents of the basic mix design—batch group 1

Quantities per m^3 of concrete	Material
240 kg	CEM11 cement
731 kg	Coarse sand
1107 kg	20 mm (max) marine gravel
0.8	Water cement ratio

Batch group 2 was afforded freeze/thaw protection through the addition of rubber crumb at 0.5% volume (7.6 kg/m^3) and batch group 3 utilized 1.0% (15.2 kg/m^3). Batch group 4 facilitated the comparison of the rubber crumb concretes to those more conventionally protected from freeze/thaw action via the addition of an air entrainment agent at 50 ml per 100 kg of cement dosage. Work by Batayneh et al (2008) and Malek et al. (2007) noted that, increasing the crumb rubber content in the mix resulted in a decrease in the unit weight and the slump of the mixtures, the later effect was also observed during the mixing process for this investigation.

The plain concrete mix design proposed for this test was provided by the ready mixed concrete producer Cemex UK. A high water/cement ratio is adopted to produce a weaker concrete exaggerating the effect of freeze thaw damage.

4.1.4 Batching water

The quality of the mixing water for production of concrete can influence the setting time, the strength development of concrete and the protection of reinforcement against corrosion. Potable water, described as water which is fit for human consumption is suitable to use according to BS 1008: 2002.

Tap water supplied by Northumbrian Water (2010), was used in the design mix, which contained the following chemicals:

- Average of 78.750 *mg/l* dissolved sulphates
- Sodium content in the water ranged between 13 and 17 *mg/l* (average of 15.5 *mg/)* which when in the form of sodium sulphate can also be harmful in concrete (Darby *et al* 2002).
- Chloride was also present in the water with an average of 14.75 *mg/l*.

The percentage of chemicals present in the water, were not thought to adversely affect the performance of the concrete with regard to freeze/thaw performance.

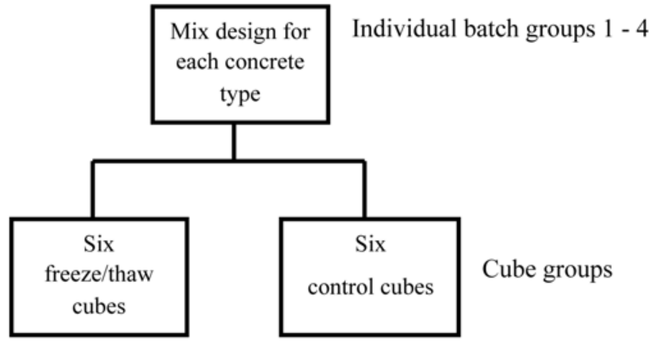
4.2 Methodology

The following sections highlight the methods employed during manufacture and testing of the concrete samples.

4.2.1 Cube manufacture

Twelve 100 mm cubes were manufactured of each design mix. Cube production was controlled with the use of a slump test to BS EN 12350-2:2000 and compaction was carried out with a vibrating table. Care was taken not to over vibrate the cubes, however it was noted the rubber crumb rose to the surface when vibration/compaction took place which is not surprising as the specific gravity for ground rubber may be in the region of 480 kg/m^3 when compared with concrete which is 2400 kg/m^3.

FIGURE 2. Batching process.



To minimize the potential for human and material variability in the quality of the cubes produced, the batching and production of all twelve cubes from each of the four mix designs occurred simultaneously as illustrated in Figure 2.

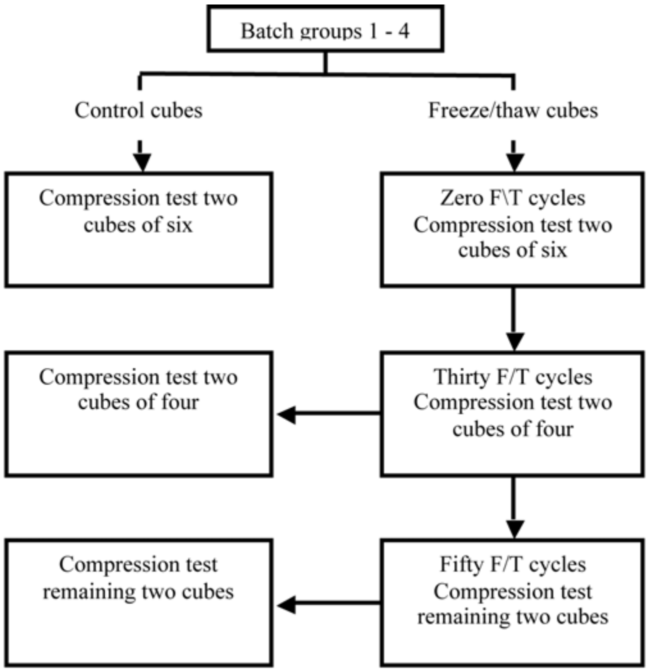
4.2.2 Cube test program

From each group of six cubes, two cubes were compression tested at five days after manufacture. This facilitated strength comparisons prior to commencing exposure to the freeze/thaw cycles and highlighted the representivity of the cubes produced from each batch. From here, the timing of the compression testing of the control cubes mirrored those of the freeze/thaw cubes to ensure consistent curing times and aid comparisons to be drawn.

The freeze/thaw cubes were initially subjected to thirty freeze/thaw cycles and on completion, compression testing was again carried out on the two remaining cubes from this group and the control cubes as shown in Figure 3.

A pilot study was carried out to determine the minimum times for freezing and unfreezing the concrete cube samples to their core, using a mercury thermometer sealed into a concrete cube with the bulb at the centre of the cube. The fully saturated cubes were removed from the temperature controlled curing tank which was set at 20.7°C and placed in the freezer with a temperature of –23°C, to evaluate the time taken for the cubes to reach -18°C; which was 5 hours. Once the cubes reached this temperature, they were removed and placed back into the curing tank to replicate a freeze/thaw cycle. The amount of time required for the blocks to unfreeze and reach just above 3°C was 22 minutes. Freeze/thaw cycles were carried out twice a day with a minimum freezing time of 7 hours and a maximum of 16 hours. This pilot study informed the timing constraints of the test programme presented.

FIGURE 3. Staged compressive strength test program.



6.0 RESULTS

6.1 Batching slump test results

The results of the slump test are shown in Table 8, and the results show that the concrete containing the rubber needed additional water to achieve a slump in keeping with the plain or air entrained concrete mixes. This is in accordance with the findings of Malek et al (2007) and Khatib Bayomy (1999) who suggested that rubber particle addition reduces the concrete slump. The additional water was used to coat the rubber crumb and ensure each mix had similar amounts of free water to afford comparable cement hydration.

6.2 Compressive strength and weight loss results from test program

The freeze/thaw test, started after 5 days from batching, and the compressive strength of the plain control cubes prior to any freeze/thaw cycles were 14 and 12.1 N/mm^2 which showed a difference of 1.9 N/mm^2 providing a mean value of 13 N/mm^2 and giving a percentage difference of 7.7% between the cubes from either side of the mean. This was considered within normal batching tolerances as the compressive strength values are within acceptable limits for each batch, being within 15% of the mean (Concrete Society, 2007).

The compressive strength standard deviations for the freeze/thaw cubes were 1.37 for plain, 0.64 for air, 0.42 for 5% and 0.68 for 10%. "In building and civil engineering much attention is given to the variability of compressive strength of concrete. A standard deviation is seldom less than 2.5 and not more than 8.5 N/mm^2" (BRE 1987). These parameters apply to concrete over 20 N/mm^2 in strength at

TABLE 8. Slump test results

Concrete batch	Initial slump results (mm)	Addition water added (ml)	Subsequent slump results (mm)
Plain	60	0	60
Air Entrained	60	0	60
1.0% Rubber	0	300 (+ 3.7%)	30
0.5% Rubber	5	100 (+ 1.3%)	20

28 days where above this strength "the standard deviation remains sensibly constant" (BRE 1987:326) This test uses concrete above 20 N/mm^2 where compressive strength is the main criterion used for judgement of similarity between the four concrete batches.

At the end of the test the concrete retained as a control sample had achieved the strength of 26.3 and 24.1 N/mm^2 respectively for each cube (2.2 N/mm^2 difference) being 4.4% above and below the mean.

During the course of the freeze/thaw cycles, the cubes were thawed and weighed in a saturated state and mean values plotted for each six cube group as shown in Figure 4. It is clear the plain concrete cubes lose mass more rapidly than the concrete with air entrainment and rubber crumb. The 1.0% rubber crumb additive concrete exhibited mass gain when compared to the other concretes. This gain is attributed to the additional; water absorption in the surface laitance, where the crumb had congregated. Comparing the durability performance of concretes mixed with an air entrainment agent and 0.5% rubber crumb it appears that comparative losses are exhibited at 50 freeze/thaw cycles. A rubber crumb addition of 1% appears to perform marginally better.

Figure 5 shows the initial starting mean compressive strengths at 5 days taken from two control cubes. The addition of rubber crumb lowers the compressive strength in accordance with the volume added. Malek et al. (2007) found similar effects with regard to the compressive strength of rubber crumb concretes although their work dealt with significantly higher doses of rubber crumb (40%) by volume. Bateynah (2008) confirms this characteristic, as substituting the harder dense aggregates with a softer less dense rubber will act as a stress concentrator, causing micro cracking of the concrete matrix, leading to a loss in strength. The design mix was the same for all of the cubes and the rubber crumb concrete shows signs of strength development despite the freeze/thaw curing conditions. Conversely the plain concrete showed a strength reduction over the 50 cycles while the air entrainment cubes coped well with the freeze/thaw process despite and early fall in strength. The fall in strength of the air entrained concrete between 0 and 30 cycles was thought to be due to the potential for minor variations in the concrete batching, which were in line with the initial observations of strength variation prior to the test; rather than an actual strength reduction due to freeze/thaw action.

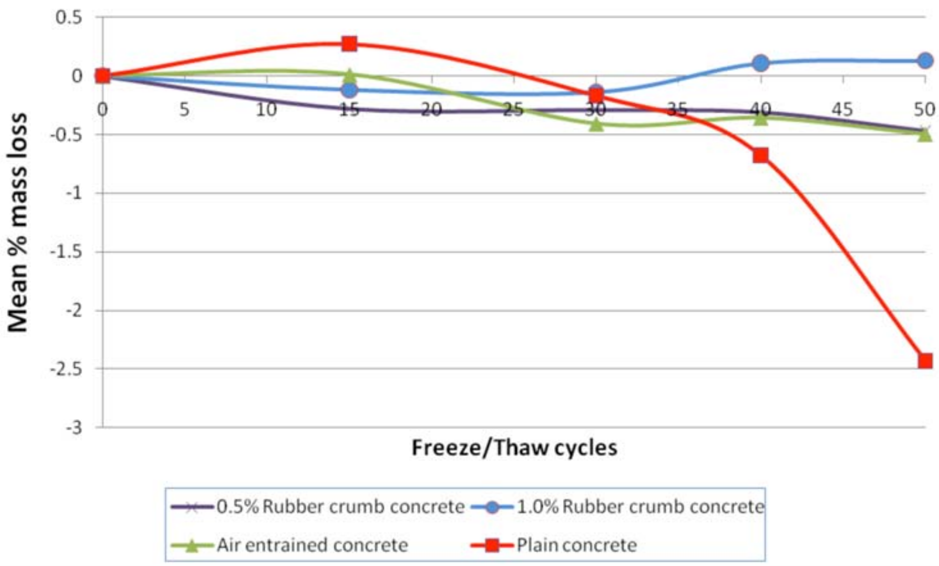


FIGURE 4. Freeze/thaw—% mass loss up to 50 cycles (mean value from cubes).

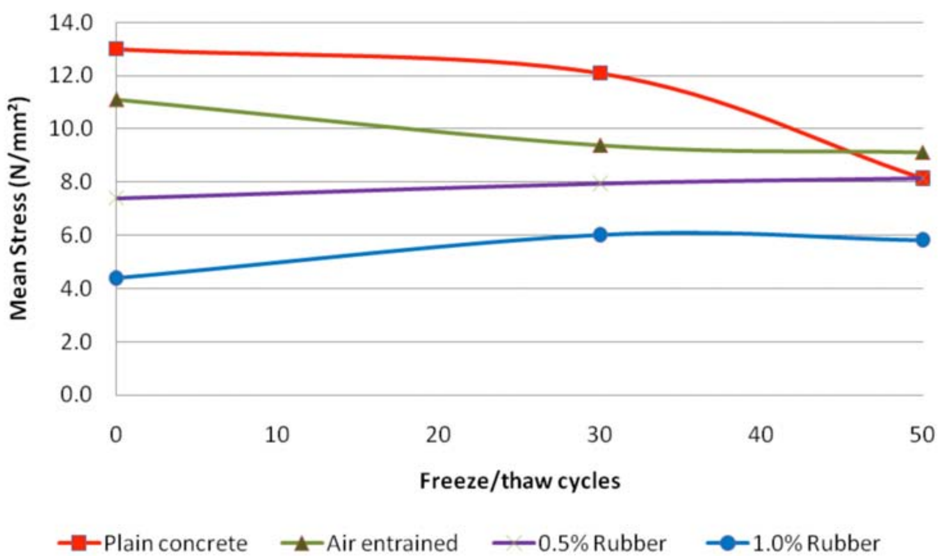


FIGURE 5. Freeze/thaw cube compressive strength between 0 and 50 freeze/thaw cycles.

Figure 6 shows the comparative concrete freeze/thaw performance using an ultra sonic test procedure that mirrors the compressive strength test. The rubber crumb concrete shows an even pulse velocity for both 0.5% and 1.0% rubber crumb addition maintaining from the start to the end of the test. Conversely the air entrained concrete is showing signs of internal cracking; as the pulse velocity is reduced towards the end of the test, indicating damage caused by the expansion of ice within the concrete. The plain concrete showed the greatest pulse reduction which indicates the greatest internal damage

The plain concrete cubes as Plate 1, showed significant deterioration after 50 cycles, exhibiting severe surface scaling and aggregate pop out, with additional mass being lost from the corners of the cubes.

Plate 2, shows the extent of superficial damage to the air entrained concrete cube, which also suffered concrete loss from the corners, which may have been due to handling.

Plate 3, illustrates minor scaling to concrete with 0.5% rubber crumb after 50 freeze/thaw cycles with all faces being relatively intact.

Plate 4, shows the 1.0% rubber crumb cube to be relatively intact after 50 freeze/thaw cycles. There is evidence of the rubber crumb separation from the plastic matrix as shown on the surface of the cube in Plate 4, this was due to the use of a vibrating table to aid compaction. The rubber crumb is exposed due to the loss of surface laitence.

The compressive strength of the concrete cubes is shown in Table 10, and Figure 6.

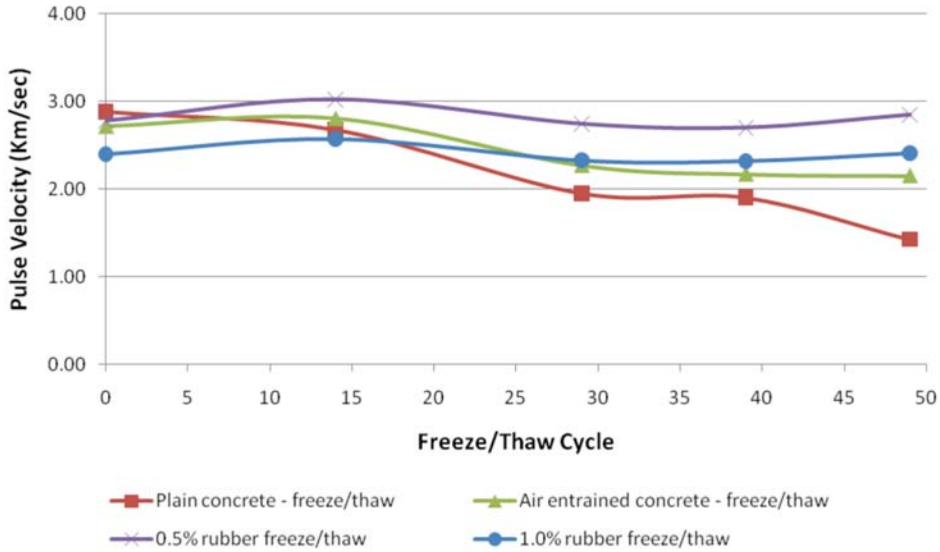


FIGURE 6. Pulse Velocity test (Freeze/thaw samples—Comparison).

PLATE 1. Plain concrete cubes at 50 freeze/thaw cycles.

PLATE 3. 0.5% Rubber sample at 50 freeze/thaw cycles.

PLATE 2. Air Entrained sample at 50 freeze/thaw cycles.

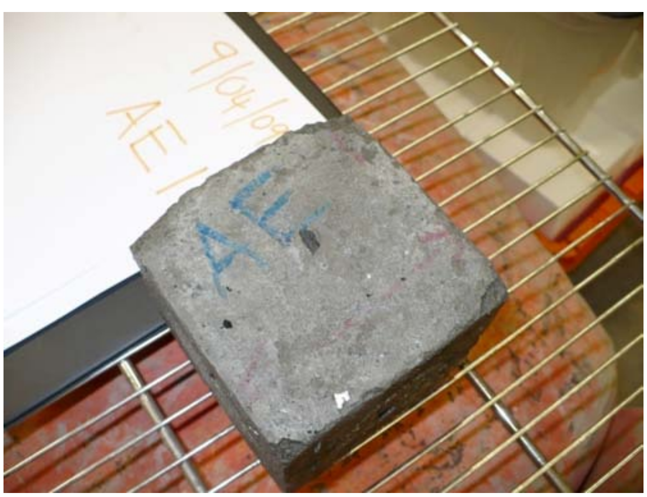


PLATE 4. 10% Rubber sample at 50 freeze/thaw cycles.

TABLE 10. Compressive strength of control concrete cubes.

Concrete Batch	Compressive strength 5 days (0 freeze thaw cycles) N/mm^2	Compressive strength 35 days (30 freeze thaw cycles) N/mm^2	Compressive strength 55 days (50 freeze thaw cycles) N/mm^2
Plain	13.1	19.6	25.2
0.5% Rubber	7.5	11.1	12.9
1.0% Rubber	4.3	6.6	7.7
Air Entrained	13.9	23.4	27.9

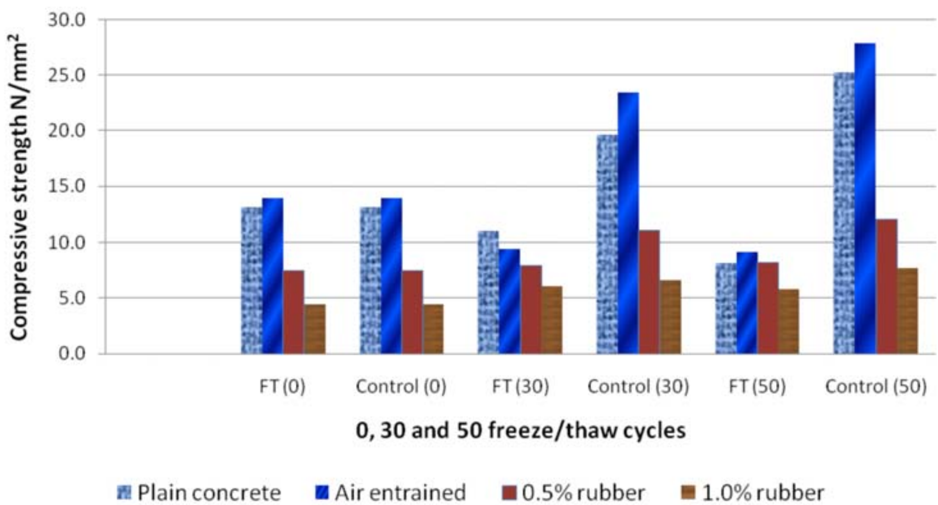


FIGURE 7. Freeze/thaw and control sample compressive strengths.

Figure 7., shows the decline in performance of plain concrete between zero and 50 freeze/thaw cycles. The air entrained concrete subjected to freeze/thaw cycles did not develop strength as the rubber samples subjected to the same treatment. However, on comparison of the freeze/thaw and control samples a marked difference in strength development is illustrated. Both rubber concrete samples exhibited lower compressive strength values due to the rubber crumb inclusion and a much lower strength difference after 50 freeze/thaw cycles when comparing the freeze/thaw sample with the control sample.

7.0 CONCLUSION

The use of rubber crumb in concrete reduces the potential freeze/thaw damage that can occur as shown in Section 6. Dosages of 0.5% and 1.0% show no significant difference in terms of freeze/thaw performance, therefore it is recommended that a 0.5% dose by volume be used to maintain the potential for greater compressive strength development afforded by the 0.5% rubber concrete mix.

The strength reductions of rubber concrete mixes increases with the increasing percentage volume of rubber crumb added to the concrete. To compensate for this aspect of strength reduction, additional cement may be used to bring the design strength back to a plain concrete equivalent. This negates the impact of rubber concrete as a freeze/thaw additive, however air entrainment also promotes concrete strength reductions that must be catered for and air entrainment is widely used in freeze/thaw damage prevention. It is apparent that 0.5% rubber crumb addition is a maximum addition for practical use in most normal applications, and this percentage may be reduced if the natural air content can be established and counted towards the total air/rubber content that enables optimum freeze/thaw protection.

An advantage of achieving freeze/thaw protection from rubber concrete mixes is that it facilitates the use of CEM 11 and CEM 111 binders. These cements are cheaper than CEM 1 due to the inclusion of by products such as pulverized fuel ash (PFA) or ground granulated blast furnace slag (GGBS) as partial replacements for cement within their binders. Chemical air entrainment works best using CEM 1, which is a more expensive cement than CEM 11 or CEM 111. Considering the findings of this work the exceptional durability performance and compressive strength of the air entrained concrete produced from CEM 11 is unexplained and may be a reflection of the small experimental sample size. It does show that the use of air entrainment produced a better performance than predicted when using CEM 11 as a binder. The purpose of this test was to evaluate rubber crumb performance and this is achieved.

8.0 FURTHER RESEARCH

Further testing should be carried out using various rubber crumb additions to find out what the minimum dose of rubber crumb would be for maximum freeze/thaw protection, whilst maintaining the maximum compressive concrete strength. The minimum dose would be determined by evaluating the naturally occurring air in the concrete and adding the percentage of entrained air created from the use of rubber crumb, taking into account the percentage of rubber added, as additional air.

Vehicle tyres have different rubber compositions and steel content, work should be undertaken to identify the best type of tyre rubber. Car tyres are less dense than lorry tyres (Papakonstantinou and Tobolski, 2006) and these differences impact upon the mechanical properties of concrete. If a percentage of the steel tyre bead could be retained within the rubber/bead admixture, then concrete can be developed with a large degree of toughness due to the post crack potential from the tyre steel beading. As Papakonstantinou and Tobolski (2006) state, "more work is needed prior to making solid conclusions on the performance of steel bead concrete mixtures".

9.0 REFERENCED WORK

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