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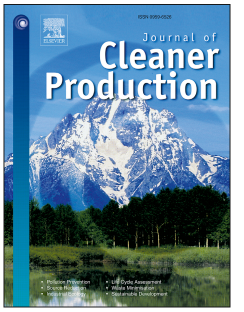

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CRUMB RUBBER USED IN CONCRETE TO PROVIDE FREEZE-THAW PROTECTION (OPTIMAL PARTICLE SIZE)

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Abstract

This research has examined the optimum particle size of crumb rubber, used as an additive to concrete that would provide maximum freeze-thaw protection whilst minimising the compressive strength loss. The crumb rubber as used in the paper was divided into five batches, with increasing particle size, graded in increments of 0.5mm, from <0.5 to 2.5mm. The primary properties of the concrete investigated were; air content, freeze-thaw durability and compressive strength. These were tested using standard test methods.

The range of tests used were conclusive in that the <0.5 the crumb rubber particle size, provided the greater degree of air entrainment. The freeze-thaw cycle results suggested that crumb rubber provided freeze-thaw protection, as the plain concrete deteriorated compared to the concrete with crumb rubber additions. There was no definitive correlation between the compressive strength and the crumb rubber particles size, although the rubberised concrete had an average strength loss of 5.24% after 28 days. This research indicates that crumb rubber graded up to <0.5mm is the optimum size to use, when crumb rubber granules are used to provide freeze-thaw protection in concrete.

Key words: Optimal crumb rubber particle size, freeze-thaw, durability, sustainability, recycling.

1. Introduction

Freeze-thaw deterioration of concrete is responsible for damage to structures and is a major cost to an aging infrastructure. Waste "rubber" tyres are a serious disposal problem and this work investigates the ~~symbiosis~~ use of a waste product to improve the performance of concrete and provide ~~between these two key problems to sugg~~est an environmentally viable solution.

The purpose of this research was to examine the freeze-thaw performance of crumb rubber in concrete with regard to particle size, and determine if there was an optimum particle size of crumb rubber, to provide freeze-thaw protection. The crumb rubber used within the test was divided into five different sized particle batches. A single concrete mix design was used with a pre-determined fixed crumb rubber content by mass. The crumb rubber was added to the concrete mix in sieved size increments of 0.5mm. The range of crumb rubber used was between <0.5 to 2.5mm. The primary properties of the concrete investigated were; air content, freeze-thaw durability using pulse velocity, mass lost and compressive strength.

1. 1 Background

Vehicle tyres are made from a chemically improved rubber, and are designed to last for long periods of time. These specific chemical properties pose difficult questions once the tyres have reached their end of life as they contain environmentally toxic substances, which in landfills break down very slowly and when they are incinerated, they produce dangerous pollutants (Siegle, 2006). The European Union identified this concern and took action by setting environmental legislation banning whole tyres from landfills from July 2003 and shredded tyres from July 2006 (Evans, and Evans 2006). Elbaba and Williams (2013) highlighted the severity of waste tyres as they suggest Europe and the USA combined produce approximately 8.3 million tons of waste tyres annually.

Since the early 1990's research has been carried out by many authors into the use of recycled rubber from vehicle tyres within concrete. Authors suggesting the greatest characteristic benefits are: improved toughness, reduced density, greater sound absorption, increased ductility and reduced water absorption (Fattuhi, and Clark, 1996), (Segre, and Joekes, 2000), Bravo, and Brito, 2012), and (Mohammed, et al 2012). Furthermore, rubber incorporated into concrete has been proven to enhance the resistance to freeze-thaw deterioration (Paine, and Dhir, 2010), Richardson, Coventry, and Ward, 2011a) and Richardson , Coventry , Dave, Pineaar, 2011b).

It is believed crumb rubber has similar qualities to traditional air-entraining agents, which create minuscule pores (gel pores) that are so small, temperatures can fall to -78^{o}C without the formation of ice crystals. These pores allow for the release of pressure and therefore protection from freeze-thaw forces (Neville, and Brooks, 2010). Benazzouk *et al* (2006), highlighted the ability of crumb rubber particles to 'artificially entrap air'. Khaloo, Dehestani and Rahmatabadi (2008) suggest this entrapment of air is due to the non-polar rough surfaces of the rubber particles, which entrain air, thus providing freeze-thaw protection.

Additionally, Benazzouk (2007) studied the hydraulic behaviour of rubber particles and discovered that "rubber additives tend to restrict water propagation and reduce water absorption." Laźniewska-Piekarczyk (2013) explains that this water repellent characteristic "will dramatically improve the durability of concrete exposed to moisture during cycles of freezing and thawing," thus aiding the protection of concrete from freeze-thaw damage.

It is well recognised that for every additional percent of entrained air added through air-entrainment agents, the compressive strength decreases by about five to six percent. Similarly, since research started investigating the use of rubber within concrete it has been accepted that there is a compressive strength loss. The overall consensus is the greater the quantity of rubber the larger the reduction in compressive strength (Topcu, 1994), (Li, et al (1998), (Khatib, and Bayomy, 1999), (Zheng, Huo, and Yuan, 2008), (Zheng, Huo, and Yuan, 2008), (Ganjian, Khorami, and Maghsoudi, 2009), and Atahan, and Yücel, 2012). However it must be noted, that the majority of this research has used crumb rubber as a substitute for fine or coarse aggregate.

The necessity to examine the crumb rubber particle, was recognised by Fattuhi and Clark (1996) who recommend that there is a need to investigate the rubber in terms of 'origin, size and shape' and to determine the effect each parameter has on concrete properties. Relatively little research has been carried out into these parameters, although Paine and Dhir (2010) suggested the freeze-thaw resistance increases as the rubber particle sizes decrease. Zhu *et al* (2011) recognised that "the size of crumb rubber has an influence on the freeze-thaw resistance of concrete," although this research introduced rubber as a sand replacement rather than additive.

This research was informed by previous work (Richardson et al 2011a) who determined that the optimum quantity of crumb rubber content for the most effective freeze-thaw protection was 0.6% by weight. This work determines the optimum particle size for freeze-thaw protection.

2. Methodology

2.1 Mix design

The mix design was influenced by the cube size, as well as being a commonly used commercial strength. 100mm cubes were chosen for reasons of sustainability and this was due to using significantly less material than a 150mm cube which would use 3.38 times more materials. The handling and moving of the cubes also caused health and safety concerns, as each 150mm cube weighed on average 5.2 kg more than the 100mm cubes. Furthermore the surface area to volume ratio for the 100mm cube is 0.67 times greater than the 150mm cube which provided a more severe testing regime. Smaller cube sizes were not considered as they would have to use a special mix design with small aggregates that is not representative of commercial practice.

The 30C characteristic test mix, as displayed in Table 1, was designed to enable the concrete to be compacted into the 100mm cubes more effectively, with a relatively low water cement ratio for additional freeze-thaw protection. The coarse aggregate was composed of washed and graded marine sandstone gravel.

Material	Quantities per m^3 (kg)
Cement (CEM 1- 42.5 N/mm^2)	403
Fine aggregate - Sand (0 - 4 mm)	837
Coarse aggregate (4 - 10 mm)	336
Coarse aggregate (10 - 20 mm)	621
Water content (ratio)	177.3 (0.44)
Crumb rubber (where applicable)	14.25 (0.6% of weight)

Table 1 – Mix design

The crumb rubber was graded into five particle sizes, increasing in instalments of 0.5mm, from < 0.5 to 2.5mm. The graded crumb rubber was added to each concrete mix at 0.6% by weight. The cubes were batched in accordance with BS 1881 : Part 108 : 1983. All cubes were cured for an initial 48 hours in their moulds, covered with visqueen before being removed from the moulds and placed in a water-curing tank at a temperature of 19^{o}C.

The chemical analysis identified that there was high level of silicon (Si) present in the rubber sample and this would explain why the rubber and water did not mix during batching; as the water would be repelled by this hydrophobic, naturally water resistant, material. Table 2 presents the chemical composition of the crumb rubber which was determined using EDS.

Composition of elements		**Percentage**
Carbon	C	75.32
Oxygen	O	6.95
Magnesium	Mg	0.097
Aluminium	Al	0.085
Silicon	Si	22.17
Phosphorus	P	0.25
Sulfur	S	1.00
Potassium	K	0.015
Calcium	Ca	0.074
Iron	Fe	0.25
Cobalt	Co	0.002
Zinc	Zn	0.64
Total		99.98

Table 2 Chemical properties

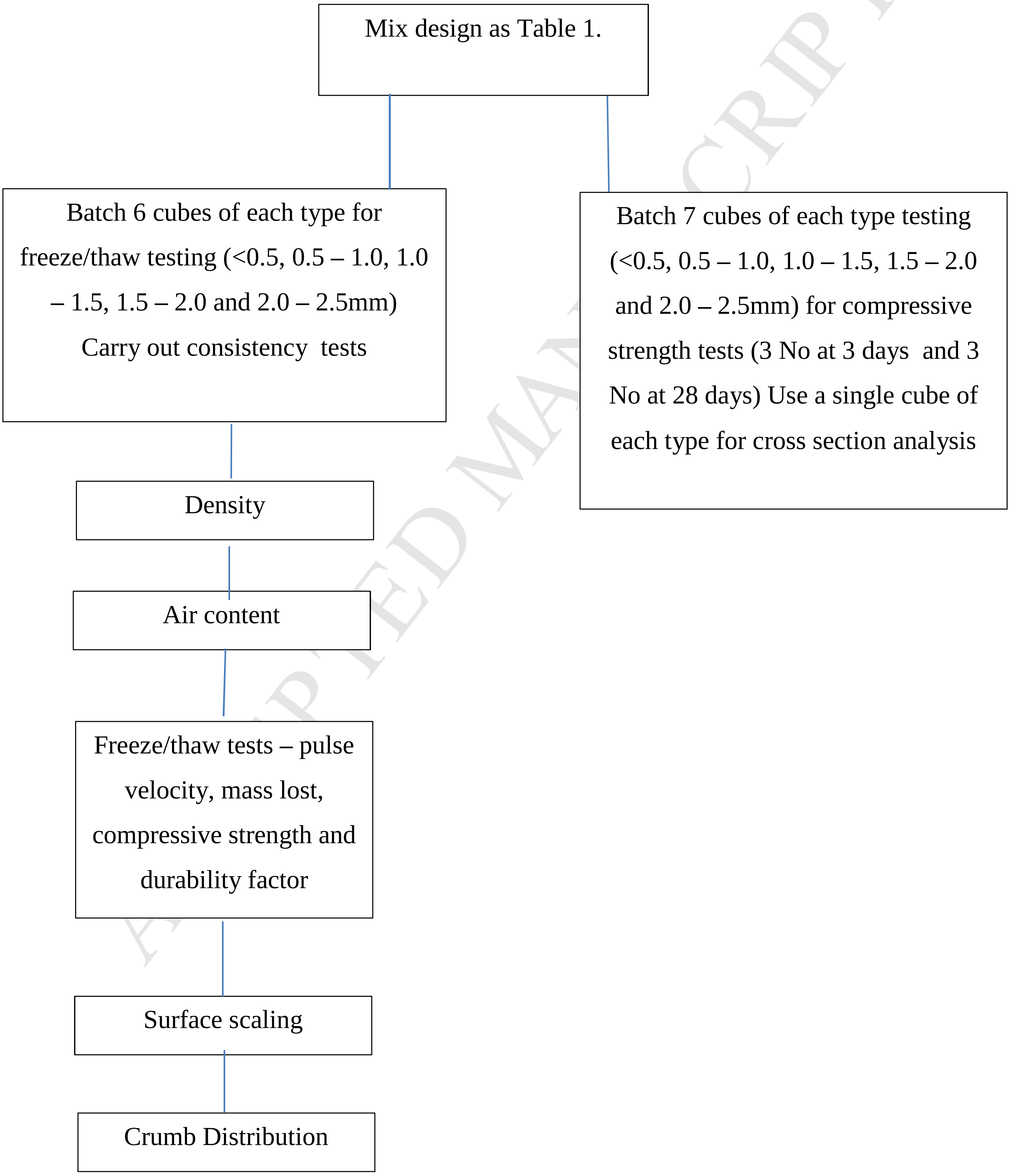
Table 2 provides a complete overview of the chemical properties of the crumb rubber as used. A full analysis of the crumb rubber can be found in The Journal of Green Building, (Richardson et al 2011) and the results are obtained from ASTM D 412, ASTM D – 2084, and IS 7490:1997. The work presented here expands upon earlier work by Richardson et al (2011) carried out on the same crumb rubber particles.

2.2 Test Programme

The key elements for examination were: air content, freeze-thaw performance, compressive strength and crumb rubber distribution. Each element was subjected to tests as displayed in

Figure 1. These tests were based upon the British Standards Institution (BS) and American Society for Testing and Materials (ASTM).

Figure 1 – Test programme



2.2.1 Density

The density of concrete can be used to determine the air content (Neville, and Brooks,2010) The test was carried out in accordance with BS 12390-7, density of hardened concrete after 28 days of curing.

2.2.2 Air entrainment

An evaluation of the air content of the mix was carried out in accordance with BS EN 12350-7 air content – pressure method to determine the air content of the plain concrete mix, thus establishing a benchmark for the crumb rubber mixes.

2.2.3 Freeze-thaw

A combination of ASTM C 666 and BS CEN/TR 15177:2006 were used to establish the principles of the freeze-thaw cycle. Time was a constraint with this research, so the initial decision was to follow the BS that recommended 56 cycles compared to the ASTM which states "300 cycles or until its relative dynamic modulus of elasticity reaches 60% of the initial modulus."

Procedure B 'Rapid Freezing in Air and Thawing in Water' taken from ASTM C 666 was the chosen method of research. A pilot study established the optimum duration of each freeze-thaw cycle. Pulse velocity is an established method used to assess the internal structure of concrete. This test measures the time taken for ultra sound waves to travel through the concrete. Freeze-thaw cycles create surface micro cracks, these initiate damage and through repeated freeze-thaw cycles, the crack propagation creates internal damage to the concrete, which in turn slows the ultra sound waves, thus increasing the transmission time. This test was carried out every 7 cycles in accordance with BS CEN/TR 15177 and BS EN 12504-4.

The pulse velocity measurements were used to determine the relative modulus and breakdown of the concrete when subject to freeze-thaw cycles. The durability factor was calculated at the end of cycle 56 and cycle 70, to discover if the modulus of elasticity had reached 60% of the initial modulus at which point the test would be terminated due to a significant failure occurring. The Equations 1 and 2 are displayed in the ASTM C666 – 97, standard 9.1 and 9.2, as displayed below.

Durability factor Equation [1]

$$\boldsymbol{DF = \frac{PN}{M}} \quad \textbf{[1]}$$

DF = durability factor of the test specimen

P = relative dynamic modulus of elasticity at N cycles (%)

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less

M = specified number of cycles

P is calculated using the Equation [2];

$$\boldsymbol{P = \left(\frac{{n_1}^2}{n^2}\right) \times 100} \quad \textbf{[2]}$$

P = relative dynamic modulus of elasticity after c cycles of freezing and thawing (%)

n = fundamental transverse frequency at 0 cycles of freezing and thawing

n_1 = fundamental transverse frequency after c cycles of freezing and thawing

c = number of freeze-thaw cycles carried out

Mass lost per cube was used to determine the degree of freeze-thaw action.. Furthermore, this test gave a greater insight into the changes each cube was subject to throughout the entire test period. The unfrozen cubes were weighed every 7 cycles, immediately before the pulse velocity test.

2.2.4 Scaling

The scaling test examined the concrete external surface resistance to freeze- thaw attack. The test was performed in accordance with the ASTM C 672, which specified the scaling categories, displayed in Table 3. Additionally ASTM states, “visual rating of the surface [should occur] after 5, 10, 15, 25, and every 25 cycles thereafter.”

Rating	Condition of Surface
0	No scaling
1	Very slight scaling (3mm depth max, 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)

Table 3 – ASTM C 672 scaling surface rating

2.2.5 Compressive strength

This research measured the compressive strength of the concrete at three separate occasions. The first occasion was after 3 days, at the same time the cubes started the freeze-thaw cycle, this was to obtain an initial control strength pre freeze thaw. The second occasion was after 28 days, this was to establish the effect the addition of rubber particle size had on the strength of the concrete. The third and final occasion was post freeze thaw cycles, and this was to measure the strength reduction following the freeze-thaw action and to identify which batch performed most effectively. The compressive strength was carried out in accordance BS EN: 12390 – 3, 2002.

2.2.6 Crumb rubber distribution

The rubber distribution was examined using the principles outlined in TR 32 (Concrete Society,1989), It was essential that the crumb rubber was evenly distributed within the concrete to ensure a uniform freeze-thaw protection. There was the possibility the rubber could either group together or rise to the top of the cube during compaction, which would be due to the rubber being less dense than the concrete mixture.

The combination of the tests provided a holistic overview of crumb rubber performance when used in concrete

3. Results and Discussions

3.1 Slump and consistency

The BS EN 12350 – 2 slump test was used to monitor consistency and the test results are within the range, 60 to 70mm for all batches. The plain concrete had the slightly higher slump when tested. The slump was measured in accordance with the standard, that being to the nearest 10mm and therefore the difference between the batches is negligible.

3.2 Density

The density of concrete can be used to indicate the air content (Neville and Brooks, 2010). Figure 2 indicates the smaller the crumb rubber particle, the greater the air entrainment, and consequently the authors recommend the particle size < 0.5mm as offering the greatest potential for freeze-thaw protection.

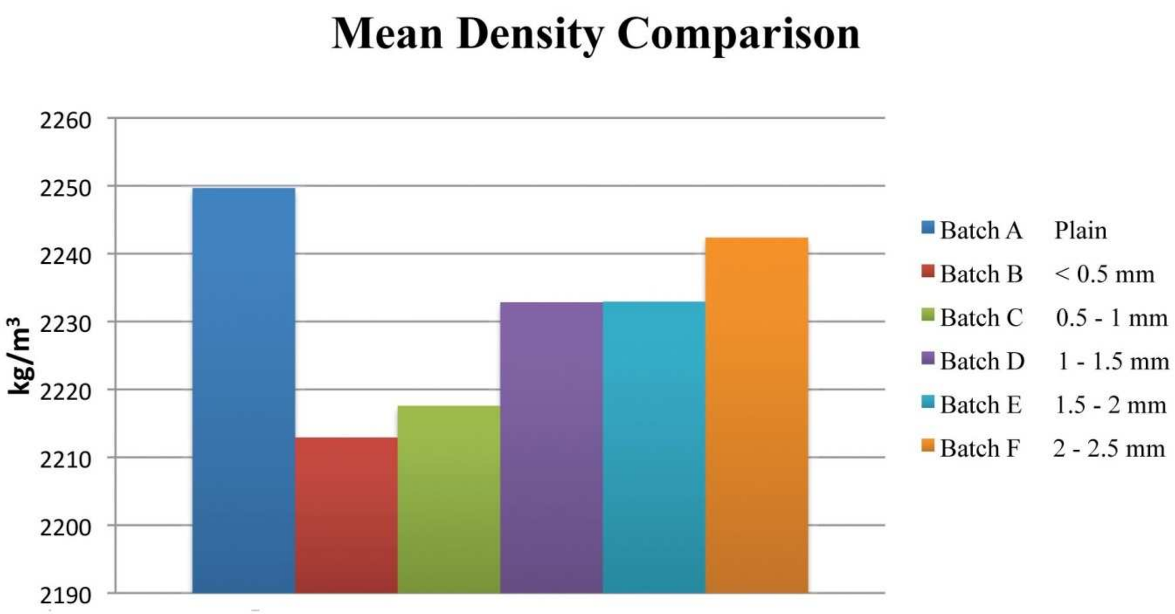


Figure 2 – Mean Density Comparison

The percentage difference between the plain concrete and the concrete with <0.5mm crumb rubber is 1.7% by mass, this is not a statistically significant differential, however when this is considered in addition to the natural air content of the concrete, it will provide additional freeze/thaw protection. Figures 2 and 3 display an inverse relationship.

3.3 Air content

The overall results for the air entrainment test are illustrated in Figure 3, and these have produced a similar trend to the density test, which suggests that the smaller the crumb rubber particle used; creates a greater degree of air entrainment. The relationship between the density and air content results adds credence to the suggestion that < 0.5mm is the optimum particle size.

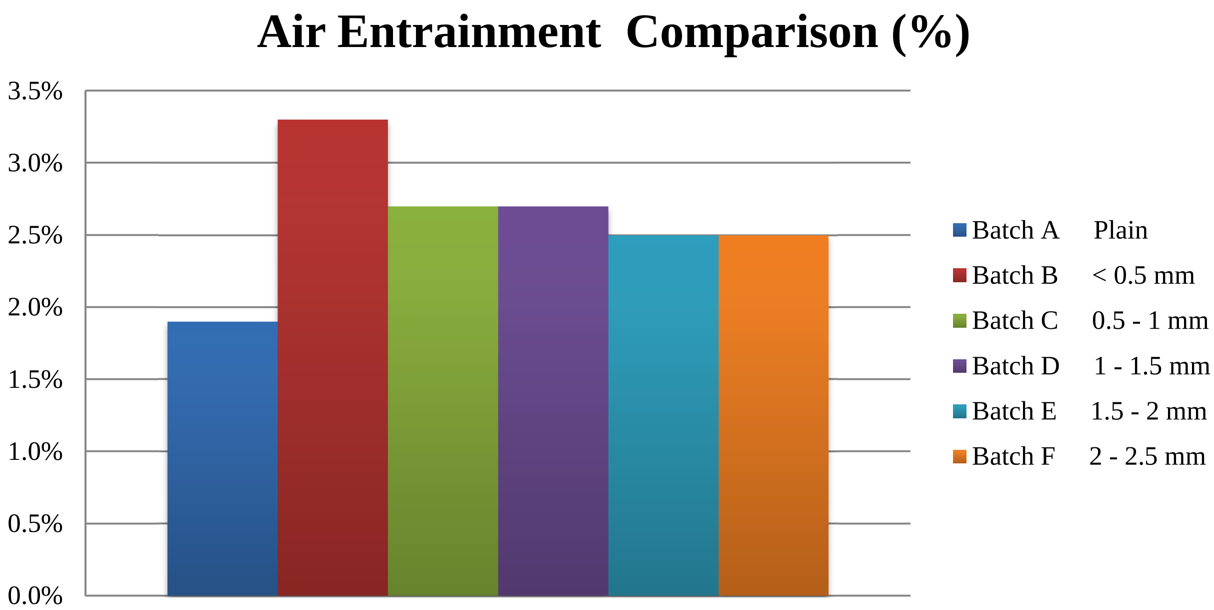


Figure 3 – Air entrainment comparison

The percentage air entrainment for plain concrete was 1.9% and the percentage value for the <0.5mm crumb rubber was 3.3%. The additional air entrained is 74% when comparing the plain sample to the <0.5mm crumb rubber sample. This is a significant differential and 3% air entrainment is adequate for providing freeze/thaw protection, especially as the mix has evenly dispersed crumb rubber particles that will permit pressure absorption, consisting of a particle size small enough to provide effective freeze/thaw protection.

3.4 Freeze-thaw, Pulse velocity

At the conclusion of the planned 56 freeze-thaw cycles, the plain concrete cubes had not failed, as the modulus of elasticity, measured using pulse velocity, had not yet reached 60% of the initial modulus, therefore the test was extended for a further 14 cycles, to provide further potential for freeze-thaw deterioration of the cubes.

The pulse velocity for all batches over the test period can be seen in Figure 4. It is evident that the pulse velocity for all batches consistently increased over the first 42 cycles. The pulse velocity increasing during curing is due to an increase in compressive strength during the freeze-thaw programme. To provide an accelerated test programme, the cubes started the freeze-thaw cycle after 3 days, and they continued to cure and increase in strength. However the most notable aspect of this test is the decrease in the plain cubes pulse velocity from cycle 42 to cycle 70, where for the same period the cubes with crumb rubber were relatively stable. Seventy freeze-thaw cycles provided an insight as to what may be expected in the longer term with regard to freeze-thaw durability.

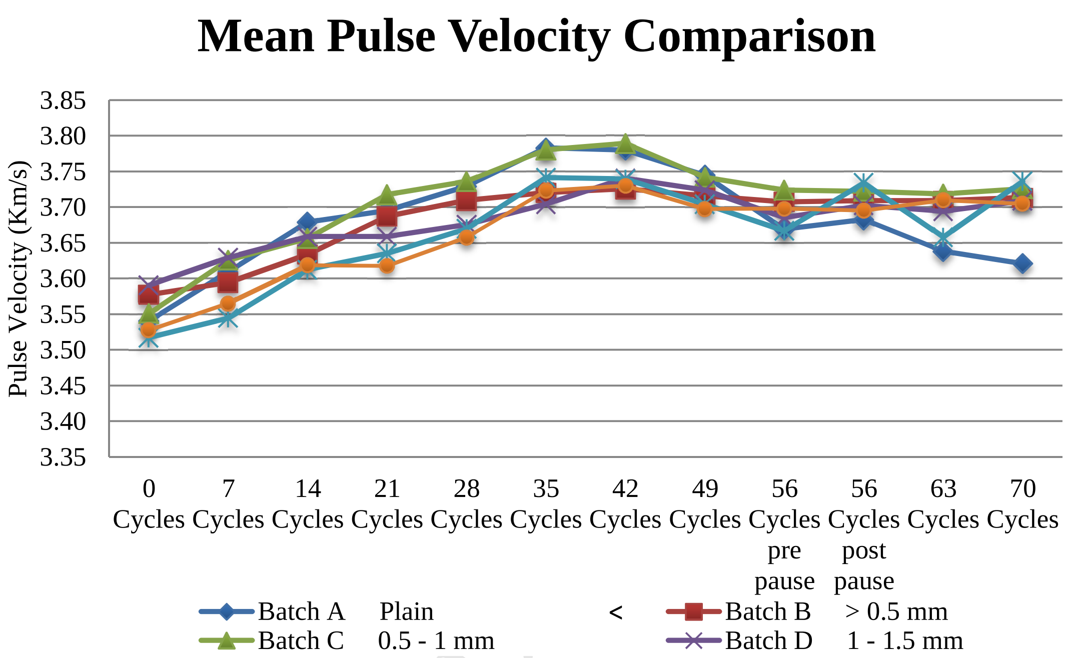


Figure 4 – Mean Pulse Velocity Comparison

The pulse velocity results are not significant at 70 cycles, but they do indicate a trend that if the freeze/thaw cycles were continued, the results would be more in line with work by Richardson et al (2012). The results support other findings within the paper.

3.5 Mass lost

During the freeze-thaw cycles, all batches experienced a mass loss, although at different rates. The plain concrete cubes had the greatest loss as illustrated in Figure 5.

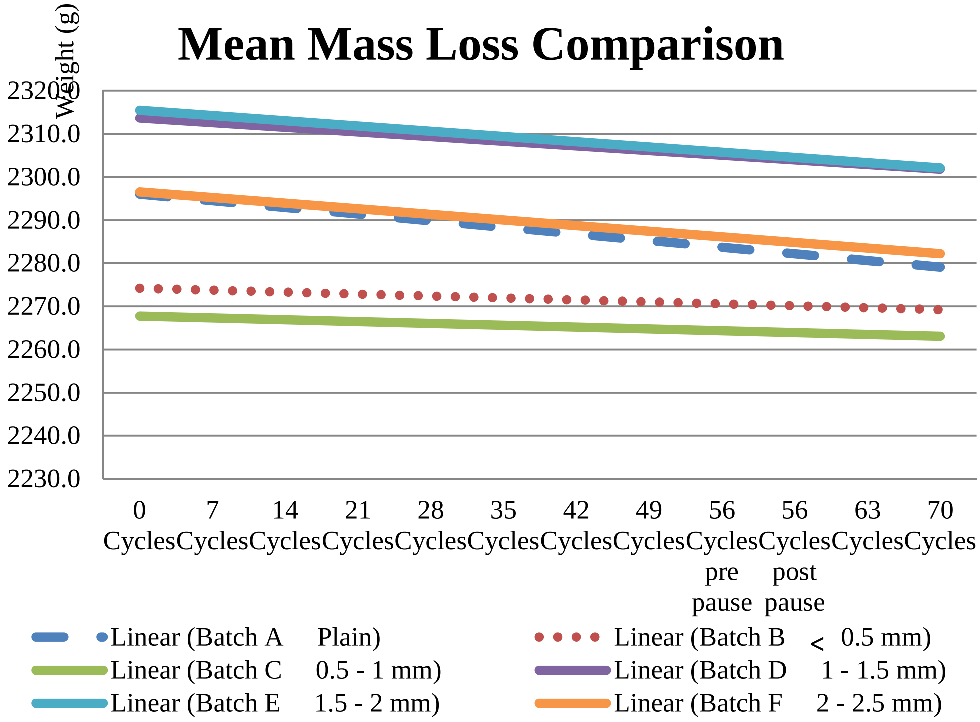


Figure 5 – Mean Weight Loss Comparison

The percentage mass lost per cube type were relatively small, however when comparing the worst performing concrete (A) against the best performing concrete (B), the relative mass lost was 0.6% and 0.07%. This displays a relative trend where type B performs 8.57 times better than type A concrete.

3.6 Compressive strength

The full comparison of compressive strength illustrated in Figure 6, is a graphical representation comparing the individual cubes at various stages of the test programme. The increase of strength from the start of the freeze-thaw cycle at three days to the post freeze-thaw cycle strength reveals the concrete has continued to cure during at least part of the freeze-thaw cycles. The strength of the 28 day old cubes is higher than the post freeze-thaw strength, which displays the effects of the freeze-thaw action and temperature on the curing process. When comparisons are drawn between earlier work by Richardson, Coventry, and Ward, (2011a), and this paper, there is a distinct difference in the performance of the plain concrete, in that the strength reduction was less with this work. The trends are sufficient to display the protective effects of crumb rubber and the performance differential can be explained by a lower density concrete which will contain more small voids and provide a better freeze/thaw resistance.

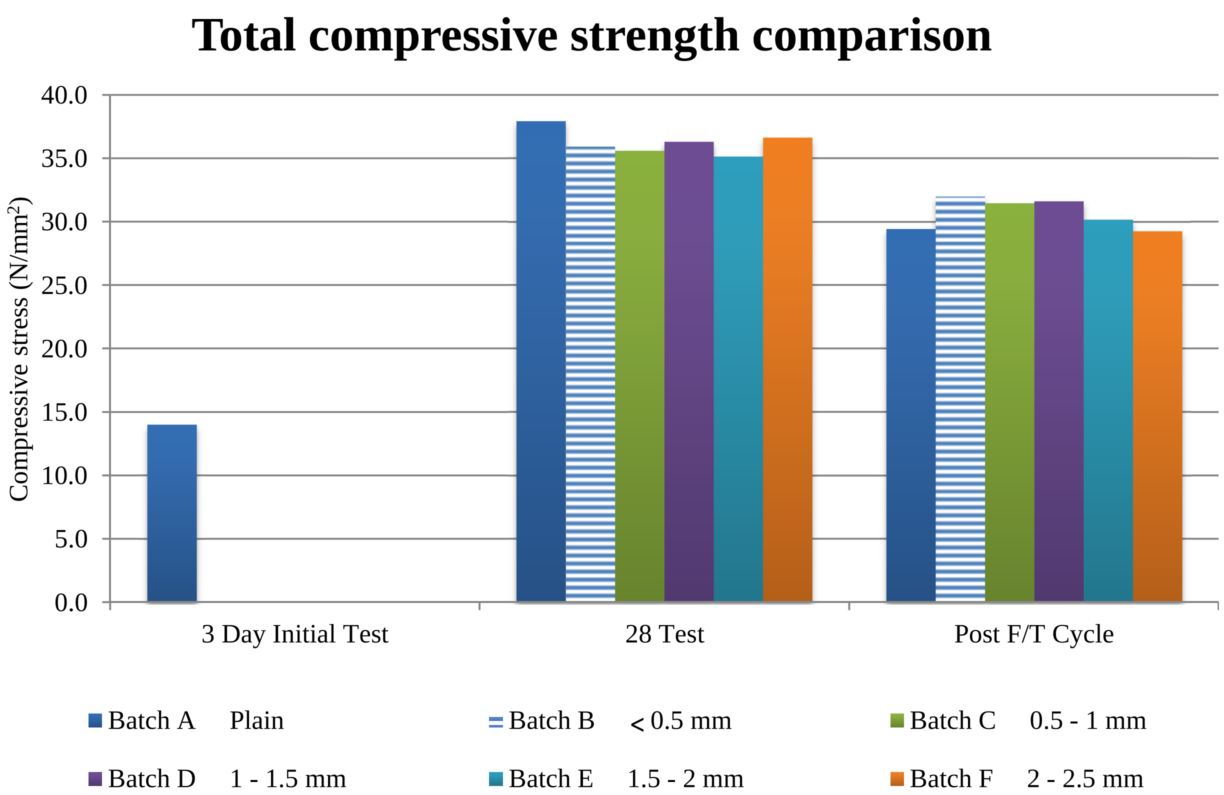


Figure 6 – Total compressive strength comparison

The <0.5mm crumb rubber additive achieved the best performing freeze-thaw performance as displayed in Figure 6.

3.7 Durability factor

The durability factor as displayed in Table 4 shows that the cubes continued to cure during the freeze-thaw programme, hence the values achieved exceeding 100%. What is evident from this test, is that Batch A, the plain concrete, has the lowest durability factor. Batch E marginally provides the best durability factor. All of the concrete samples containing crumb rubber outperformed the plain concrete with regard to freeze-thaw durability.

Batch	Description	Durability Factor
Batch A	Plain	101.3%
Batch B	< 0.5 mm	104.9%
Batch C	0.5 - 1 mm	103.8%
Batch D	1 - 1.5 mm	103.3%
Batch E	1.5 - 2 mm	105.2%
Batch F	2 - 2.5 mm	105.0%

Table 4 – Durability factor

Richardson et al (2012) discovered that concrete continued curing during the testing programme (ASTM 666 – 300 cycles) when concrete was subject to freeze/thaw cycles. These results mirror earlier work for batches B to F. However the plain concrete was starting to show signs of deterioration at 70 cycles hence the durability factor difference of -3.6%. This difference is explained in part in Section 3.6, however concrete being a heterogeneous material with a large standard deviation, the plain concrete appeared to be more resistant to the action of freeze/thaw cycles in this particular case. However when viewed in the light of all of the results, there is a clear trend and a case for favouring crumb rubber as a protection against freeze/thaw action.

3.8 Surface scaling

Table 5 displays the recorded scaling (ASTM C 672) for each cube and the mean value for each test over 70 cycles.

Concrete types						
No. Cycles	Inspection Mean Score					
	Batch references					
	A	B	C	D	E	F
0	0	0	0	0	0	0
5	0	0	0	0	0	0
10	0	0	0	0	0	0
15	0	0	0	0	0	0
25	0.5	0	0.8	0.5	0	0.83
50	1.6	0.16	1.2	0.83	0.6	1.0

70	1.6	0.16	1.2	0.83	0.83	1.0

Table 5 – Batch A scaling results

The results for the scaling are in keeping with the mass loss test results. The plain concrete performed least well and this is where the greatest scaling occurred, as displayed in Figure 7 (Table 5 - A), most notably on the corners. Batch B performed exceptionally well with almost no scaling on all cubes, displayed in Figure 8 (Table 5). There is a factor of ten difference between Plain (A) and <0.5mm crumb rubber (B), this is a significant difference in performance and it is particularly relevant as the surface is where damage is initiated.

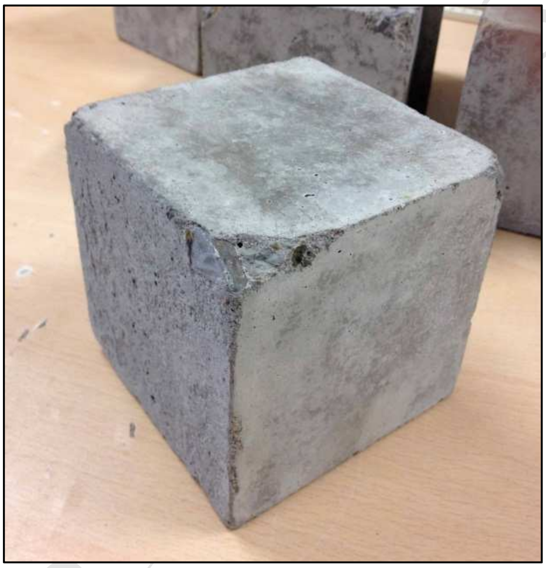


Figure 7 – Batch 'A' surface at final scaling inspection (70 cycles)

Figure 8 – Batch 'B' surface at final scaling inspection (70 cycles)

3.9 Crumb rubber distribution

The cubes were cut and split centrally using a water cooled masonry saw to expose a cross section, displaying the crumb rubber distribution. Figures 9 and 10 display an even crumb rubber distribution through the cross-section of the cubes. When all of the cubes were examined there was an equal distribution of crumb rubber through the section, and this equal spacing of the crumb rubber is essential to provide an even freeze-thaw protection to the cubes.

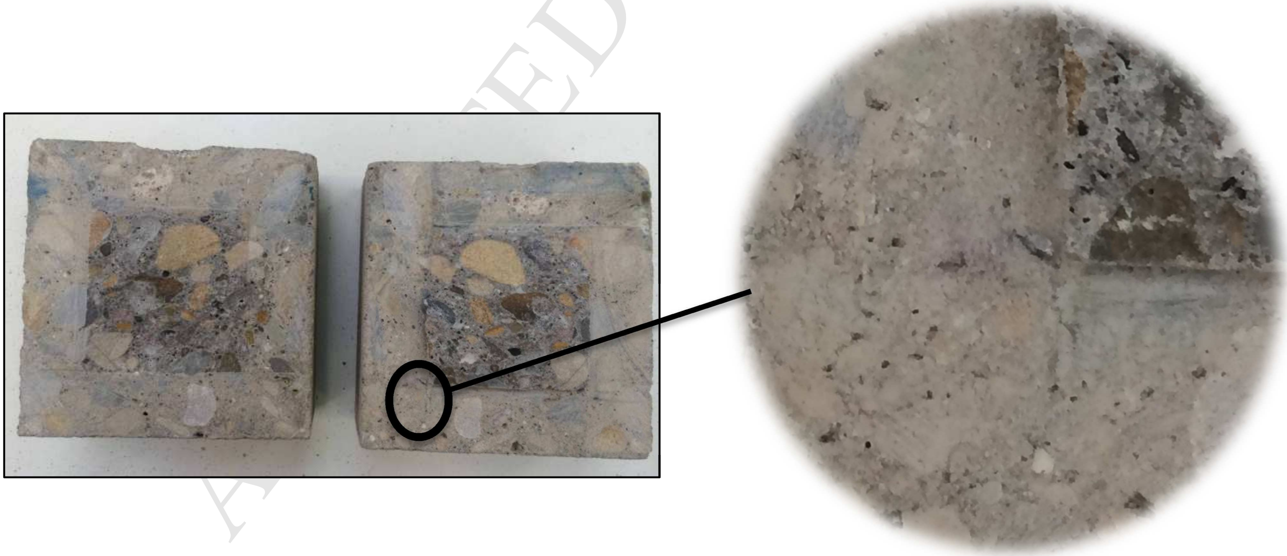


Figure 9 – Batch C cross section analysis

Figure 10 – Batch cross section analysis

3.9.1 Crumb rubber detail

The Leica S6D scanning electron microscope (SEM) was used to examine the rubber crumb particles used within the study. Figure 11 displays the irregular nature of the <0.5mm crumb rubber surface finish when viewed at various magnification. The irregular surface will entrap air and create an air void system for freeze-thaw protection. Figure 12 views the surface finish at a magnification of 500x.

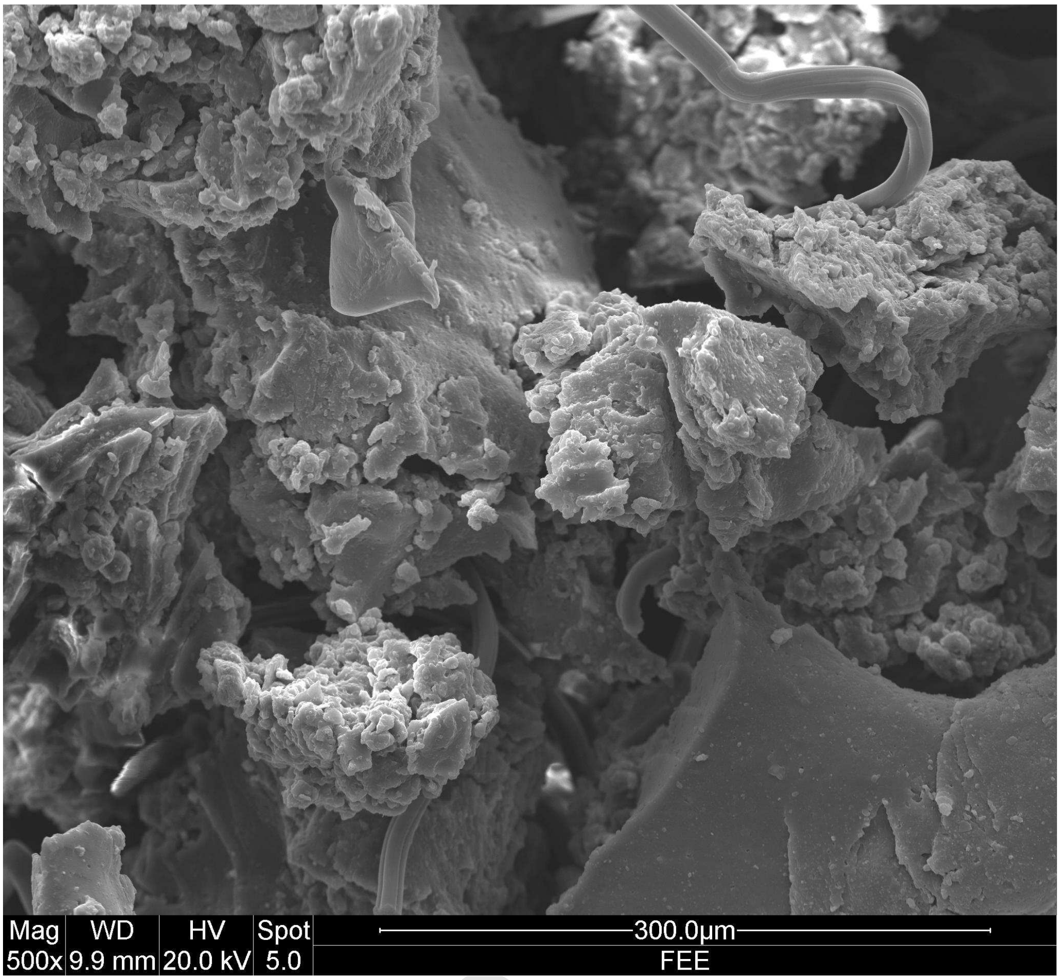


Figure 11 – Crumb rubber surface finish

As the <0.5mm crumb rubber particle size proved to be most efficacious in providing freeze-thaw protection when compared against the other crumb particle sizes, a grading profile was taken to establish the component parts of the <0.5mm crumb rubber. Table 6 displays the particle profile of the <0.5mm crumb rubber.

Sieve size	% passing each sieve	Amount retained per sieve (grams)	% Retained
1.18 mm	100	0	0
600 μ	100	0	0
425 μ	3.40	8.12	3.37
300 μ	34.40	74.64	30.95
212 μ	71.00	88.32	36.68
Pan		69.74	29.00
Total sample size		240.82	

Table 6 - <0.5mm crumb rubber particle distribution

The percentage of fine material in the sample, fine being defined as being under half the size of the maximum particle size stated is 65.68%.

4. Conclusion

When all of the results were analysed, there was a notable improvement in freeze-thaw resistance between plain and crumb rubber concrete. The optimum crumb rubber particle size that performed best was <0.5mm. There was no definitive correlation between the compressive strength and the crumb rubber particles size, although the rubberised concrete had an average strength loss of 5.24% after 28 days.

It was established that the crumb rubber had non-polar rough surfaces, which supported the theory claiming this is how air is entrained. Consequently, the smaller the particle size the greater the surface area for the same mass of rubber and thus, the greater the opportunity to entrain air. This premise was supported by the use of an air entrainment pressure test, which discovered that the batch with rubber smaller than 0.5 mm entrained 3.3%, compared to plain concrete of 1.9%. The density test also suggests that the smaller the particle size, the greater the air entrained, and this provides freeze-thaw protection.

~~The quality of the concrete used was relatively freeze-thaw resistant without any additives and this was thought to be due to the water cement ratio used during the batching process.~~ Low density of the samples was indicative of a high percentage of pore spaces which provided a natural freeze/thaw protection..

Visual inspections of the cubes also suggested that the addition of crumb rubber provided freeze-thaw protection. The greatest scaling occurred on the plain concrete cubes but relatively low scaling occurred on the concrete with the addition of crumb rubber. The concrete with the crumb rubber smaller than 0.5 mm had almost no scaling whatsoever. The smaller the crumb rubber particle size will permit crumb rubber to be contained in the surface laitance, which is subject to the initiation of freeze-thaw induced cracking.

The compressive strength, post freeze-thaw cycles reveal the plain concrete had the weakest strength, supporting the evidence that the addition of crumb rubber provides freeze-thaw protection. Furthermore, the post freeze-thaw compressive strength test found the concrete with the crumb rubber smaller than 0.5 mm had the highest strength, indicating this batch had the least amount of structural damage.

The crumb rubber was distributed evenly throughout all batches, generating an even distribution of entrained air and therefore an even protection.

This research indicates that a crumb rubber particle size smaller than 0.5mm is the optimum size to afford maximum freeze-thaw protection in concrete when using a waste product within the concrete supply chain. However, the downside of this, is that the smaller the particle size used , the longer the processing time, the more the energy and labour consumption, and the higher the production cost. Whilst the cost of producing smaller crumb particles may be relatively high at present, new production techniques may bring this cost down in the future and waste tyre disposal costs, may make the use of end of life tyres very attractive when compared against disposal tax costs.

The benefits of this research illustrate a potential means of reducing the environmental impact of waste tyres whilst improving the concrete product and lowering the life cycle costs, due to freeze/thaw damage.

5.0 Further work

Plain concrete deterioration during the freeze-thaw cycle, was evident, although the rate at which the plain cubes deteriorated was slower than expected, given the early age at which the concrete was placed into the freezer. Had more time been available for this research to allow the full 300 cycles as recommended by the ASTM C666; the trends observed may have continued until the plain cubes would break down, and possibly fail. A larger scale and longer duration test would be appropriate for future research. According to Tantala et al, (1996) the toughness (energy absorption capacity, generally defined as the area under the load-deflection curve of a flexural specimen) of a rubber modified concrete beam with 5% shredded rubber by volume of coarse aggregate, exhibited greater toughness than that of a plain control beam. The synergy of increased toughness and freeze thaw protection is worthy of a full scale real world long term test.

Tyres have many uses with regard to their end-of-life management. They are composed of three main components, those being rubber, textile and steel wire. The steel wire could be used as steel fibre reinforcement in concrete Tlemat, Pilakoutas, and Neocleous (2004) suggest that reclaimed steel fibre from tyres is comparable to equivalent industrial reinforcement fibres. In addition the rubber and textile components have many uses ranging from the manufacture of carpet underlay to that of firing a furnace for cement production. Clearly, one potential use of waste tyres when they are recycled as rubber crumb is to be used in concrete to provide freeze-thaw protection.

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Highlights

This research confirms the efficacy of rubber crumb used as a freeze thaw protection

The rubber crumb selection as used has identified the most effective particle size

Rubber crumb use provides a use for waste and reduces the problem of tyre disposal

The use of a waste product enhances the performance of the concrete

The rubber crumb usage reduces the life cycle cost of a building/structure