Citation for published version:
Paine, KA & Dhir, RK 2010, 'Research on new applications for granulated rubber in concrete', Proceedings of the Institution of Civil Engineers: Construction Materials, vol. 163, no. 1, pp. 7-17. https://doi.org/10.1680/coma.2010.163.1.7

DOI:
10.1680/coma.2010.163.1.7

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Proceedings of the Institution of Civil Engineers
Construction Materials 163
February 2010 Issue CM1
Pages 7–17
doi: 10.1680/coma.2010.163.1.7

Paper 800045
Received 03/10/2008
Accepted 18/02/2009

Keywords:
concrete technology & manufacture/ recycling & reuse of materials/ strength & testing of materials

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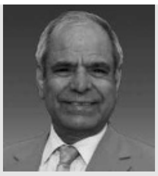

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Research on new applications for granulated rubber in concrete

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This study was undertaken to assess the feasibility of using granulated rubber as an aggregate or filler in concrete construction, by exploiting the inherent stability, impact, crack and thermal resistance characteristics that granulated rubber could bring to concrete. The research showed that there was potential for use of granulated rubber for increasing the freeze–thaw resistance of concrete as, under scaling conditions, fine granulated rubber provides similar performance to air-entrained concrete, but has the advantage of being an inert material suitable for use with all types of cement and concrete. The research also showed that granulated rubber leads to concrete with lower thermal conductivity, and that concrete with low U-values, suitable for use in floors and foundations, can be produced without the need for complementary insulation. Thus, there is now an opportunity for industry to develop granulated rubber concrete products that can be used on a commercial basis, which will facilitate sustainable urban development from both economic and environmental perspectives.

1. INTRODUCTION

Since 2006, European Union directives have banned the disposal of used tyres (whole and shredded) in landfills. Since the UK discards 46 million tyres each year (WRAP, 2007), this has resulted in an urgent need to identify routes for reuse or for recycling the component materials for new purposes. A number of possible routes for utilising used tyres have been suggested within civil engineering applications, for example as bales for construction, landfill cover, and drainage, and the use of granulated rubber (GR) as aggregate in lightweight concrete (Hylands and Shulman, 2003).

The potential of using GR in concrete has been investigated by a number of researchers who have concluded that the most desirable properties of GR concrete are: ductility, high impact and toughness resistance, and low density (Ali *et al.*, 1993; Eldin and Senouci, 1994; Topçu, 1995; Fattuhi and Clark, 1996; Savas *et al.*, 1996; Lee *et al.*, 1998; Li *et al.*, 1998; Khatib and Bayomy, 1999; Benazzouk and Queneudec, 2002; Benazzouk *et al.*, 2007; Chou *et al.*, 2007; Hernandez-Olivares *et al.*, 2007; Topçu and Demir, 2007; Turatsinze *et al.*, 2007; Zheng *et al.*, 2008). However, all researchers have reported that GR concrete has a lower compressive strength than an equivalent normal concrete. The reduction in compressive strength is generally attributed to the rubber acting as a weak inclusion of low elastic modulus (Fattuhi and Clark, 1996; Lee *et al.*, 1998). This produces high internal tensile stresses perpendicular to the applied load when the concrete is stressed. However, other theories have been postulated, that suppose that the failure mechanism is dependent on the shape of the particle (Eldin and Senouci, 1994). Furthermore, it has been argued that the loss in strength can be associated with increased air content in GR concrete (Ali *et al.*, 1993). This possibly occurs because various compounds of rubber (polyisoprene, polybutadiene, styrene, butadiene and neophrene) have hydrophobic or water-repelling properties and therefore air bubbles formed during mixing become attached to the rubber and are prevented from escaping. However, research using microscopic studies has alternatively suggested that GR leads to imperfections in cement hydration which disturb the early-age water transfer. Consequently channels are formed in the concrete as it sets and hardens and these are later prone to cracking (Chou *et al.*, 2007).

Whatever the mechanism for lower cracking strength, GR concrete has a higher capacity for absorbing plastic energy under compression. Indeed, the failure of GR concrete tends not to be brittle but much more ductile, akin to the behaviour of fibre-reinforced concrete. Previous research has, for example, reported an increase in toughness (the area under the compressive stress–strain curve) of 30% for 20% GR content (replacement of fine aggregate) by volume (Topçu, 1995) and linear reductions in brittleness index (ratio of elastic energy deformation to plastic energy deformation) as GR content increases (Zheng *et al.*, 2008). Failure of GR concrete in tension has also been observed to be ductile, with specimens capable of absorbing high amounts of energy and withstanding measurable post-failure loads and considerable strain capacity (Turatsinze *et al.*, 2007). It has been suggested that this is because GR does not fail under the tensile stresses that are capable of splitting the cement paste and mineral aggregate, and as a result cracks can only propagate throughout the specimen by circumnavigating the GR (Lee *et al.*, 1998). This prolongs the crack path and increases the area of the failure surface. During propagation, cracks must therefore overcome the bond between the paste and the rubber. The tensile stresses acting on the specimen eventually produce several independent and disconnected cracks at different points in the specimen. Furthermore, it has been observed that the strain capacity of GR leads to significantly reduced shrinkage cracking in concrete (Turatsinze *et al.*, 2007).

The extra ability of GR to incorporate impact resistance into concrete has been further observed under collision impacts in which it has been noted that damage is reduced because of the lower elastic modulus of GR concrete (Topçu, 1995). Tests have concluded that GR concrete containing fine GR (0/4 mm) had the greatest energy absorption and was thus most effective in reducing the amount of damage. These results have been confirmed by dynamic impact tests using the Charpy apparatus (Eldin and Senouci, 1994). In these latter tests, the GR was used as fine aggregate replacement at 5% mass of cement. The results showed that GR concrete could absorb 34% more energy than standard concrete – similar to the improvements in static compressive toughness reported above. Due to this favourable static and mechanical behaviour, the use of GR in rigid concrete pavements has been investigated using up to 5% GR by volume (Hernandez-Olivares *et al.*, 2007). However, this was found to be an unpromising application, because in order to obtain equivalent performance to conventional rigid pavements, increased slab thicknesses were required to compensate for differences in material stiffness.

In addition to mechanical performance, there have been limited studies investigating aspects of durability. Research on GR concrete exposed to acid and sulfate attack have shown GR concrete to have similar performance to conventional concrete (Benazzouk *et al.*, 2007), while a few studies on freeze–thaw behaviour have suggested that the GR may reduce damage (Savas *et al.*, 1996; Benazzouk and Queneudec, 2002); however, to achieve significant improvements, results seem to suggest that GR contents need to be very high (15 to 40% by volume), although for economical reasons an optimum GR content of 10% by volume has been suggested (Topçu and Demir, 2007).

An extensive literature review on the potential use of GR in concrete has argued that most of the past research in this area has tended to be too general in nature, focusing on the properties of concrete, and has not developed the technology of GR concrete for specific applications (Siddique and Naik, 2004). The work reported in this paper provides a response to this by reporting on research commissioned by the UK government and industry (Dhir *et al.*, 2002) to assess the feasibility of using GR as an aggregate or filler in concrete construction, with the aim of developing ways to exploit the inherent stability, impact, crack and thermal resistance characteristics that GR could bring to concrete. This would (*a*) create a disposal route for millions of used tyres and (*b*) improve the performance of concrete, while (*c*) reducing the environment impact.

The research had three specific objectives.

(*a*) To examine the influence of GR on the fundamental mechanical, durability and environmental properties of concrete when used as an aggregate or filler material.
(*b*) To conduct detailed studies on the most appropriate applications.
(*c*) To provide guidance that covers the incorporation of GR in concrete, in order to provide a further environmentally friendly disposal route for used tyres.

2. EXPERIMENTAL PROGRAMME

The experimental programme was split into three main phases. Initially preliminary experimental studies were carried out to confirm the findings in the literature using a particular GR type available in the UK, and to better understand the implications of using such a lightweight, compressible material in normal designed concrete mixes. These studies focused on the fundamental mechanical, durability and environmental properties of the concrete (Dhir *et al.*, 2002). Based on these findings, further research was carried out to understand and develop the use of GR for two of the most promising properties

(*a*) freeze–thaw resistance
(*b*) thermal insulation.

The GR used throughout the experimental programme was recovered from used tyres through a number of mechanical shredding and ripping stages that reduce the tyres in size, and remove the steel and fibre cord. The GR used in this study was obtained from mechanical shredding of lorry tyres, and was supplied in three sizes, namely 0·5–1·5 mm, 2–8 mm and 5–25 mm, which are respectively referred to as GR1, GR8 and GR20 throughout this paper. The particle size distribution of the GR is shown in Figure 1, and compared with the natural aggregate (river sand and gravel) also used in the study. The grading of the two coarsest GRs (GR8 and GR20) fell within the current limits for 4/10 mm and 10/20 mm single-sized aggregates specified in BS EN 12620 (BSI, 2002b). The finest GR (GR1)

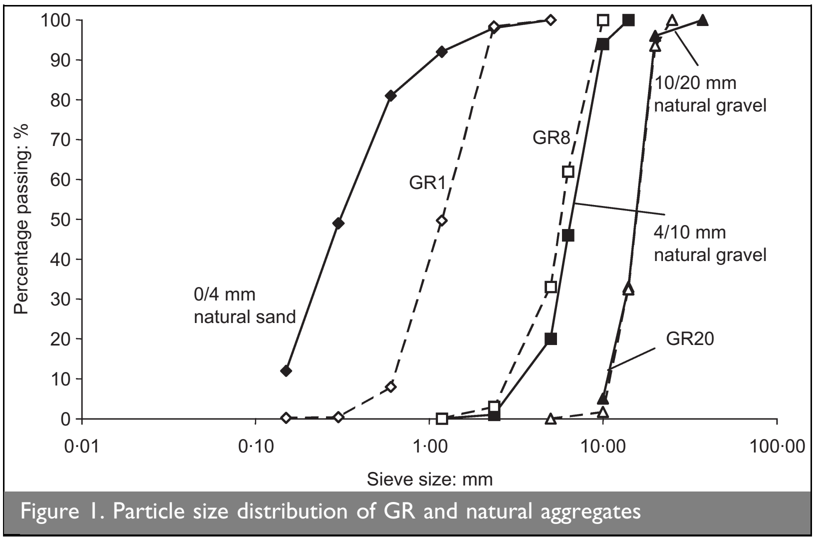

Figure 1. Particle size distribution of GR and natural aggregates

did not meet the requirements for fine aggregate (0/4 mm), falling slightly on the coarse side.

The physical properties of GR, using standard aggregate tests (BSI, 1988a, b, 1989a, 1990a, b, 1995, 1998a) are given in Table 1. Water absorption values were found to be similar to those of natural aggregate; however, this test and the associated density tests were somewhat difficult to carry out because of the nature of GR, namely, despite carrying out the tests in non-aerated water, a substantial amount of air bubbles attached themselves to the GR. Subsequently, the values recorded were on the low side. Furthermore, the results show that GR has a mean particle density of between 1020 and 1140 kg/m^3, although in all three-size fractions approximately 5% by mass of the GR was found to float. Whereas many common aggregate properties, for example shape, crushing values and impact values, are not applicable to GR, approximate values are given in Table 1 for indicative purposes. The composition of the GR based on ASTM D5603 (ASTM 2008) is also given.

2.1. Preliminary studies

The preliminary studies investigated concrete at four water/cement (w/c) ratios between 0·35 and 0·65, using all three sizes of GR separately as partial aggregate replacement. Normal concretes were proportioned using the BRE mix design procedure (Teychenne *et al.*, 1997) for natural gravel concrete, and GR concretes were proportioned by replacing natural river gravel or sand with an appropriate volume of similarly-sized GR in order to produce concretes containing 3, 5, 7 or 10% GR by volume of concrete. In all cases, the equivalent normal concrete, containing no GR, was produced for comparative purposes. The tests used (BSI, 1988c, 1989b, 2000b, 2002a; CEN, 1994; Dhir *et al.*, 1991; Jones and McCarthy, 2006; NNI, 1995) throughout this preliminary phase are summarised in Table 2.

2.2. Freeze–thaw resistance study

Although there has been a relatively low incidence of serious freeze–thaw damage to concrete reported in the UK, due to the recognised practice of entraining air, it does not follow that this is necessarily economical. Furthermore, there are a number of concerns with the use of air entrainment as a method for providing freeze–thaw resistance. These include (Harrison *et al.*, 2001): (*a*) losses in air-content during transportation; (*b*) erratic air entrainment when using fly ash; (*c*) reduced air entrainment with low alkali/sulfate-resisting cements; (*d*) difficulties with air entraining low workability concretes; and (*e*) the formation of blowholes on the surface following vibration. The use of solid, compressible, inert GR particles into the concrete mix, which can be accurately batched, is a possible solution.

Property	GR size		
	GR1	GR8	GR20
Elongation index: %	–	–	44
Aggregate impact value*: %	–	–	0
Aggregate crushing value*: %	–	–	0
Water absorption: %	0·4	0·8	1·0
Particle density: kg/m^3	1040	1075	1120
Loose bulk density: kg/m^3	405	460	455
Water-soluble chlorides: %	0·00	0·00	0·00
Water-soluble sulfates: g/l	0·1	0·0	0·0
Acid-soluble sulfates: %	1·6	3·1	–
Ash content: %	6·8	5·1	7·3
Fibre content: %	1·1	2·4	2·0
Free fibre content: %	1·1	0·5	0·4
Iron content: %	0·0	0·0	0·5

*10–14 mm fraction only.

Table 1. Physical and chemical properties of GR

To investigate the potential for using GR as an alternative mechanism for providing freeze–thaw resistance, GR concretes were designed and cast for a cube strength of 37 MPa, the minimum strength permitted by BS 8500-1 (BSI, 2006) where air entrainment is used. For comparative purposes, a normal and an air-entrained concrete of 37 MPa design strength were also produced. Three additional concretes – a normal concrete and two GR concretes – were also designed for 50 MPa, the minimum strength permitted without air entrainment (BSI, 2006).

The BRE method (Teychenne *et al.*, 1997) was used as the basis for concrete mix proportioning for the normal and air-entrained concretes, and as for the preliminary mixes, GR8 and GR20, were included as direct replacement, volume-for-volume, for the 4/10 and 10/20 mm aggregate, respectively, while GR1 was used as direct replacement, volume-for-volume, for 0/4 mm aggregate. The resulting concretes contained 2, 4 or 6% GR by volume of concrete.

The mix proportions used are given in Table 3 with w/c ratio reduced as the GR content increased. The reduction was based on the strength results from the initial studies (Table 2) that showed that the loss in strength when using GR was similar in magnitude to that of an equivalent amount of air. Because of the consistence-enhancing properties of air-entraining admixtures, the water content for the air-entrained concrete was reduced to 160 kg/m^3 and, therefore, for equal w/c ratio contained less cement than an equivalent GR concrete. For this reason, there appears to be an economic disadvantage in using GR. However, had a water-reducing admixture been used with the GR mixes, it is likely that equal strength could have been achieved with lower cement contents. Care should, therefore, be used when attempting to consider the economic issues associated with the results.

Freeze–thaw testing was carried out using two methods: the CEN slab test (CEN, 1994), which measures freeze–thaw damage by means of scaling from a concrete surface, and the ASTM prism test, ASTM C666 Procedure A, where damage results from disintegration of the concrete mass (ASTM, 1992).

2.3. Thermal insulation study

The maximisation of energy conservation in cold weather and reduction of the environmental impacts associated with heating of buildings are important. Indeed, heating of buildings in the UK accounts for around 25% of the total CO_2 emissions (Concrete Society, 2003), and partly for this reason, in April 2002 the UK Building Regulations became more stringent in terms of thermal transmittance (U-value) requirements (OPPM, 2002). For example, the maximum U-value for exposed ground slabs was lowered from 0·45 to 0·25 W/m^{2}K. Most conventional building materials do not meet this requirement without the need for additional and complementary insulating layers.

Property	Test method	Effect of GR	Comments
Cube strength	BS EN 12390–3 (BSI, 2002a)	Loss of 2–6% in strength for each addition of 1% by volume of GR (up to 10% by volume).	GR1 led to higher strength losses than the coarser GR sizes. Bonding agents had no significant effect.
Flexural strength	BS EN 12390–5 (BSI, 2000b) two-point-loading	Loss in strength. Generally proportional to losses in cube strength.	Some evidence that coarser GR particles provided crack-arresting properties akin to fibre-reinforced concrete.
Static modulus of elasticity	BS 1881–121 (BSI, 1988c)	Losses in modulus of elasticity. Directly proportional to GR content.	No significant effect of GR size.
Drying shrinkage	BS 812–120 (BSI, 1989b)	Increase in drying shrinkage. Proportional to loss in static modulus of elasticity.	Use of coarser GRs led to higher recorded drying shrinkage.
Impact resistance	14 kg ball dropped 0·3 m onto a 70 mm ball resting on a 130 mm × 130 mm × 50 mm concrete slab	Increase in impact resistance.	Concrete with the coarsest GR required significant number of blows before failure.
Energy absorption	Pendulum swung 90° onto a 100 m thick concrete wall, and angle of pendulum resting on opposite wall measured	Increase in energy absorption.	No significant effect of GR size.
Abrasion	Modified BCA method (Dhir *et al.*, 1991)	Improved abrasion resistance.	Probably due to GR particles 'kicking' rollers away from surface, thus preventing abrasion taking place.
Freeze–thaw resistance	CEN/TC 51 test method (CEN, 1994)	Improvement in resistance to scaling. Cumulative scaling after 56 days up to 10 times lower than normal concrete.	Fine GR was more effective than coarse GR.
Thermal insulation	Insulated hot-box apparatus (Jones and McCarthy, 2006)	GR reduces indicative thermal conductivity of concrete by 15 to 30% for 10% addition of GR by volume.	Effect of GR becomes more pronounced as water/cement (w/c) ratio increases.
Leaching	NEN 7345 (NNI, 1995)	Leaching of heavy metals below EU drinking water limits.	

Table 2. Summary of findings of initial studies on use of GR in concrete

To investigate whether GR concrete could lead to improvements in thermal efficiency of low-rise dwellings, tests were carried out to measure the indicative thermal conductivity (λ_{ind}) of: (*a*) concrete containing high GR contents, (*b*) a specially optimised GR concrete, and (*c*) foamed concrete containing GR as fine aggregate.

Parameter λ_{ind} was measured using an apparatus developed at the University of Dundee (Giannakou and Jones, 2002). Three 290 mm square slabs of 50 mm thickness for each mix were sealed-cured for 28 days and then oven-dried until constant mass at 30°C. The specimens were then placed in the apparatus (comprising a refrigerating unit and hot box) with three Type K thermocouples attached to each slab surface. The upper and lower temperature limits were chosen as 30 and 10°C, respectively. Heat was allowed to flow through the specimen

		Mix constituents: kg/m^3							
					Aggregates: mm				
Mix	GR: % by volume	CEM I	Water	GR	0/4	4/10	10/20	w/c ratio
Design strength = 37 MPa								
Normal	0	330	180	0	660	410	815	0·55
Air entrained *	0	400	160	0	505	395	790	0·40
GR1	2	360	180	20	640	420	840	0·50
	4	400	180	40	515	400	795	0·45
	6	450	180	60	485	375	750	0·40
GR8	2	360	180	25	555	380	865	0·50
	4	400	180	45	545	320	845	0·45
	6	450	180	70	530	255	825	0·40
GR20	2	360	180	25	555	435	810	0·50
	4	400	180	45	545	425	740	0·45
	6	450	180	70	530	410	670	0·40
Design strength = 50 MPa								
Normal	0	400	180	0	635	395	785	0·45
GR1	4	515	180	40	480	370	745	0·35
GR8	4	515	180	45	510	290	795	0·35

*Actual measured air content = 6·4%.

Table 3. Mix proportions used in freeze–thaw investigation

until the system stabilised. On stabilisation, λ_{ind} was calculated using the Fourier heat flow equation as follows

$$\lambda_{\text{ind}} = \frac{\boldsymbol{Q}\ D}{A\ \Delta T} \tag{1}$$

where $\boldsymbol{Q}$ is the time rate of heat flow (W); D is the specimen thickness (m); A is the exposed area of specimen (m^2); and ΔT is the temperature differential between either side of the specimen (K).

The average of three (hourly) λ_{ind} values was calculated at each temperature setting and reported to the nearest 0·01 W/mK.

2.3.1. High GR contents. Tests were carried out using GR contents from 0 to 63% by volume of concrete. Both GR1 and GR8 were used. Mix proportions were based on a requirement to obtain adequate compaction at high GR volumes, with cube strength of at least 2·5 MPa. The initial mix was based on that which gave adequate performance at 44% GR content following a number of trials. The water and cement contents were then fixed at this level as GR contents were reduced (and increased).

2.3.2. Optimised GR concrete. In order to further demonstrate the potential for using GR as a thermal insulating material, a concrete was specially designed to optimise the proportions of GR to create a concrete with a low thermal conductivity and a compressive strength as high as possible using only GR as aggregate (GR content of 83% by volume of concrete). The mix proportions (Table 4) were based on the BRE mix design approach (Teychenne *et al.*, 1997) with changes made for the lower density of GR compared with sand. The proportions of fine GR required were large (75% by mass of aggregate) due to the coarser nature of GR1 compared with concreting sand. The cement content of 290 kg/m^3 was significantly lower than that used in the concretes discussed in Section 2.3.1 (500 kg/m^3); this yielded a higher w/c ratio of 0·7.

2.3.3. Foamed GR concrete. Further tests were carried out to investigate whether GR could be used in foamed concrete and provide further thermal insulation benefits. Foamed concrete is utilised in a wide range of construction projects, due to its high flowability, low self-weight, minimal consumption of primary aggregate, controlled low strength and excellent thermal insulation properties (Giannakou and Jones, 2002). As foamed concrete contains no coarse aggregate, in order to provide optimum thermal insulating properties, low fine aggregate contents (sometimes coarse fly ash) are used where possible. However, this has a resulting effect on strength and stiffness. Tests were carried out to investigate whether the replacement of fine aggregate with GR1 would enable lower indicative thermal conductivities to be achieved at similar strength levels.

Foamed concretes of plastic densities 1000, 1200 and 1400 kg/m^3 were prepared using a CEM I content of 300 kg/m^3

		Aggregate	
Water	CEM I	GR1	GR8
205	290	685	230

Table 4. Mix proportions (kg/m^3) for optimised GR concrete

and w/c ratio of 0·50. Two conventional fine aggregates were investigated: (*a*) natural sand, and (*b*) a natural sand and coarse fly ash blend. GR1 was treated as fine aggregate and was added (without pre-washing or other conditioning) to the mixer with the rest of the dry materials as a replacement of 25 or 50% by mass of total fine aggregate, which depending on target plastic density gave a range of GR contents from 12 to 43% by volume of foamed concrete.

The mix proportioning method used in the study was that developed by Dhir *et al.* (1999) in which the fine aggregate content was calculated by equating the sum of solids and water content to the target plastic density value as

$$C + W + F = D \tag{2}$$

where C is the cement content (kg/m^3), W is the water content (kg/m^3), F is the fine aggregate (sand and/or GR) content (kg/m^3) and D is the target plastic density (kg/m^3).

When coarse fly ash conforming to BS 3892-2 (BSI, 1996) was used as partial fine aggregate, it was also considered within the w/c ratio, in order to ensure there was sufficient free water available to 'wet' the large surface area of these particles (Dhir *et al.*, 1999).

3. RESULTS AND DISCUSSION

3.1. Preliminary studies

Trial mixes indicated that a w/c ratio of 0·45 provided an optimum quality GR concrete with regard to cohesion and consistence. At a w/c ratio of 0·35 the GR concrete tended to have low slump, while at the higher w/c ratios, slight segregation occurred due to GR tending to migrate through the matrix to the surface during vibration and compaction. There is an opportunity for significant potential research in this area, and it is possible that the use of filler aggregates could beneficially modify the matrix and allow the use of GR across a much wider range of concrete types. However, as a result of the limited time available in the present research, the majority of the tests were carried out at a w/c ratio of 0·45.

The main results and observations from these preliminary studies are reported in Table 2. While the tests indicated that the inclusion of GR in concrete reduced strength and stiffness, there were a number of promising aspects to the use of GR in concrete, in particular for

(*a*) increasing freeze–thaw resistance
(*b*) providing enhanced thermal insulation
(*c*) improving impact resistance.

Based on these findings, further research was carried out to understand and develop the use of GR for these applications. The result of work on freeze–thaw-resisting concrete and thermal-insulating concrete are described in this paper, while the work on impact-resisting concrete will be reported in a later paper.

3.2. Freeze–thaw resistance

The effect of GR content on the resistance of concrete to freeze–thaw scaling is shown in Figure 2. As the GR content increased, the resistance of concrete to freeze–thaw scaling also increased. When results were compared with the Swedish criteria (SIS,

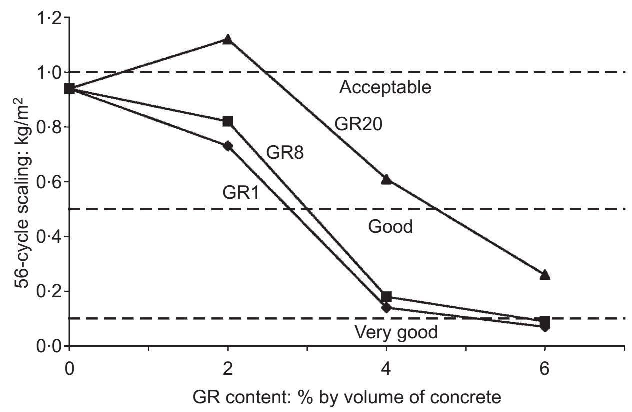

Figure 2. Effect of GR content on scaling resistance. Acceptance criteria are those given in SS 13 72 44 (SIS, 1995)

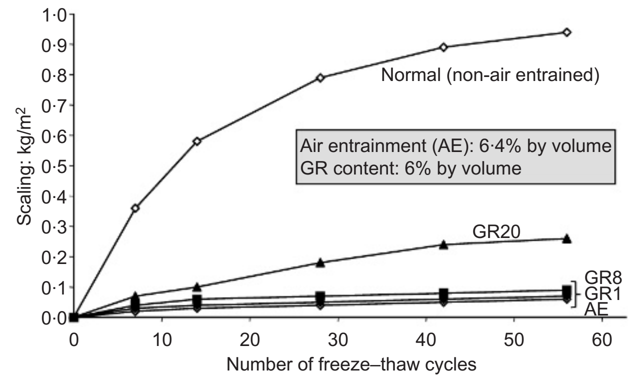

Figure 3. Comparison of cumulative scaling of non-air entrained, air entrained and GR concretes

1995), it was seen that the amount of resistance improved from *acceptable* at 0% GR to *very good* resistance at 6% GR. Resistance to freeze–thaw also increased as the GR size diminished, GR20 concretes having clearly less resistance to scaling than GR8 and GR1.

A comparison of the resistance to freeze–thaw scaling for 6% GR and 6% air-entrained concrete are shown in Figure 3, and it can be seen that the GR8 and GR1 concretes gave similar performance to that of the 6% air-entrained concrete. All three of these concretes had scaling less than 0·1 kg/m^2 after 56 cycles, corresponding to *very good* resistance in the Swedish criteria (SIS, 1995). For GR20, the amount of scaling after 56 cycles corresponded to *good* resistance ($<$ 0·5 kg/m^2).

With respect to scaling, it can be seen that it is necessary to use GR content greater than 4% to achieve improved freeze–thaw resistance when using the lower cube strength. The use of GR in concretes designed for 50 MPa improved resistance further (Table 5).

The effect of GR content on relative dynamic modulus after 294 freeze–thaw cycles is shown in Figure 4. The loss of relative dynamic modulus as a result of freeze–thaw was between 32 and 50% less than that of non-air entrained concrete, suggesting that GR provides resistance to internal disintegration. Although the resistance to deterioration for GR concrete was better than non-air entrained concrete in all cases, the greatest resistance was found at a GR content of 2% by volume, with losses in relative dynamic moduli increasing by approximately 15% for GR contents of 6% by volume. The precise reason for this is unclear, suggesting that further work may be required to fully understand the mechanism through which GR provides freeze–thaw resistance. For all GR contents investigated, the best resistance to freeze–thaw disintegration was found using the smallest GR sizes.

Figure 5 shows the loss of dynamic modulus in relation to the number of freeze–thaw cycles. The difference between GR concrete and air-entrained concrete was notably more significant than for the scaling form of freeze–thaw shown above. However, it should be noted that the resistance to freeze–thaw for all GR concretes of strength 37 MPa was better than normal concrete of strength 50 MPa, which is permitted for use in freeze–thaw conditions within BS 8500-1 (BSI, 2006). Furthermore, in the UK, conditions for most concrete will resemble that used in the scaling test in which water pools on the surface prior to freezing, rather than water completely encasing the whole element prior to freezing.

Mix	GR: % by volume	Cube strength: MPa	Flexural strength: MPa	Scaling: kg/m^2	Dynamic modulus: %
		28 days	28 days	56 cycles	294 cycles
Design strength = 37 MPa					
Normal	0	40·0	3·50	0·94	44
Air entrained	0	31·0	3·10	0·06	98
GR1	2	38·0	3·60	0·73	82
	4	31·0	2·80	0·14	77
	6	28·0	2·70	0·08	74
GR8	2	36·0	3·40	0·82	79
	4	28·0	2·70	0·18	65
	6	26·0	2·50	0·10	61
GR20	2	35·5	3·10	1·12	65
	4	27·0	2·50	0·62	60
	6	25·0	2·40	0·26	64
Design strength = 50 MPa					
Normal	0	51·0	4·00	0·34	52
GR1	4	47·5	3·90	0·06	87
GR8	4	45·0	3·70	0·08	84

Table 5. Results of CEN scaling and ASTM freeze–thaw tests

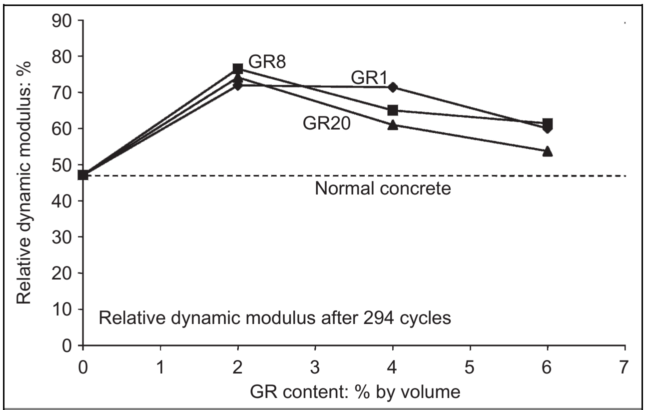

Figure 4. Effect of GR content on relative dynamic modulus after 294 cycles

3.3. Thermal insulation

The results of this work are given in Table 6, in addition to measurements of slump, density and 28-day cube strength measured in accordance with BS EN 12350-2 (BSI, 2000a), BS EN 12390-7 (BSI, 2000c) and BS EN 12390-3 (BSI, 2002a), respectively.

For clarity, the effect of GR content on indicative thermal conductivity is plotted in Figure 6. It can be seen that thermal conductivity reduces with an increase in GR content (a GR content of 63% by volume giving a thermal conductivity approximately 70% lower than that of normal concrete). The dotted line in Figure 6 shows the estimated theoretical thermal conductivity based on a classical parallel model for thermal conductivity of a multi-phase material, and includes the contributions of cement paste, GR, aggregates and air voids, where the air-voids content was approximated using a modified De Larrard particle-packing model (Jones *et al*., 2003). It can be seen that the results resemble this theoretical trend showing that the lower thermal conductivity of GR concrete can be related to the lower thermal conductivity of GR (0·50 W/mK) as compared with that of natural aggregates (2·45 to 5·20 W/mK). Results for GR contents of 13 and 19% by volume are clear anomalies, and this variability in performance may be related to fluctuations in unintentional air entrainment, since air bubbles attach themselves to GR in water, as previously mentioned.

The indicative thermal conductivity value recorded for the optimised GR concrete was found to be 0·30 W/mK. This compared favourably with most typical brick and blocks, and is at the low end for most commercially available foamed concretes (0·2 to 0·6 W/mK). Furthermore, the density of this concrete was measured as 1190 kg/m^3, which falls in the mid-range of commercially available foamed concretes (600 to 1600 kg/m^3), while the cube strength was measured as 5 MPa, which is again in the mid-range of typical foamed concretes (1 to 10 MPa), and is of similar magnitude to aircrete blocks, which are widely used in housing construction. The higher cube strength, in comparison with that of the 100% GR concrete (Table 6) was probably due to the optimum packing of the materials and lower water content, which resulted in lower voids content.

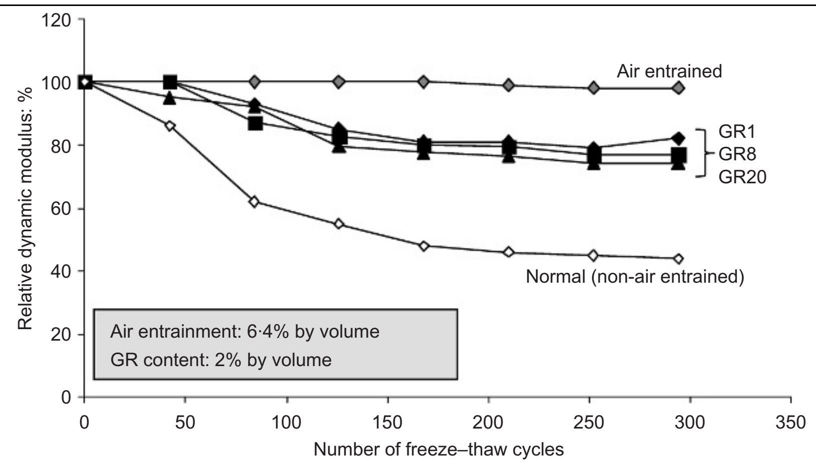

Figure 5. Change in relative dynamic modulus during freeze–thaw for non-air entrained, air entrained and GR concretes of design strength 37 MPa

GR: % by volume of concrete	Slump: mm	Density: kg/m^3	Cube strength: MPa	λ_{ind}: W/mK
0	110	2325	55·0	1·30
6	95	2215	32·0	1·02
13	80	2110	22·5	0·57
19	60	1975	13·0	0·68
25	50	1840	8·0	1·08
32	45	1760	7·0	0·83
38	40	1625	4·0	0·47
44	35	1540	3·0	0·71
50	30	1500	3·0	0·53
57	30	1425	3·0	0·45
63	20	1350	2·0	0·38

Table 6. Results of tests on indicative thermal conductivity over a range of GR contents

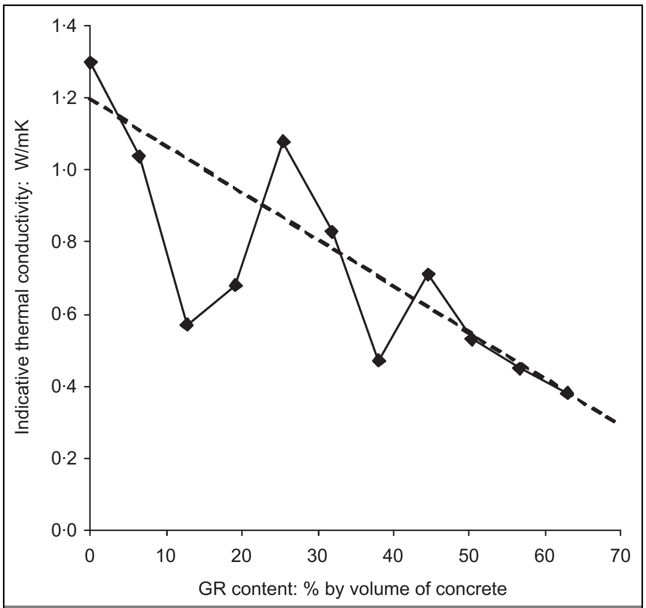

Figure 6. Relationship between GR content and indicative thermal conductivity

The 28-day compressive strengths of the foamed concrete series with GR1 are plotted in Figure 7. Overall, the replacement of fine aggregate with GR1 led to reduced compressive strengths, in line with earlier results. For both sand and sand/fly ash fine aggregate types, the strengths obtained at a density of 1000 kg/m^3 with 50% GR by mass of aggregate (20% by volume of concrete) were greater than with 25% addition of GR by mass of aggregate (12% by volume of concrete). The reverse was observed in 1200 and 1400 kg/m^3 density foamed concretes, perhaps indicating a greater benefit with high GR contents at lower densities.

The indicative thermal conductivities measured for the series of foamed concretes are plotted in Figure 8. The values ranged from 0·30 to 0·55 W/mK and, as expected, increased with density. Despite some trend inconsistencies, overall the indicative thermal conductivity of the foamed concrete specimens reduced with 25% GR content by mass (up to 30% reduction compared to conventional foamed concrete), due to its enhanced insulating capacity, compared with natural sand.

As a demonstration of the ability for GR concrete to improve the thermal efficiency of low-rise dwellings, an example calculation of U-value for a typical dwelling sitting on a 600 mm wide and 1·5 m deep foundation with a 250 mm deep ground slab (Figure 9) is given in Table 7. The U-values were calculated in accordance with BS EN ISO 13370 (BSI, 1998b) using a spreadsheet devised by the University of Dundee (Jones *et al.*, 2004).

In the first example, the floor slab and foundation were constructed using normal weight concrete (λ_{ind} = 1·25 W/mK), and a 25 mm thick Styrofoam insulation layer has been laid under the slab to provide additional insulation. The calculated U-value for this construction is 0·42 W/m^{2}K. Although this meets the regulations prior to April 2002, clearly this type of construction is no longer permitted. As a comparison, the calculation of U-value for the same construction using GR concrete (λ_{ind} = 0·30 W/mK) is also given. In this instance, the maximum U-value of 0·25 W/m^{2}K is met.

4. CONCLUSIONS

It has been shown that GR improves the performance of concrete in relation to lower density, higher impact and toughness resistance, and enhanced ductility. In particular, it was noted that there was considerable potential for use of GR to: (*a*) provide enhanced freeze–thaw resistance and (*b*) thermal insulation properties to concrete.

Detailed studies on these two promising applications lead to the following conclusions.

(*a*) With respect to scaling, use of GR at approximately 4% by volume of concrete provides good resistance to freeze–thaw attack for concrete of strength 37 MPa. This is equivalent to the performance of air-entrained concrete. Very good resistance to scaling can be achieved at higher GR contents or in higher-strength concretes.

(*b*) In mix proportioning, GR can be treated as equivalent to the same volume of air, meaning that similar w/c ratios are required to achieve a specified design strength. Although the use of GR has no consistency-improving capability, it

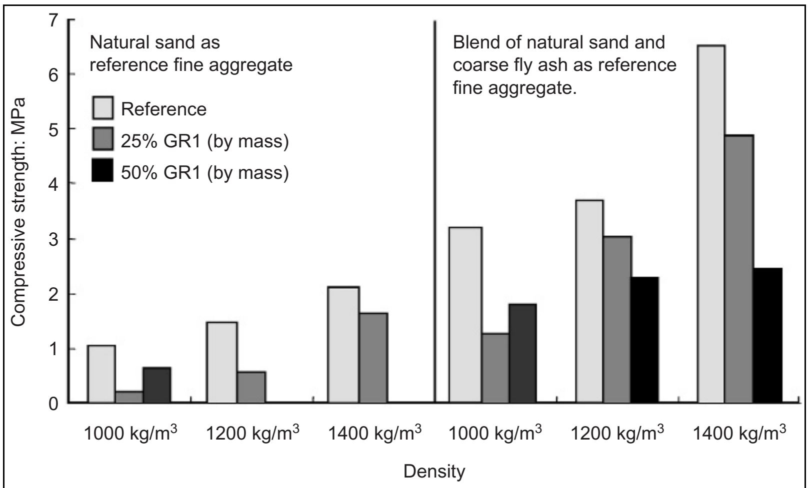

Figure 7. Effect of GR as fine aggregate on compressive strength of foamed concrete

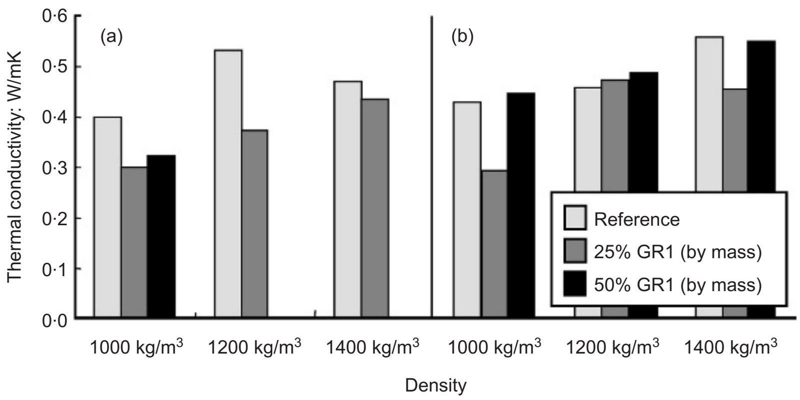

Figure 8. Effect of GR as fine aggregate on indicative thermal conductivity of foamed concrete: (a) natural sand as reference fine aggregate, (b) blend of natural sand and coarse fly ash as reference fine aggregate

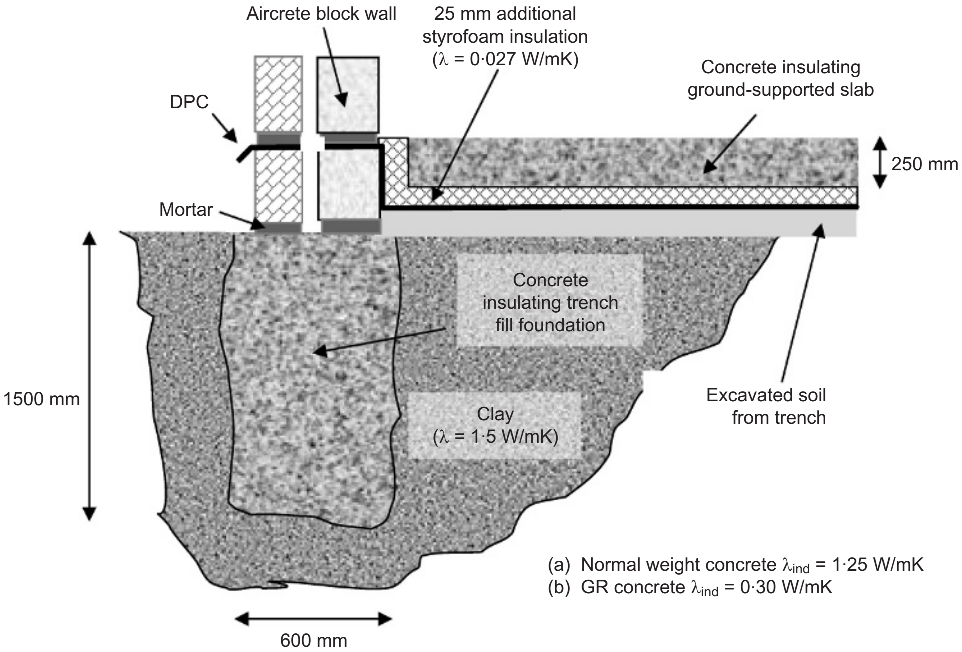

Figure 9. Section drawing of example ground slab and foundation

Values	Normal weight concrete	GR concrete
Foundation depth D: m	1·5	1·5
Foundation width d_n: m	0·6	0·6
Thermal conductivity of foundations: W/mK	1·25	0·30
Thermal resistance of foundations R_n	0·48 *	2
Slab depth d_f: m	0·25	0·25
Thermal conductivity of slab: W/mK	1·25	0·30
Thickness of slab insulation	0·025	0·025
Thermal conductivity of slab insulation	0·027	0·027
Thermal resistance of slab insulation	0·93	0·93
Thermal resistance of floor R_f	1·13	1·76
Thermal conductivity of soil: W/mk	1·5	1·5
Wall thickness w: m	0·3	0·3
Internal surface resistance R_{si}	0·15	0·15
External surface resistance R_{se}	0·04	0·04
Perimeter of dwelling: m	28	28
Area of dwelling: m^2	40	40
U-value: W/m^2K	0·42	0·25

*Note that dense concrete should normally be neglected in calculations of thermal resistance, and based on this approach a U-value of 0·47 would be calculated for conventional concrete. To achieve a U-value of 0·25 a total of 70 mm of additional styrofoam insulation would be required.

Table 7. Comparison of U-values for normal weight concrete and GR concrete used as ground slab and foundation

has the advantage of being an inert material suitable for use with all types of cement and concrete.

(*c*) Thermal conductivity reduces with an increase in GR content and this may be directly related to the lower thermal conductivity of GR in comparison with aggregate and cement. Indeed, when used at very high percentages (50 to 63% by volume of concrete) in normal concrete, or when used as partial replacement (25 to 50% by mass) of fine aggregate in foamed concrete, GR provides similar strength and thermal conductivity properties to widely and commercially used aircrete blocks.

(*d*) If used in low-rise dwellings for flooring and foundations, GR concrete can achieve a U-value of 0·25 W/m^{2}K, which meets the current building regulations, without the need for additional and complementary insulating layers.

(*e*) As a result of this research, the feasibility of exploiting the inherent impact, stability, thermal and crack resistance characteristics of GR to improve concrete performance in two specific and industrially viable areas has been developed. There is now an opportunity for industry to create GR concrete products that can be used on a commercial basis. Such an approach to the recycling of used tyres will facilitate sustainable urban development from both economic and environmental perspectives.

ACKNOWLEDGEMENTS

This work was carried out by the authors whilst at the University of Dundee, as part of a 'Partners in Innovation' collaborative research project. The authors are grateful to Dr Robert Moroney for his assistance with the experimental work; and, for funding of the project, to the Department of Trade and Industry, Aberdeenshire Council, Castle Cement Ltd, Charles Lawrence Group Ltd, DME Tyres Ltd, Environment Agency, Highways Agency, Lafarge Aggregates, Marshalls plc, Quarry Products Association, and the Used Tyre Working Group of DTI.

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