Recycled and Secondary Aggregates in Foamed Concrete

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Executive Summary

This report describes a 7 month study into the use of recycled and secondary aggregates (RSA) in foamed concrete. The project builds upon the successful outcome of a previous study (MAGCON), which identified foamed concrete as the concrete formulation with the greatest scope for reducing primary aggregate consumption, mainly due to its high air content. In addition, the MAGCON work demonstrated the ability of foamed concrete to easily incorporate two RSA materials, namely demolition arisings fines and conditioned fly ash, whilst achieving enhancements in performance.

Given this background, this study aimed to explore the full potential of RSA foamed concrete and thereby provide designers, specifiers and users of foamed concrete with a greater flexibility in the selection of RSA type. The specific objectives of the work were to assess (i) the performance of a wider range of RSA in foamed concrete both in the laboratory and on large-scale production, (ii) the market for RSA in foamed concrete in the UK, (iii) the overall environmental impact and (iv) cost-effectiveness of RSA foamed concretes, thereby leading to sustainable technologies that are readily exploitable. In addition, tentative guidance on the specification and quality control of RSA foamed concrete was developed and the findings of the study disseminated.

The laboratory investigation considered foamed concretes at 1000 and 1400 kg/m³ plastic densities with 300 and 400 kg/m³ CEM I contents, water/cement ratio of 0.50 and partial (50% by mass) or full replacement of primary fine aggregate. The primary aggregates used as a reference/benchmark were sand and quarry fines, whilst the main RSA test materials comprised incinerator bottom ash, recycled glass, rubber tyres (crumb rubber), foundry sand and china clay sand. Two additional RSA considered were glass reinforced plastics (GRP), in powder and fibre form. Overall, the performance of the RSA foamed concretes in the laboratory, in terms of consistency and cube strength development, was found to be comparable with or, in some cases better than, that of equivalent primary aggregate foamed concretes. All RSA foamed concretes were free-flowing and self-levelling with cube strengths up to 4 N/mm² at 56 days. However, further work is required to examine the effect of RSA on a wider range of RSA foamed concrete properties, including permeation, thermal and durability.

The two full- and four smaller-scale demonstration projects carried out by Propump with four different RSA materials (demolition arisings fines, incinerator bottom ash, recycled glass and crumb rubber) demonstrated the ease of production and placement of RSA foamed concretes and their free-flowing, self-levelling nature and mix stability in the fresh state. Foamed concrete with quarry fines was also produced as the reference/benchmark primary mix. These demonstration projects formed part of a seminar during which findings of the work were presented, and was attended by around 55 industry delegates.

The market analysis, carried out by the BCA, assessed the (i) the primary aggregate consumption in the UK, (ii) issues regarding the use of RSA instead of primary aggregates, (iii) the market for the use of foamed concrete in mainstream construction applications and (iv) potential primary aggregate savings by the use of RSA in foamed concrete. It revealed that there is significant scope for primary aggregate savings (up to 1,300,000 tonnes a year, which is 1.4% of the aggregate used by the concrete industry or 0.6% of the total aggregate market annually) with RSA in foamed concrete. However, in order to maximise the uptake of foamed concrete with RSA, both foamed concrete and secondary aggregates would need to be incorporated in existing National Standards/Guideline documents.

The high air content (in excess of 20% by volume) and lack of use of coarse aggregate in its matrix makes foamed concrete an environmentally friendly construction material. This reduced impact of foamed concrete on the environment (established by the BRE) can be further enhanced by the replacement of primary aggregates with RSA (preferably those with low monetary value and requiring little or no secondary processing), and the use of low CEM I contents or cement combinations.

The cost benefit assessment showed that using RSA in foamed concrete instead of primary aggregates could lead to significant cost savings. The majority of RSA materials examined in the study are currently available at prices lower than those of the primary aggregates, whilst additional savings are made by avoiding Landfill Tax, Landfill Gate fee and Aggregate Levy. In addition, there are several indirect benefits with using RSA in foamed concrete, including reduction of primary aggregate consumption, decrease in RSA sent to landfill and enhanced foamed concrete performance.

Finally, the tentative specification and quality control test framework for RSA foamed concrete was modelled on the basic methods, clauses and format of BS 8500. It gives a range of terms and definitions, considers the constituent materials (cements and combinations, recycled and secondary aggregates, admixtures and mixing water) and reviews the requirements (mix stability, consistence, plastic density, composition and concrete temperature for the fresh, and difference in values between oven-dry and target plastic densities and cube strength (where required) for the hardened foamed concrete) for the material. In addition, production control (production procedures, responsibility of the producer), transport and placement issues are also addressed. Guidance on the method for specifying RSA foamed concrete and description of the test methodology for the slump flow spread of RSA foamed concrete are also given.
Recycled and Secondary Aggregates in Foamed Concrete

1 Introduction

1.1 Background

The introduction of the Aggregate Levy in April 2002 has created a demand for means, through which, the consumption of primary aggregates by the construction industry can be reduced. In order to achieve this, the use of recycled and re-used aggregates, in addition to suitable alternative sustainable/waste materials, especially in the cases where high performance is not required, needs to be considered. More specifically, the industry has to contribute to meeting the National target of consumption of 55 million tonnes of recycled and secondary aggregates by 2006 (MPG6).

In response to this challenge, a preliminary pilot study was carried out into the development of concrete formulations (i.e. foamed, high volume fly ash and dry-pressed concretes) that would require minimal or no primary aggregate (BRE, 2004). Foamed concrete, which is currently used in a wide range of mainstream concreting applications (Van Dijk, 1991; BCA, 1994; Kearsley, 1996; Jones and Giannakou, 2004 & 2005), exhibited the greatest scope for reductions in primary aggregate concrete, mainly due to its high air content. In addition, the study demonstrated the ability of foamed concrete to easily incorporate two recycled and secondary aggregate materials, namely demolition arisings fines and conditioned fly ash, whilst achieving enhancements in performance (BRE, 2004).

However, the limited scope of the pilot study did not provide the opportunity to explore the full potential of foamed concrete in reducing the need for primary aggregates by accommodating a wider range of recycled and secondary aggregates (RSA). In order to address this issue, this study was aimed at assessing (i) the performance of a wide range of RSA in foamed concrete both in the laboratory and on large-scale production, (ii) the market for RSA in foamed concrete in the UK, (iii) the overall environmental impact and (iv) cost-effectiveness of RSA foamed concretes, thereby leading to sustainable technologies that are readily exploitable.

The project was undertaken by an experienced team with considerable experience in foamed concrete (University of Dundee and Propump Engineering Ltd), environmental assessment (Building Research Establishment), market assessment studies (British Cement Association) and dissemination. In addition, a set of industrial companies/Institutions joined the Project Team in an advisory capacity, forming a Project Steering Group. This comprised representatives from Ballast Phoenix, British Cement Association, BSI Concrete Group, Building Research Establishment, Concrete Technology Unit, Hydrock Consultants, John Doyle Construction, Propump Engineering, Quarry Products Association, Scott Wilson, Transport Research Laboratory and the United Kingdom Quality Ash Association.

1.2 Overall Aim and Objectives

This project builds upon the successful outcome of the recently completed Minimal Aggregate Concrete work (MAGCON), which identified foamed concrete as an ideal material through which fine, RSA could be used instead of primary aggregates (BRE, 2004). Whilst the MAGCON study was mainly laboratory-based, this study aimed to explore the full potential of foamed concrete in minimising the consumption of primary aggregates, by examining the use of a wide range of RSA and their influence on the environmental impact and cost of RSA foamed concrete projects.
The more specific objectives of the study are summarised below:

- Establish the properties of foamed concretes using a wide range of RSA in the laboratory
- Carry out demonstration projects in both building and infrastructure applications with RSA in foamed concrete
- Carry out a market analysis for the use of a wide range of RSA in foamed concrete
- Carry out an environmental assessment of the RSA foamed concretes studied
- Analyze the cost benefit (both direct and indirect savings) by using RSA in foamed concrete
- Disseminate findings of the work.

1.3 Programme of Work

An outline of the programme of work carried out in this study and timescale within which each Work Item was completed is given in the Gantt chart in Table 1. Initially, suitable sources of a range of RSA were identified and the materials obtained (Work Item 1). The work was then formulated as both laboratory-based (i.e. developing the use of a broad range of RSA in foamed concrete: Work Item 2) and full-scale site demonstrations (Work Item 3). In parallel, analyses of the market for RSA in foamed concrete (Work Item 4) were undertaken and environmental (Work Item 5) and cost-benefit (Work Item 6) assessments carried out. In the final stages of the work, a tentative specification for RSA foamed concretes was developed (Work Item 7) and dissemination of the project findings initiated (Work Item 8). The Work Items are described in greater detail below:

**Work Item 1: RSA material resourcing**

Sources of all RSA materials, for both the laboratory-based study and the demonstration projects (comprising incinerator bottom ash, recycled glass, crumb rubber, foundry sand, china clay sand and GRP), were identified through the WRAP information service for sustainable aggregates 'AggRegain' and the test materials were obtained.

**Work Item 2: Laboratory-based assessment of a wide range of RSA in foamed concrete**

Previous work at the Concrete Technology Unit (CTU) of the University of Dundee on foamed concrete had considered the use of pulverized-fuel ash (in dry and conditioned form) and demolition arisings fines in foamed concrete for partial or full replacement of primary sand aggregate (Dhir et al, 1999; BRE, 2004; Jones et al, 2004). However, as the availability of recycled and secondary aggregates varies significantly with geographical location, this laboratory study examined the use of a wider range of RSA products in foamed concrete, to provide designers, specifiers and users with a greater flexibility in the selection of RSA type. The RSA materials currently used in building and infrastructure applications were established through the AggRegain information service.

The main recycled and secondary aggregates selected for use in foamed concrete were as follows:

- Incinerator bottom ash
- Recycled glass
- Rubber tyres (crumb rubber)
- Foundry sand
- China clay sand.

In addition to the above, glass reinforced plastics (GRP), in powder and fibre form, were examined as additional RSA materials. All RSA test materials were selected as they were expected to be easily incorporated in foamed concrete, as a replacement for primary aggregate, due to their relatively low densities and small particle sizes, whilst additional benefits were expected from some RSA due to their potential reactivity.

The laboratory assessment of foamed concretes with the above RSA comprised characterisation of the materials and examination of the consistence and strength development of concretes with partial (50% by mass) and full replacement of primary sand or quarry fines with RSA at 1000 and 1400 kg/m³ plastic densities and 300 and 400 kg/m³ CEM I contents.

The laboratory study was led by the CTU at the University of Dundee.

**Work Item 3: Demonstration projects with RSA in foamed concrete**

Given the limited possibility of suitable (for using RSA) foamed concrete projects arising during the short duration of the project, a series of demonstration projects were planned instead. These were carefully selected to ensure that they covered typical infrastructure and building applications.
Table 1. Gantt chart of the work activities

<table>
<thead>
<tr>
<th>Work Item</th>
<th>Time, months/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>07/04</td>
</tr>
<tr>
<td>Work Item 1 – Procurement of RSA test materials</td>
<td></td>
</tr>
<tr>
<td>a. Obtain incinerator bottom ash, recycled glass, crumb rubber, foundry sand and china clay sand</td>
<td></td>
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<tr>
<td>Work Item 2 – Developing the use of a wide range of RSA in foamed concrete in the laboratory</td>
<td></td>
</tr>
<tr>
<td>a. Characterisation of RSA</td>
<td></td>
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<tr>
<td>b. Development of RSA foamed concrete mixes</td>
<td></td>
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<tr>
<td>c. Consistence measurements</td>
<td></td>
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<tr>
<td>d. Strength development</td>
<td></td>
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<tr>
<td>e. Refinement of RSA foamed concrete mixes</td>
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<tr>
<td>f. Assessment of variability through exploratory tests on one RSA type from multiple sources</td>
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</tr>
<tr>
<td>Work Item 3 – Full- and smaller-scale demonstration projects with RSA in foamed concrete</td>
<td></td>
</tr>
<tr>
<td>a. Void/trench filling/highway application demonstration projects with selected RSA</td>
<td></td>
</tr>
<tr>
<td>b. Housing low-rise construction application demonstration projects with selected RSA</td>
<td></td>
</tr>
<tr>
<td>Work Item 4 – Market analysis for RSA in foamed concrete</td>
<td></td>
</tr>
<tr>
<td>a. Identify scope of potential for foamed concrete applications</td>
<td></td>
</tr>
<tr>
<td>b. Establish effects of lack of Standards on uptake of foamed concrete</td>
<td></td>
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<tr>
<td>c. Analyze the relative distances between sources of RSA materials and projects</td>
<td></td>
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<tr>
<td>Work Item 5 – Environmental assessment of RSA foamed concrete</td>
<td></td>
</tr>
<tr>
<td>a. Impact on climate change, fossil fuel depletion and minerals extraction</td>
<td></td>
</tr>
<tr>
<td>b. Ecopoint scores</td>
<td></td>
</tr>
<tr>
<td>Work Item 6 – Cost benefit assessment of using RSA in foamed concrete demonstration projects</td>
<td></td>
</tr>
<tr>
<td>a. Construction cost</td>
<td></td>
</tr>
<tr>
<td>b. Direct savings</td>
<td></td>
</tr>
<tr>
<td>c. Indirect savings</td>
<td></td>
</tr>
<tr>
<td>Work Item 7 – Tentative specification</td>
<td></td>
</tr>
<tr>
<td>a. Quality control test framework</td>
<td></td>
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<tr>
<td>b. Guidance on the specification of RSA foamed concrete</td>
<td></td>
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<tr>
<td>Work Item 8 – Dissemination</td>
<td></td>
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<tr>
<td>a. Demonstration seminars</td>
<td></td>
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<tr>
<td>b. Journal publications</td>
<td></td>
</tr>
<tr>
<td>c. BRE IP and/or Concrete Society Digest</td>
<td></td>
</tr>
<tr>
<td>d. Web-based publicity on AggRegain website</td>
<td></td>
</tr>
<tr>
<td>e. Study report</td>
<td></td>
</tr>
</tbody>
</table>
The majority of RSA types considered in the laboratory study were used in the demonstration projects. The performance of the RSA foamed concretes produced was examined both in-situ and on specimens prepared alongside the pours.

The in-situ production of the various RSA foamed concretes on the large-scale applications was carried out as a demonstration seminar (deminar), which formed part of the dissemination process. The demonstration projects were carried out with input from Propump Engineering Ltd, the CTU and the BRE.

In addition to the demonstration projects, a search was carried out to identify the existence of any foamed concrete case studies, where a form of recycled or secondary aggregates had been used.

**Work Item 4: Market analysis for use of RSA in foamed concrete**

The market analysis assessed the opportunity for the introduction of these new technologies in the UK. More specifically, the study considered the scope of potential for use of foamed concrete in mainstream construction applications. In addition, the effect of lack of standards (covering foamed concrete production, quality control and specification) in the uptake of foamed concrete in the building and infrastructure market will be examined. The study also examined any potential impediments to the adoption of RSA by the construction market (e.g. availability across the UK).

The market analysis was carried out by the British Cement Association (BCA) and a report prepared.

**Work Item 5: Environmental assessment of the RSA foamed concretes**

An environmental assessment on the introduction of RSA as a replacement for primary aggregate replacement in foamed concrete was carried out. This considered the impact of the new RSA foamed concrete technologies from mineral extraction and manufacture, through to installation on site, following the ‘cradle to site’ approach. The study quantified the overall effect in terms of climate change (e.g. greenhouse gas emissions from the use of fossil fuels and from electricity produced with these), fossil fuel depletion (e.g. use of coal, oil, natural gas), minerals extraction (e.g. quarrying resulting in noise, dust, landscape disturbance and biodiversity degradation) and other environmental issues. The collective consideration of these issues (adopting weighting factors) was then used to calculate the corresponding Ecopoints (single score, measure of environmental impact) for each foamed concrete with RSA examined.

The scope of evaluation comprised a range of RSA foamed concretes considered in the laboratory study and those used in the small-scale trials.

The environmental assessment was carried out by the BRE and a report prepared.

**Work Item 6: Cost benefit analysis of RSA in foamed concrete**

In addition to minimising primary aggregate consumption, the use of RSA in foamed concrete was expected to have significant cost benefits. These were examined in a cost comparison desk study of the RSA foamed concretes produced in the demonstration projects.

The overall construction cost of the RSA foamed concrete applications was evaluated and comparisons made with corresponding costs of equivalent foamed concretes with primary sand aggregate or other materials used in the same application. Areas where potential cost savings could be obtained, both by direct (e.g. reduced cost of RSA aggregates) and indirect (e.g. avoiding Landfill Tax, waste management charges and fee for transport of aggregate from a quarry to the plant) means, were identified.

The cost benefit analysis of the RSA foamed concretes used in the demonstration projects was carried out by the CTU and a report prepared.

**Work Item 7: Tentative specification for RSA foamed concrete**

Although a Highways Agency and TRL Application Guide exists (with contribution from the University of Dundee), this does not consider the use of RSA in foamed concrete and focuses on a specific end use (i.e. backfill). This, coupled with the limited research into foamed concrete, lack of coverage of the material within existing concrete standards and lack of experience of designers, specifiers and users with it, has led to the need for the development of a guidance document for RSA foamed concrete.

The knowledge obtained from the laboratory study and demonstration projects was used to compile a tentative specification, which aimed to familiarise designers, specifiers and users with RSA foamed concrete. This built upon standards linked with BS 8500, considering the different aggregate types, and provides (i) a quality control test framework for the use of RSA in foamed concrete and (ii) guidance on the specification of RSA foamed concretes.
Work Item 8: Dissemination

The dissemination process, which was initiated during the study, comprises (in addition to the demonstration seminars already carried out and completion of this study report) preparation of journal publications and a BRE Information Paper and/or Concrete Society Digest or Practice Sheet, in addition to web-based publicity. These are discussed in greater detail below.

- Demonstration seminars (deminars): The demonstration projects carried out, which were in the form of deminars, are a significant part of the dissemination process, as they give the opportunity to designers, specifiers and users to observe foamed concrete production and performance in the fresh state in two different applications. In addition, the ease of incorporating various RSA materials in foamed concrete was demonstrated.

- Study report: Following completion of Work Items 1-7, this study report was prepared. It provides a summary of the project findings and identifies areas, where further research into the use of RSA in foamed concrete is required.

- Journal publications: A number of journal publications are planned. These will cover (i) the observations of the laboratory study considering the performance of a wide range of RSA in foamed concrete, (ii) an overview of the demonstration projects and corresponding cost benefit analysis and (iii) a market and environmental assessment of RSA foamed concretes. Preparation of the publications will commence after completion of the study.

- BRE Information Paper and/or Concrete Society Technology Digest or Practice Sheet: In addition to the journal publications, a BRE Information Paper and/or Concrete Society Technology Digest or Practice Sheet will be prepared, since these are known to communicate with and have an impact on the industry and clients. These will provide an overview of the study into the use of RSA in foamed concrete, in order to minimise aggregate consumption and summarize the range of activities carried out in the project and the main observations made.

- Web-based publicity: The demonstration projects with RSA foamed concrete carried out during the study will be posted on the AggRegain website, alongside all other case studies with RSA in construction applications.

2 Use of RSA in Foamed Concrete in the Laboratory

2.1 Test Materials

In the laboratory study, sand conforming to BS EN 12620 and quarry fines were used as reference (benchmark) primary fine aggregates. The main recycled and secondary aggregates (RSA) selected for testing in the laboratory-based study were incinerator bottom ash (IBA; by-product of waste incineration), recycled glass (building flat glass), crumb rubber (from shredded truck tyres), foundry sand (used as a moulding material in the metal casting industry) and china clay sand (by-product of china clay production). In addition to the above, glass reinforced plastic (GRP) grindings (in powder and fibre form, by-products of GRP roofing and rooflights manufacture) were used in selected mixes. All test materials (summarised below) were obtained from sources across the UK.

<table>
<thead>
<tr>
<th>Primary Aggregates</th>
<th>Main RSA</th>
<th>Additional RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Incinerator bottom ash (IBA)</td>
<td>GRP powder</td>
</tr>
<tr>
<td>Quarry fines</td>
<td>Recycled glass</td>
<td>GRP fibres</td>
</tr>
<tr>
<td></td>
<td>Crumb rubber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foundry sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>China clay sand</td>
<td></td>
</tr>
</tbody>
</table>

The visual appearance of the primary aggregates, main and additional RSA test materials, at a (i) macroscopic and (ii) microscopic level, can be seen in Figures 1a and 1b respectively.

Following characterisation of all test materials, the foamed concrete mixes with RSA were developed and consistence and cube strength development measurements carried out.
Primary aggregates
Figure 1a: Macroscopic visual appearance of the primary and different recycled and secondary aggregates

- Sand
- Quarry fines

Main recycled and secondary aggregates

- Incinerator bottom ash
- Recycled glass
- Crumb rubber
- Foundry sand
- China clay sand

Additional recycled and secondary aggregates

- GRP powder grindings
- GRP fibre grindings
Primary aggregates

- Sand
- Quarry fines

Main recycled and secondary aggregates

- Incinerator bottom ash
- Recycled glass
- Crumb rubber
- Foundry sand
- China clay sand

Additional recycled and secondary aggregates

- GRP powder grindings
- GRP fibre grindings

Figure 1b  Microscopic appearance of the primary and different recycled and secondary aggregates considered (the distance between each line on the scale is 1mm)
2.2 Characterisation of RSA

The RSA test materials were characterised in terms of their particle size distribution, physical and chemical properties. The results are summarised in Sections 2.2.1 to 2.2.3 below.

2.2.1 Particle size distribution

The particle size distribution of the sand, quarry fines and the different RSA types was determined in accordance with BS EN 933-1. These are compared with the grading limits of BS EN 12620 for category G785 aggregates in Figure 2.

Figure 2 Particle size distribution of primary (sand and quarry fines) and recycled and secondary aggregates

As can be seen, the primary aggregates (sand and quarry fines), china clay sand and foundry sand all exhibited similar particle size distribution, with between 90% and 96% of the sample’s particles smaller than 4mm in size. The particle size distribution of these aggregates was within the grading limits for fine aggregate given in BS EN 12620. The recycled glass was the coarsest RSA examined, whilst the incinerator bottom ash and crumb rubber were coarser than the BS EN 12620 upper limits for particles greater than 0.6mm and smaller than 0.5mm respectively. The GRP fibres were up to 15mm in length, whilst the GRP powder particles were less than 300µm and included some fibres (52mm length and 0.04mm diameter).

2.2.2 Physical properties

The typical physical properties of all RSA materials examined are compared with those of sand in Table 2. The apparent particle densities of all fine aggregate types ranged between 2265 and 2795 kg/m³, with the exception of crumb rubber, which exhibited a density of 1075 kg/m³. The water absorption value of the glass was minimal (0.01%) and that of IBA was the highest at 8.5%, whilst the values of the remaining test materials were around 0.5%.
2.2.3 Chemical properties

The chemical composition of the primary aggregates and different RSA examined are summarised in Tables 2 and 3, while additional chemical properties of crumb rubber are given in Table 4.

### Table 2 Chemical composition and physical properties of sand and RSA

<table>
<thead>
<tr>
<th>Chemical composition, %</th>
<th>Primary Aggreg.</th>
<th>Recycled and Secondary Aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>SiO₂</td>
<td>78.5</td>
<td>73.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>MgO</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>MnO</td>
<td>-</td>
<td>0.07</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Cl</td>
<td>&lt; 0.01</td>
<td>-</td>
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</tbody>
</table>

-: not detected

### Table 3 Composition of crumb rubber (Document CR/10a, 2001)

<table>
<thead>
<tr>
<th>Content, % wt</th>
<th>Crumb Rubber</th>
<th>ASTM D 5603 Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>6.8</td>
<td>8</td>
</tr>
<tr>
<td>Fibres</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>Free Fibres</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Iron</td>
<td>0.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Table 4 Chemical properties of crumb rubber (Document CR/10a, 2001)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Crumb Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-Soluble Chlorides, % wt</td>
<td>0.00</td>
</tr>
<tr>
<td>Water-Soluble Sulfates, g/l</td>
<td>0.10</td>
</tr>
<tr>
<td>Water-Soluble Bromides, % wt</td>
<td>0.01</td>
</tr>
<tr>
<td>Loss on Ignition (LOI), % wt</td>
<td>93.0</td>
</tr>
</tbody>
</table>

As can be seen in Table 3, the ash content in the crumb rubber sample, remaining after ignition for one hour at 550°C, was under the maximum permissible of 8%. However, the CR contained large amounts of fibrous material, probably due to the additional shredding and separation of the fibres and subsequently this did not meet the ASTM limits. In addition, the magnetic removal of iron during processing meant that no iron was found. As regards crumb grades, this was classified as ‘Rubber/Fluff Grade 3’ (Document CR/10a, 2001).
The water-soluble chloride, sulfate and bromide contents of CR (measured in accordance with BS 812-117 and BS 812-118) given in Table 4 were very low, while the loss-on-ignition (LOI) is consistent with the ash content recorded in Table 3.

### 2.3 Experimental Details of Laboratory Investigation

The experimental programme, mix proportions, foam generation, preparation of RSA foamed concrete specimens and test procedures are described in Sections 2.3.1 to 2.3.5 below.

#### 2.3.1 Experimental programme

The laboratory investigation of RSA foamed concretes considered 50% and 100% by weight replacement of primary sand with RSA in mixes of 1000 kg/m³ plastic density and 400 kg/m³ CEM I content. In addition, total replacement of sand with RSA were examined on 300 kg/m³ CEM I mixes at 1000 kg/m³ plastic density and on 400 kg/m³ CEM I concretes at 1400 kg/m³ plastic density.

A schematic illustration of the partial and total replacement of sand with RSA in foamed concrete mixes is given in Figure 3 (Note: as the replacement of primary with RSA was carried out by wt, minor adjustments were made to the volume of air in each mix to reflect slight changes in the volume of aggregate).

All fine aggregates were dried in laboratory air prior to their use in foamed concrete. The RSA foamed concretes were tested for consistence (slump flow spread and flow time) and 100mm sealed-cured cube strengths at 1, 3, 7, 28 and 56 days.

#### 2.3.2 Mix proportions

The mix proportioning method used in the study was that developed at the University of Dundee (Dhir et al, 1999; Giannakou and Jones, 2002) and described below. For a given cement content and water/cement (w/c) ratio, the fine aggregate (sand and/or RSA) content is calculated by equating the sum of solids and water content to the target plastic density value.

\[
C + W + F = D, \quad \text{Equation 1}
\]

where

- \( C \) = cement content, kg/m³
- \( W \) = water content, kg/m³
- \( F \) = fine aggregate (sand and/or RSA) content, kg/m³
- \( D \) = target plastic density, kg/m³

Adjustments are then made to the sand/RSA and water contents (as with normal weight concrete) to take account of their water absorption and laboratory air dry (not SSD) condition.

The level of water contained in foam is minimal and, therefore, not considered in the calculations. Although it is recognised that foam collapse occurs during mixing, hence the actual w/c ratio of the mix is slightly higher than the...
batched quantity, the degree of collapse varies with mix constituents and can’t be predicted in advance and is therefore ignored in mix proportioning (Dhir et al, 1999).

In order to establish the theoretical foam quantity required to achieve the target plastic density, the volume of air in the mix is calculated by considering a unit volume, as shown below:

\[ V_{\text{cem.}} + V_{\text{water}} + V_{\text{fine agg.}} + V_{\text{foam}} = 1 \text{m}^3 \]
\[ \Rightarrow V_{\text{foam}} = \ldots \text{m}^3 \]
\[ \Rightarrow M_{\text{foam}} = V_{\text{foam}} \cdot d_{\text{foam}} \]

Equation 2

where \(V = \) quantity / particle density of each material, m³
\(M_{\text{foam}} = \) quantity of foam, kg
\(d_{\text{foam}} = \) density of foam, kg/m³

The w/c ratio for the foamed concretes was maintained at 0.50 as a basis of comparison and because it provided sufficient consistence for the majority of mixes within the range of densities and constituent materials considered.

The mix proportions of the RSA foamed concrete mixes examined in the study are given in Table 5.

<table>
<thead>
<tr>
<th>Fine Aggr. Type</th>
<th>Target Plastic Density, kg/m³</th>
<th>Mix Constituent Proportions, kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CEM I</td>
<td>Sand</td>
</tr>
<tr>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>400</td>
</tr>
<tr>
<td>Quarry fines</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>400</td>
</tr>
<tr>
<td>b) Recycled and secondary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBA</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>400</td>
</tr>
<tr>
<td>Glass</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>400</td>
</tr>
<tr>
<td>Crumb rubber</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>Foundry sand</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>China clay sand</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>GRP powder</td>
<td>1000</td>
<td>400</td>
</tr>
<tr>
<td>GRP fibres</td>
<td>1000</td>
<td>400</td>
</tr>
</tbody>
</table>

1 quarry fines were used as an alternative (to sand) primary fine aggregate
2.3.3 Foam generation

The concentration of the surfactant solution used for the production of foam was typically 60g per litre of water, which represents the critical micelle concentration of the synthetic type agent used in this study. A schematic illustration of the foam generator used can be seen in Figure 4.

The pump is powered by compressed air. The compressed air is directed to the pump air chamber with the main air valve, while the surfactant solution is drawn by the pump into the fluid chamber. The two chambers are separated by a diaphragm/membrane. The pressure of the diaphragm on the fluid, forces it out of the pump discharge, where it is combined with the compressed air. The combination of solution and air is then forced through restrictions (e.g. scouring pads) in the foam lance, where it expands and foam is created to the required density.

![Figure 4 Schematic illustration of the foam generator and production of foam (courtesy of Propump)](image)

In this study, the pressure gauge of the foam generator was set at 50 psi, which reduced (due to losses) to 40 psi during operation, as this was known to achieve the lowest foam density for a range of solution concentrations (Jones, 2000). The amount of air and solution entering the foam lance was adjusted until the foam density achieved was 50±5 kg/m³, as this exhibited the greatest stability, before addition to the base mix. This was established by measuring the weight of a foam sample (to the nearest 0.1g) in a tall container of a known volume (to the nearest 1.0 ml).

2.3.4 Preparation of specimens

Preparation of forms
As a chemical interaction takes place between the mould oil and the pre-formed foam, causing a soft layer to form on the surface of the specimens, the steel moulds used in the laboratory study were wrapped with cling film, in which the foamed concrete was placed.

Mixing
Foamed concrete production in the laboratory was carried out in a rotary drum (free-falling action) mixer, which is more suitable for incorporating foam in the base mix than a typical horizontal force action pan mixer (Sach and Seifert, 1999). This was modified in order to simulate the action of a ready-mix truck, by tilting the drum at an angle of 15° from the horizontal level and introducing a variable voltage transformer to enable reduction of mixing speed to between 12 and 13 revolutions per minute, which is typical of a ready-mix truck (Wilson, 1999).

As there doesn't exist a standard for foamed concrete preparation, the mixing was carried out following the sequence described by Kearsley (1996). The dry materials, i.e. cement and fine aggregate, were combined in the mixer for half a minute. The total quantity of water was then added (along with the superplasticising admixture, where used) and mixed with the dry materials for four minutes, or until a homogeneous mortar or grout with no lumps of undispersed cement was obtained.

The pre-formed foam was then produced by the foam generator and the approximate quantity (calculated by the mix proportions) added to the mix, immediately after preparation. This was combined with the mortar or grout for at least 2 minutes, until all foam was uniformly distributed and incorporated in the mix. The plastic density of the mix is then measured and values within ±50 kg/m³ accepted. If the density was higher, additional foam is prepared and added incrementally until the target value is achieved, followed by further mixing. Mixes with densities lower than the range of acceptable values were rejected and repeated.
Following measurements of consistence (slump flow and flow time), sampling of foamed concrete was carried out in accordance with BS EN 12350-1. The concrete was poured into the moulds (wrapped with cling film) but no compaction was provided, as this would cause collapse of the pre-formed foam, and was finished by float.

Curing
Following placement of concrete in the moulds, the exposed surface of the specimens was covered with cling film to prevent moisture evaporation, and demoulding carried out 24 hours after production. The foamed concrete specimens were cast in cling film and sealed-cured at 20°C until testing.

2.3.5 Test procedures

Consistence
The consistence of RSA foamed concrete was assessed in terms of slump flow spread and efflux time from a modified Marsh cone.

The slump flow test, described in Annex B of Appendix C, is effectively the measurement of the diameter of a sample after a collapse slump has been obtained (Domone, 1998). The slump flow values are thought to reflect trends of yield stress in concrete (Tattersall, 1991; Marrs and Bartos, 1996).

The flow time of 1.0l of sample from a 1.5l capacity modified Marsh cone with an orifice diameter of 12.5mm was also measured. This is thought to reflect the plastic viscosity of cementitious materials (Marrs and Bartos, 1996; Murata and Suzuki, 1997).

Cube strength development
Strength was measured in accordance with BS EN 12390-3 on 100mm cube sealed-cured (S-C) specimens. The cube strengths were measured following 1, 3, 7, 28 and 56 days curing and two specimens were tested at each age.

2.4 Consistence Measurements

The consistence measurements (see Section 2.3.5 and Annex B of Appendix C) obtained on the RSA foamed concretes are summarised in Table 6, whilst the performance of primary and RSA foamed concretes is compared in Figures 5 to 7.

As can be seen, the majority of RSA foamed concrete mixes (1000 and 1400 kg/m³ plastic density, with 300 and 400 kg/m³ cement content) were self-flowing, with slump flow spreads between 340mm and 720mm. More specifically, with the exception of the IBA and china clay sand mixes, the slump flow spreads of the 1000 kg/m³ plastic density and 400 kg/m³ cement content foamed concretes with 50% replacement of sand with RSA were greater than that of the mixes with 100% RSA. The foamed concretes with crumb rubber exhibited smaller flow spreads than both the sand and quarry fines primary aggregate mixes. This can be attributed to the more lightweight crumb rubber particles, compared to the 2.5 times heavier sand. The reduction in consistence of the GRP mixes (though still free-flowing) is due to the very fine particle size (greater surface area, higher water demand) of the powder, whilst the addition of fibres is generally known to have an adverse effect on workability. The consistence of the RSA foamed concretes with 300 kg/m³ CEM I was broadly similar to that of the 400 kg/m³ content mixes. Finally, the 1400 kg/m³ RSA foamed concretes exhibited smaller spreads than the 1000 kg/m³ plastic density mixes.

No flow was observed from the modified Marsh cone from the majority of RSA foamed concretes due to the increased plastic viscosity of the mixes and, in some cases, RSA particle sizes greater than sand (glass, IBA).

2.5 Cube Strength Development

The cube strengths of 100mm sealed-cured (S-C) cube specimens measured at 1, 3, 7, 28 and 56 days on the RSA foamed concretes are summarised in Table 7, whilst the 28 day strengths of primary and RSA foamed concretes are compared in Figures 8 to 10.

The RSA foamed concretes exhibited ultimate (56 day) cube strengths between 0.4 and 3.9 N/mm². In general, the RSA concrete strengths were between the values obtained on the two primary aggregate foamed concretes (i.e. containing sand and quarry fines) throughout the test period. At 1000 kg/m³ density with 300 and 400 kg/m³ CEM I contents, the strengths of the foamed concrete mixes with IBA and glass exceeded those of the sand mixes. As expected, the strengths of 1400 kg/m³ density primary and RSA...
## Table 6  Consistence measurements of RSA foamed concretes

<table>
<thead>
<tr>
<th>Target Plastic Density, kg/m³</th>
<th>CEM I Content, kg/m³</th>
<th>Fine Aggregate Type¹</th>
<th>Slump Flow, mm</th>
<th>Flow Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>400</td>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td>650</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/Quarry fines</td>
<td>670</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quarry fines</td>
<td>795</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Primary aggregate/RSA combination</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/IBA</td>
<td>695</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBA</td>
<td>720</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/Glass</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glass</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/Crumb rubber</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crumb rubber</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/Foundry sand</td>
<td>650</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foundry sand</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/China clay sand</td>
<td>660</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>China clay sand</td>
<td>685</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/GRP powder</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand/GRP fibres³</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td>715</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quarry fines</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Recycled and secondary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBA</td>
<td>640</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glass</td>
<td>670</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foundry sand</td>
<td>545</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>China clay sand</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td>1400</td>
<td>400</td>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td>625</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quarry fines</td>
<td>495</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Recycled and secondary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBA</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glass</td>
<td>645</td>
<td></td>
</tr>
</tbody>
</table>

¹ Primary aggregate/RSA combinations are either 100% or 50%/50% unless specified otherwise
² Insufficient efflux
³ 75% sand/25% GRP fibres
Figure 5  Influence of RSA on slump flow of 1000 kg/m³ concretes with 400 kg/m³ CEM I

Figure 6  Influence of RSA on slump flow of 1000 kg/m³ concretes with 300 kg/m³ CEM I

Figure 7  Influence of RSA on slump flow of 1400 kg/m³ concretes with 400 kg/m³ CEM I
<table>
<thead>
<tr>
<th>Target Pl. Density, kg/m³</th>
<th>CEM I Content, kg/m³</th>
<th>Fine Aggregate Type</th>
<th>100mm Sealed-Cured Cube Strength, N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>0.8 ±²</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Sand/Quarry fines</td>
<td>0.1 ±²</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Quarry fines</td>
<td>0.2 ±²</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>b) Primary aggregate/RSA combination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand/IBA</td>
<td>0.6 ±²</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>IBA</td>
<td>0.6 ±²</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Sand/Glass</td>
<td>0.7 ±²</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Glass</td>
<td>0.7 ±²</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Sand/Crumb rubber</td>
<td>0.4 ±²</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Crumb rubber</td>
<td>±²</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Sand/Foundry sand</td>
<td>0.1 ±²</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Foundry sand</td>
<td>0.3 ±²</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Sand/China clay sand</td>
<td>0.2 ±²</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>China clay sand</td>
<td>0.1 ±²</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Sand/GRP powder</td>
<td>0.9 ±³</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Sand/GRP fibres</td>
<td>0.9 ±³</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1000</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Primary aggregates</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>0.2 ±²</td>
</tr>
<tr>
<td>Quarry fines</td>
<td>&lt;0.1 ±²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1000</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>b) Recycled and secondary aggregates</td>
<td></td>
</tr>
<tr>
<td>IBA</td>
<td>±²</td>
</tr>
<tr>
<td>Glass</td>
<td>±²</td>
</tr>
<tr>
<td>Foundry sand</td>
<td>±²</td>
</tr>
<tr>
<td>China clay sand</td>
<td>±²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1400</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Primary aggregates</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>±²</td>
</tr>
<tr>
<td>Quarry fines</td>
<td>±²</td>
</tr>
</tbody>
</table>

| b) Recycled and secondary aggregates | |
| IBA  | ±²   | 1.0 | 3.0 | 3.8 | 3.9 |
| Glass| ±²   | 1.6 | 2.1 | 2.2 | 2.3 |

1 Primary aggregate/RSA combinations are either 100% or 50%/50% unless specified otherwise
2 Data not available
3 75% sand/25% GRP fibres
Recycled and Secondary Aggregates in Foamed Concrete

Figure 8  Influence of RSA on strength of 1000 kg/m³ concretes with 400 kg/m³ CEM I

Figure 9  Influence of RSA on strength of 1000 kg/m³ concretes with 300 kg/m³ CEM I

Figure 10  Influence of RSA on strength of 1400 kg/m³ concretes with 400 kg/m³ CEM I
foamed concretes were greater than those at 1000 kg/m³ throughout testing. There were no significant increases in strength after 28 days. Overall, the majority of RSA mixes gave either comparable or greater strengths to the foamed concrete mixes made with primary aggregates.

Whilst the composition of the primary aggregate and RSA foamed concretes was kept constant (fixed CEM I content and w/c ratio at a given density) for comparison purposes, further mix optimisation of each RSA foamed concrete individually would result in greater strength development and foamed concrete performance in terms of engineering properties, permeation and durability.

### 2.6 Refinement of RSA Foamed Concrete

In terms of refinement of foamed concrete mixes, adjustments were made to the following:

- **crumb rubber content in the mixes**: due to the very low density of crumb rubber, no preformed foam was required to achieve the target plastic density at 1400 kg/m³ density or at 1000 kg/m³ density with 300 kg/m³ CEM I content. As a result, these mixes were not carried out.
- **w/c ratio of the GRP powder mix**: this was increased from 0.50 to 0.60 to enhance mix consistence.
- **% addition of GRP fibres**: this was reduced to 25% of the total fine aggregate, to prevent adverse effects on mix consistence.

### 2.7 Repeatability of Foamed Concrete with Demolition Fines

The repeatability of RSA foamed concrete was examined on a 1000 kg/m³ density mix with a w/c ratio of 0.50, 300 kg/m³ CEM I content and 100% demolition fines (DF) as fine aggregate. Demolition fines were selected as the test RSA material because of the volume of the material available. The mix was designed assuming the average of all DF particle densities (2482 kg/m³) and water absorptions (8.85%) throughout. The demolition fines were obtained from 10 different sources from around the UK. Repeatability of the ten DF foamed concretes produced was examined in terms of (i) plastic density achieved following the addition of a given quantity of foam to the base mix and (ii) foamed concrete mix consistence.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Appar. Particle Density, kg/m³</th>
<th>Water Absorption, %</th>
<th>Plastic Density, kg/m³</th>
<th>Slump Flow, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF 1</td>
<td>2300</td>
<td>10.4</td>
<td>1145</td>
<td>490</td>
</tr>
<tr>
<td>DF 2</td>
<td>2535</td>
<td>8.1</td>
<td>1035</td>
<td>500</td>
</tr>
<tr>
<td>DF 3</td>
<td>2515</td>
<td>8.3</td>
<td>1130</td>
<td>500</td>
</tr>
<tr>
<td>DF 4</td>
<td>2500</td>
<td>8.5</td>
<td>1210</td>
<td>500</td>
</tr>
<tr>
<td>DF 5</td>
<td>2660</td>
<td>9.2</td>
<td>1300</td>
<td>490</td>
</tr>
<tr>
<td>DF 6</td>
<td>2310</td>
<td>8.5</td>
<td>1225</td>
<td>500</td>
</tr>
<tr>
<td>DF 7</td>
<td>2485</td>
<td>8.7</td>
<td>1035</td>
<td>500</td>
</tr>
<tr>
<td>DF 8</td>
<td>2410</td>
<td>8.0</td>
<td>1225</td>
<td>500</td>
</tr>
<tr>
<td>DF 9</td>
<td>2680</td>
<td>8.2</td>
<td>1050</td>
<td>500</td>
</tr>
<tr>
<td>DF 10</td>
<td>2425</td>
<td>10.6</td>
<td>1020</td>
<td>470</td>
</tr>
</tbody>
</table>

Mean 2482 8.85 1138 497
Range 2300-2680 8.0-10.6 1020-1300 470-520
SD 127.5 0.935 99.8 12.5
CV, % 5.1 10.6 8.8 2.5

As can be seen in Table 8, the 10 demolition materials had significantly different particle densities (between 2300 and 2680 kg/m³) and water absorption rates (8.0% to 10.6%). As a result, the plastic densities achieved following the addition of a given quantity of foam to the base mix varied considerably (between 1020 and 1300 kg/m³). However, once the target plastic density of 1000 kg/m³ was met by all DF foamed concretes (with the addition of further quantities of foam), the consistence of these mixes was very similar, with slump flow spreads within 50mm measured, and the performance of DF foamed concretes in the fresh state was generally repeatable. However, it must be noted that, in reality, production control would have
been better as the mixes would have been designed using the particle density and water absorption of the individual DF samples.

2.8 Summary of Findings of Laboratory Study

Overall, the laboratory study has shown that the partial (50%) or full (100%) replacement of natural primary aggregates (sand and quarry fines) with a total of seven different RSA materials (incinerator bottom ash, recycled glass, crumb rubber, foundry sand, china clay sand, GRP fibres and GRP powder) had little effect on foamed concrete properties.

More specifically, in terms of consistence, all RSA foamed concretes (1000 and 1400 kg/m³ plastic density, with 300 and 400 kg/m³ CEM I content) were self-flowing mixes, with slump flow spreads between 340mm and 720mm. Similarly, the strengths of all RSA foamed concretes ranged between those of the two primary aggregate mixes (sand and quarry fines) throughout the test period, with values up to 4.0 N/mm² noted after 56 days sealed-curing. In addition, the foamed concretes with 100% IBA and 100% glass exhibited strengths greater than the equivalent sand mixes. Finally, the repeatability of foamed concrete made with demolition fines obtained from ten sources was generally good, with slump flow spreads within 50mm.

3 Full- and Smaller-Scale Demonstration Projects with RSA in Foamed Concrete

3.1 Introduction

Given that the likelihood of foamed concrete projects using RSA during the short duration of the study was limited, specific end-user focussed case studies were created in the form of full- and smaller-scale site demonstration projects. The range of RSA materials used, types of demonstration projects, production and placement methods of RSA foamed concrete in-situ, concrete assessment and the possibility of a RSA foamed concrete case study in the future are discussed in Sections 3.2 to 3.6 below.

3.2 RSA Material Selection

In total, 4 different types of RSA were used to produce foamed concrete during the full- and smaller-scale demonstration projects. The RSA materials selected for the demonstrations comprised demolition arisings fines, incinerator bottom ash, granulated (crumb) rubber and recycled glass. In addition, foamed concrete with quarry fines was also produced, to provide a ‘benchmark’ foamed concrete with primary aggregate.

3.3 Range of Demonstration Projects

Two full-scale and four smaller-scale demonstration projects were carried out at the BRE. Details of the projects are summarised in Table 9, whilst a schematic of the former can be seen in Figure 11. The full-scale demonstration projects comprised (i) a 3m square, 300mm deep slab (2.70m³ of foamed concrete) and (ii) a 3m x 3m L-shaped trench, 1m deep and 600mm wide (3.24m³ of foamed concrete) to a total RSA foamed concrete volume of around 6m³. The types of demonstration projects were carefully selected to ensure that they were typical of foamed concrete projects and covered both infrastructure (i.e. trench fill) and building (i.e. slab) applications.

Both slab and trench were manufactured with 1000 kg/m³ plastic density RSA foamed concrete with 100% demolition arisings fines as fine aggregate and 300 kg/m³ CEM I content. Demolition fines were selected for the full-scale projects given the availability of the material in volume terms. However, a range of other RSA was examined in the smaller-scale projects.

Recycled and Secondary Aggregates in Foamed Concrete
Table 9  Summary of details of demonstration projects with RSA in foamed concrete

<table>
<thead>
<tr>
<th>Demonstration Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full-Scale</strong></td>
</tr>
<tr>
<td><strong>Application</strong></td>
</tr>
<tr>
<td>Highway application: Trench fill</td>
</tr>
<tr>
<td>Housing application: Slab</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Smaller-Scale</strong>¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RSA Material</strong></td>
</tr>
<tr>
<td>Incinerator bottom ash</td>
</tr>
<tr>
<td>Crumb rubber</td>
</tr>
<tr>
<td>Recycled glass</td>
</tr>
</tbody>
</table>

¹ Quarry fines was also used in the smaller-scale trials as a benchmark primary aggregate.

Figure 11  Plan of full-scale demonstration projects

During the smaller-scale demonstration projects, 3 RSA foamed concretes (at 1000 kg/m³ plastic density, comprising 300 kg/m³ CEM I and 100% RSA fine aggregate) were prepared in a 100 litre capacity rotary drum mixer. The RSA materials tested were:

- incinerator bottom ash
- crumb rubber
- recycled glass

In addition, the mix described above was repeated with quarry fines as a benchmark primary material.
3.4 In-Situ Production and Placement of RSA Foamed Concrete

The materials of the base mix (i.e. CEM I, RSA and water) for the full-scale demonstration projects were combined in a ready-mix truck and the mortar fed to the Propump in-line mixing/pumping system (see Figure 12), where the blending with the preformed foam took place. The density of the material was monitored via an on-board density monitor (see Figure 13) and adjustments made within until the target plastic density was achieved. Following this, the RSA foamed concrete was pumped in place, as shown in Figures 14 and 15.
Figure 14  Full-scale foamed concrete trench fill with demolition fines

Figure 15  Full-scale foamed concrete slab construction with demolition fines
Figure 16  Smaller-scale demonstrations with IBA, crumb rubber, glass and quarry fines (quarry fines were used as a benchmark primary aggregate)
The production of the three types of RSA foamed concrete on a smaller-scale broadly followed the same methodology, except that the preformed foam was produced from a mobile foam generator and the mixing of the base mix and foam was carried out in a rotary drum mixer (see Figure 16).

3.5 Assessment of RSA Foamed Concrete

The free-flowing and self-levelling consistence of the site-produced RSA foamed concretes was determined in-situ by visual observation upon placement and cube specimens were prepared alongside the demonstrations and sealed-cured for cube strength measurements.

3.6 RSA Foamed Concrete Case Studies

In addition to the full- and smaller-scale demonstration projects, a search was carried out to identify the existence of any foamed concrete projects, where RSA had been used. As expected, the search for a RSA foamed concrete case study revealed that no such construction/current project existed (to the knowledge of the Project Steering Committee members).

3.7 Summary of Full- and Smaller-Scale Demonstration Projects

An audience of around 55 industry delegates attended the RSA Foamed Concrete Demonstration Seminar (the programme of the seminar is given in Appendix A). In total, four RSA materials and a primary aggregate were used successfully in the full- and smaller-scale demonstration projects. All RSA foamed concretes produced were self-flowing and stable mixes. Following the end of the demonstration, an excellent question and answer session was undertaken. All demonstration projects were recorded for future dissemination purposes.

4 Market Analysis for RSA in Foamed Concrete

4.1 Introduction

Previous work on the Minimal Aggregate Concrete (MAGCON) project identified foamed concrete as an ideal material through which, otherwise difficult to use fine, recycled and secondary aggregates (RSA) could be used instead of primary aggregates. This report seeks to take the next steps in encouraging the uptake of RSA in foamed concrete by establishing the market for RSA foamed concrete in the UK. More specifically, the market analysis considers (i) the primary aggregate consumption in the UK, (ii) issues regarding the use of RSA instead of primary aggregates, (iii) the market for the use of foamed concrete in mainstream construction applications and (iv) potential primary aggregate savings by the use of RSA in foamed concrete.

4.2 Primary Aggregate Consumption in the UK

The annual consumption of primary aggregates across the UK is estimated at around 210 million tonnes (see Table 10; QPA, 2000), with Scotland, East Midlands, the South West and East producing in excess of 30 million tonnes of aggregate each annually. Approximately 43% (90 million tonnes) of the total amount of primary aggregates are consumed by the concrete industry, as is shown in Figure 17 (BCA, 2004), whilst the remainder are probably used in other applications, such as granular fill.
Table 10  Production of aggregate and ready-mixed concrete in the UK during 2000 (QPA)

<table>
<thead>
<tr>
<th>Region</th>
<th>Aggregate Produced, million tonnes</th>
<th>Ready-mixed Concrete Produced, million m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scotland</td>
<td>32.9</td>
<td>1.9</td>
</tr>
<tr>
<td>North</td>
<td>12.8</td>
<td>1.2</td>
</tr>
<tr>
<td>North West</td>
<td>9.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Yorkshire &amp; Humberside</td>
<td>16.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Wales</td>
<td>22.1</td>
<td>1.1</td>
</tr>
<tr>
<td>West Midlands</td>
<td>15.5</td>
<td>2.2</td>
</tr>
<tr>
<td>East Midlands</td>
<td>38.8</td>
<td>1.8</td>
</tr>
<tr>
<td>East Anglia</td>
<td>7.1</td>
<td>0.9</td>
</tr>
<tr>
<td>South West</td>
<td>30.3</td>
<td>1.9</td>
</tr>
<tr>
<td>South East</td>
<td>32.8</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>218.6</strong></td>
<td><strong>23.2</strong></td>
</tr>
</tbody>
</table>

Figure 17  Annual demand for primary aggregates (QPA; BCA, 2004) and range of concrete products consuming 43% of primary aggregates annually (Portland Cement Association)
Although the amount of aggregates used by the concrete industry in the UK has been established, the specific quantities of different concrete products produced with them are not known. However, it is expected that the majority of aggregates are used in ready-mixed concrete, as has been reported by the Portland Cement Association (PCA) for the United States. Indeed, the PCA estimate that ready-mixed concrete accounts for 75% of all American concrete products (see Figure 17), whilst the remainder 25% comprise architectural concrete, autoclaved cellular concrete, concrete masonry, controlled low-strength material, high strength concrete, insulating concrete forms, concrete pavement and pipe, precast, prestressed and roller-compact ed concrete, shotcrete, soil-cement and tilt-up concrete. A similar breakdown of the concrete construction industry may be expected in the UK.

In the UK, the QPA have reported that 23.2 million m³ of ready-mixed concrete were produced in 2000 (see Table 10), the majority of which (33%) was in the South East.

### 4.3 Use of Recycled and Secondary Aggregates

Given that the supplies of primary aggregate are not incessant and renewable, there is a growing pressure by the Government (reflected in the introduction of the Aggregate Levy) on the construction industry to adopt more sustainable resources. These include recycled (reprocessed materials, previously used in construction) and secondary (by-products of other industrial processes, not previously used in construction, either manufactured or natural) materials (RSA). A summary of such RSA is given in Table 11.

<table>
<thead>
<tr>
<th>Recycled Aggregates</th>
<th>Secondary Aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled aggregate (RA)</td>
<td>Blast furnace slag</td>
</tr>
<tr>
<td>Recycled concrete aggregate (RCA)</td>
<td>Steel slag</td>
</tr>
<tr>
<td>Recycled asphalt</td>
<td>Pulverized-fuel ash (PFA)</td>
</tr>
<tr>
<td>Recycled asphalt planings (RAP)</td>
<td>Incinerator bottom ash (IBA)</td>
</tr>
<tr>
<td>Spent rail ballast</td>
<td>Furnace bottom ash (FBA)</td>
</tr>
<tr>
<td></td>
<td>Used foundry sand</td>
</tr>
<tr>
<td></td>
<td>Spent oil shale</td>
</tr>
<tr>
<td></td>
<td>Recycled glass</td>
</tr>
<tr>
<td></td>
<td>Recycled plastic</td>
</tr>
<tr>
<td></td>
<td>Recycled tyres</td>
</tr>
<tr>
<td></td>
<td>Slate aggregate</td>
</tr>
<tr>
<td></td>
<td>China clay sand</td>
</tr>
<tr>
<td></td>
<td>Colliery spoil</td>
</tr>
</tbody>
</table>

It is estimated that the UK already use around 65 million tonnes of primarily recycled materials annually (AggRegain), in addition to the 210 million tonnes of primary aggregates (QPA). However, if the rate of demand for aggregates continues to increase by 1% per year, by 2012 an additional 20 million tonnes will be required in the UK (AggRegain). As a result, it is important to continue promoting the use of RSA in construction and carry out research into their comparative performance with primary aggregates.

#### 4.3.1 Benefits of using RSA to replace primary aggregates

Whilst the specific environmental and cost benefits from using RSA in this study are examined in Sections 5 and 6 respectively, an example of the range of anticipated benefits with the use of RSA are given below:

- reduced cost of RSA compared to primary aggregates
- closer proximity of RSA suppliers to site than primary aggregate reduces transportation costs
- avoidance of RSA material deposited to landfill and saving from landfill tax
- the cost of processing some RSA can probably be outweighed by the savings from not using primary aggregates and avoiding requirement for costly off-site disposal
- avoiding Aggregate Levy
- units with RSA may be lighter in weight, hence easier to transport and manoeuvre during construction
• lighter RSA (e.g. crumb rubber, IBA) replacing heavier primary aggregates by volume result in additional savings
• enhanced performance of the product with RSA material compared to primary aggregate
• aid towards implementation of environmental management system ISO 14001
• reduction in vehicle movements due to the reduced requirement for primary aggregates.

4.3.2 Availability of RSA

One of the issues potentially affecting the use of RSA instead of primary aggregates by the construction industry is their geographic distribution across the UK. An example of this can be seen in Figure 18 where indicative sources of granulated rubber, recycled glass and incinerator bottom ash have been identified. As can be seen, the availability of a single RSA type may be concentrated in certain parts of the country. However, it may be expected that a source of any type of RSA and a source of primary aggregates are likely to be of similar distance to a construction site. As a result, it is important to determine the suitability of a wide range of RSA materials for a variety of construction applications.

![Indicative sources of (a) granulated rubber, (b) recycled glass and (c) incinerator bottom ash across the UK (AggRegain)](Figure 4.2)

4.3.3 National/European standard on recycled and secondary aggregates

In order to ease the adoption of RSA by producers and consumers, these have to be included in National and European standards for aggregates. The British standard for aggregates up until 2002 (BS 882: 1992) provided a specification for aggregates only from natural sources. The range of recently introduced (2002) European Standards for Aggregates (comprising BS EN 12620, BS EN 13043, BS EN 13055, BS EN 13139, BS EN 13242, BS EN 13383 and BS EN 13450) do not discriminate between different sources. Indeed, they specify ‘the properties of aggregates and filler aggregates obtained by processing natural, manufactured or recycled materials and mixtures of these aggregates’, however, secondary aggregates are not included.

However, it must be noted that, whilst standardisation of recycled materials is in progress, further work is required to define the origins and characteristics of a range of unfamiliar materials from secondary sources. In the meantime, the secondary aggregates must conform to standards and regulations relevant to their intended use, whilst additional characteristics and requirements may be specified on a case by case basis, depending upon experience of use of the product. For concrete in particular, although BS 8500 provides ‘generic requirements’ for the use of natural, manufactured or recycled aggregates, the Standard recognises that ‘project specifications need to include additional requirements specific to the type of RA’.

4.4 Use of Foamed Concrete in the UK

Foamed concrete was first patented in 1923, mainly for use as an insulation material, although it is suggested that its initial applications date back to Roman times (Sach and Seifert, 1999). For more than 60 years though, lack of specialised materials and equipment, limited its use to small-scale projects. Development of necessary resources, including significant improvements in production equipment and better quality surfactants (foaming agents), enabled the use of foamed concrete on a large scale in the late 1980s,
mostly for reinstatement of utility trenches (Walker and Clark, 1988). In addition, an extensive research programme carried out in the Netherlands to help promote foamed concrete as a new building material (Van Dijk, 1991) and its recommendation in the Horne report for use in highway reinstatement works (Horne, 1985) and Highways Authorities and Utilities Committee (HAUC) Specification for the Reinstatement of Openings in Highways (1992 and 1996), have helped increase production and broaden the scope of applications of foamed concrete in the last 15 years (Dransfield, 2000).

In the UK, foamed concrete was introduced as a backfill material, when the HAUC Specification recommended use of the material within the new Road and Street Works Act in 1991. This was intended to replace the traditional granular fill in highway reinstatement works (Moorfield, 1994) because of its (i) ease of application and re-excavation if necessary, (ii) its self-compacting nature, (iii) resistance to settlement and (iv) good ability to distribute loads (BCA, 1991). Since then, foamed concrete has been used on a large scale in bulk fills, trench reinstatements and a variety of other applications, as described below.

### 4.4.1 Foamed concrete applications

Foamed concrete is used in a variety of applications (see Figure 19), which range from void-filling to thermal and acoustic insulation, fire protection and building elements (Van Dijk, 1991; Kessler, 1998). It was initially recommended in the Horne report (Horne, 1985) and HAUK specifications (Chandler, 2000; Dransfield, 2000) for use in trench reinstatement of roads (following pipe laying or repairs) given its self-compacting and load-spreading characteristics, preventing the direct transmission of axial loads to the services. In addition, foamed concrete develops sufficient strength and can be re-surfaced as soon as 12 to 18 hours after trench filling (Walker and Clark, 1988), hence minimising disruption of traffic. Since then, it has been widely used in void filling (especially when access is a problem) of old sewerage pipes, wells, cellars and basements of old buildings, storage tanks, tunnels and subways (BCA, 1994) for its ability to flow easily under its own weight. However, precautions must be taken when water is present in the void, when considering suitable material density (Dransfield, 2000).

Bridge abutments have, on several occasions, been built with foamed concrete, as the lateral load imposed on the structure is significantly lower than with other materials and no settlement is observed due to its light weight. In addition, its use allows a reduction in the size of the bridge foundations (Pickford and Crompton, 1996) and savings in steel reinforcement (Kessler, 1998). For the same reasons, foamed concrete is also used instead of other common backfill materials (Walker and Clark, 1988) or to provide soil stability in embankment slopes (BCA, 1991).

The light weight and excellent thermal properties of foamed concrete have been advantageous in roofing insulation applications in the Middle East (EABASSOC, 1996) and South Africa (De Rose and Morris, 1999), while its low density and resulting high thixotropy enables the creation of roof slopes (Dransfield, 2000; Cox and Van Dijk, 2003). Foamed concrete has also been used for blinding (Basiurski, 2000), levelling terrain, raising floor levels as sub-floor material to provide thermal and sound insulation to both to new and renovated structures (BCA, 1991a) or to provide a base for storage tanks (Van Dijk, 1991). Some cases of raft foundations for houses, or foundations of sports fields and athletic tracks using foamed concrete have also been reported (Van Dijk, 1991). However, it has not been used in reinforced structural sections, as it is thought to be highly permeable and hence, of low durability, despite findings of a study by Kearsley and Booyens (1998) concluding that it was equally durable to C25 normal weight concrete.

Other applications of foamed concrete include (i) insulating fill in fire walls, (ii) building precast elements (Masanja, 2002), (iii) replacing existing soil, (iv) enhancing bearing capacity with cast-in-place foamed concrete piles, (iv) grouting the finished surface of tunnels, as well as (v) backfilling the voids behind the tunnel lining (Van Dijk, 1991). Some innovative foamed concrete applications include its use as underfloor heating systems, sprayed insulating material for concrete domes, decorative panels for wall fences and low retaining walls, lightening GRC panels and precast elements (e.g. fence posts, poles, lintels, window and door frames) (Basiurski, 2000).

### 4.4.2 Examples of foamed concrete projects in the UK

As indicated in Section 4.2, the majority of foamed concrete projects in the UK have been carried out in the highway and transportation sector. Some of these are described below:

Foamed concrete was used for the new railway bridge embankments in Colchester (Pickford and Crompton, 1996). Its application was recommended because the ground beneath the bridge was soft clay and the concrete supply was provided by RMC (Eastern Counties) Ltd. As both low density and relatively high strength were required, two separate mixes were specified. The top 1m was filled with foamed concrete of 4.5 N/mm² cube strength at 28 days and 1450 kg/m³ target plastic density. At depths greater than 1m, a mix with lower density (1250 kg/m³) and strength (3.0 N/mm²) was specified. The concrete was foamed on site, while plastic density measurements and specimens for
Figure 19  Examples of foamed concrete applications (courtesy of Propump Engineering Ltd)
monitoring cube strength were taken every few loads. By using foamed concrete, the required number of piles reduced by 40, while the wall thickness of the abutment was halved (Aldridge, 2000).

Foamed concrete was also employed during the emergency works carried out following the collapse of a temporary concrete tunnel lining and caving in of two other tunnels at Heathrow Airport in 1994. Thousands of cubic metres of lightweight foamed concrete were placed into the ground to seal the damaged tunnels and protect the vulnerable open faces of the works (Anon, 1999).

When the waterproofing membrane of the 25 year old bridge deck of a flyover in North Wales, connecting Llandudno junction and Deganwy, had to be replaced, repairs were carried out with foamed concrete by RMC (Wales) Ltd. A 34% CEM I/66% sand mix with 1300 kg/m³ dry density and 28 day strength of 4 N/mm² was specified, which was placed to a depth of up to 400mm. The surface was then covered with a black top wearing course (Pickford and Crompton, 1996).

The new Kingston Bridge was built adjacent to the already existing 7-arch masonry bridges, to increase the traffic capacity crossing the Thames, after a weight limit was decided in 1993. Foamed concrete was used to fill the voids between the arches and final road surface. The two old bridges were strengthened similarly. The mix specified (31% CEM I/69% sand) for the upper 700mm was one with a required density of 1400 kg/m³ and 7 N/mm² strength at 28 days, while at greater depths, 1 N/mm² foamed concrete with 600 kg/m³ density (64% CEM I/12% PFA/24% sand) was employed (Aldridge, 2000).

Foamed concrete was also used as the fill for the arch of the Sir Thomas Fairfax Bridge spanning the River Weaver in Nantwich, Cheshire. As a result, the dead weight of the structure was reduced by 15%, which was important, as the site investigation revealed alluvial river clay and sand to a depth of up to 30m (Weir, 2004).

The Canary Wharf project in London’s Docklands involved the construction of two access roads, the foundations of which were produced with foamed concrete to reduce the vertical load on the foundations and prevent settlement. Two different foamed concrete mixes were specified and provided by Voorbij Groep. The 500mm thick layer, which was 1m below the road surface, was filled with 670 kg/m³ density foamed concrete with a minimum cube strength of 0.9 N/mm², while 480 kg/m³ density and 0.3 N/mm² 28 day strength were required for the foamed concrete in the layer beneath (Van Dijk, 1991).

Finally, 500 to 600 kg/m³ density foamed concrete is currently being used to stabilise a former stone mine site in Combe Down, near Bath. This project involves an 18-hectare underground site with an approximate void volume of 400,000m³ and is expected to be completed within 4 years. The foamed concrete placed consists of cement at up to 30% by volume and limestone dust as filler, providing adequate cured strength of around 1 N/mm² (Dolecki, 2003).

4.4.3 Lack of National specification on foamed concrete

As foamed concrete is typically used in applications with ‘low structural performance level’ (e.g. void filling, trench reinstatement, backfill, thermal insulation, bridge abutments, blinding layer etc), the construction and technical control requirements of the material are generally limited. As a result, there has never been a need to consider (i) including foamed concrete in existing National Standards for construction materials or (ii) developing a Guidance document covering foamed concrete production, quality control and specification (with the exception of an Application Guide by Highways Agency and TRL (2001) and Clause 1043 in the Specification for Highway Works Volume 1 Series 1000 (2004)).

However, recent studies on foamed concrete have shown that the material has the potential to be used in more structural applications. Indeed, foamed concrete can exhibit strengths up to 40 N/mm² (Kearsley, 1996; Dhir et al, 1999; Kearsley and Wainwright, 2001b), has good freeze/thaw resistance (BCA, 1994; Basiurski, 2000), permeability and chloride corrosion resistance equivalent to that of a C25 normal weight concrete (Kearsley and Booyseans, 1998), is non-combustible (Kessler, 1998) and exhibits high thermal insulation capacity (BCA, 1994; Kessler, 1998; De Rose and Morris, 1999). However, the lack of a National Specification on the use of foamed concrete and the limited publications reporting its performance have perhaps prevented the uptake of foamed concrete in more projects with higher structural performance requirements.

Currently, the ‘special’ nature of foamed concrete, its mix constituents and relatively low strength preclude its inclusion in BS EN 206-1 and BS 8500. However, in order for foamed concrete to be considered by National Standards and Regulations, such as the Building Regulations or the National Building Specification, at least one standardized prescribed foamed concrete mix (e.g. FC1) would need to be included in BS 8500 in the future. The FC1 should ideally be able to achieve at least equivalent performance to that of a GEN1, but with the added benefit of significantly reduced dead load and considerably greater thermal insulating capacity compared with normal weight concrete.
4.5 Primary Aggregate Savings Through the Use of RSA in Foamed Concrete

Previous work on foamed concrete (BRE IP 11/04, 2004) has established that a wide range of recycled and secondary materials (RSA) can be used to partially or fully replace primary aggregate with little or no adverse effect on its performance. Given the wide range of applications that foamed concrete can be used in (see Sections 4.4.1 and 4.4.2), it becomes apparent that the use of RSA with this material could have significant environmental benefits, particularly in terms of primary aggregate savings. Currently, the concrete industry consume approximately 90 of a total 210 million tonnes of primary aggregates each year (BCA, 2004).

Although precise data on the use of foamed concrete in the UK does not exist (to the Author's knowledge), the UK's largest supplier of ready-mixed concrete, Readymix, estimated, a few years ago, that the annual industry market size for foamed concrete in the UK was around 250,000m³ (Pickford and Crompton, 1996). The majority of this would be expected to be used in construction applications as an alternative to traditional granular fill. Assuming that all foamed concrete produced contained 100% RSA instead of primary fine aggregate, this would translate into a potential primary aggregate saving of up to 650,000 tonnes annually (assuming average aggregate density of 2600 kg/m³ and average foamed concrete density of 1000 kg/m³).

The potential for primary aggregate savings with RSA foamed concrete could be even greater if the material was considered, in the future, for use in more structural applications. An example of this, explored for the study by the British Cement Association (BCA, 2004), is the use of foamed concrete (which could contain RSA) in thermally efficient low-rise housing trench fill foundations and slabs. This was the scope of a project carried out by the CTU during 2000-2003 (Jones et al, 2004). The potential aggregate savings from extending the use of RSA foamed concrete in this area are considered in Sections 4.5.1 and 4.5.2 (Note: the data produced by the BCA is based on market information extrapolated from results for finite samples of concrete suppliers and users).

4.5.1 RSA foamed concrete in low-rise housing trench fill foundations and other trench fill applications

In order to calculate the potential aggregate savings with RSA foamed concrete in low-rise trench fill foundations for housing, the mix constituents of a typical RSA foamed concrete mix are compared with those of two normal weight concretes that are often used in this application. The foamed concrete is a 1000 kg/m³ plastic density mix (52% air) with 400 kg/m³ RSA content, whilst the normal weight concretes comprise a designated (GEN1, C8/10, 2025 kg/m³ primary aggregate content) and a standardized prescribed (ST2, 1915 kg/m³ primary aggregate content) concrete, in accordance with BS 8500-2. The results are summarised in Table 12.

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Mix Constituents, kg/m³</th>
<th>Concrete Density, kg/m³</th>
<th>PA², kg/m³</th>
<th>Concrete Market, m³</th>
<th>RSA, tonnes</th>
<th>PA², tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN 1³</td>
<td>CEM 180, FA 805, CA 1220, RSA 0, W 195, Air, 0%</td>
<td>2400</td>
<td>2025</td>
<td>520,000</td>
<td>0</td>
<td>1,053,000</td>
</tr>
<tr>
<td>ST 2³</td>
<td>CEM 285, FA 765, CA 1150, RSA 0, W 200, Air, 0%</td>
<td>2400</td>
<td>1915</td>
<td>520,000</td>
<td>0</td>
<td>995,800</td>
</tr>
<tr>
<td>Foamed Concrete</td>
<td>CEM 400, FA 0, CA 0, RSA 400, W 200, Air, 52%</td>
<td>1000</td>
<td>0</td>
<td>520,000</td>
<td>208,000</td>
<td>0</td>
</tr>
</tbody>
</table>

Maximum aggregate savings, tonnes 1,053,000

1 FA: fine aggregate (primary), CA: coarse aggregate (primary), RSA: recycled and secondary aggregate, W: water
2 PA: primary aggregate
3 as specified in BS 8500-2
As can be seen, for a concrete market of 520,000 m³ per year (although this is only 10% of the estimated trench fill market; BCA, 2004), primary aggregate savings of up to 1,053,000 tonnes could be achieved if a foamed concrete with RSA is used instead of a GEN1 or ST2 normal weight concrete.

However, it must be noted that, for this particular application, the BCA database was unable to distinguish between the concrete market for trench fill foundations and that for trench fill reinstatement of roads, following excavations by utility services.

4.5.2 RSA foamed concrete in floor construction

Table 13 shows the mix proportions of a typical C30 normal weight concrete (NWC) with 1970 kg/m³ primary aggregate content and that of an equivalent strength 1600 kg/m³ plastic density foamed concrete with 645 kg/m³ RSA content. The former is considered typical of that used in housing floor construction.

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Mix Constituents¹, kg/m³</th>
<th>Concrete Density, kg/m³</th>
<th>PA², kg/m³</th>
<th>Concrete Market, m³</th>
<th>RSA, tonnes</th>
<th>PA², tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C30 NWC³</td>
<td>260 785 1185 0 170 0</td>
<td>2400 1970</td>
<td></td>
<td>128,800 0</td>
<td>254,000</td>
<td></td>
</tr>
<tr>
<td>Foamed Concrete⁴</td>
<td>500 0 0 645 455 10</td>
<td>1600 0</td>
<td>128,800</td>
<td>83,000</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Maximum aggregate savings, tonnes 254,000

¹ FA: fine aggregate (primary), CA: primary coarse aggregate (primary), RSA: recycled and secondary aggregate, W: water
² PA: primary aggregate
³ C30 normal weight concrete (NWC) to BS 8500
⁴ C30 foamed concrete

As the BCA database could not identify the proportion of the total market of concrete slabs for housing (1,288,000 m³ annually) that could be constructed with foamed concrete (e.g. ground-supported slab, suspended composite tin deck floor, etc), this proportion was assumed as 10% of the total.

As the proposed C30 RSA foamed concrete does not contain any primary aggregate, the calculated maximum aggregate saving by using this RSA foamed concrete mix in slab construction for housing is around 254,000 tonnes per year.

4.6 Summary of Market Opportunities with RSA in Foamed Concrete

The free-flowing, self-compacting and thermal properties, light weight and relatively low strength of foamed concrete have made it an attractive material for a variety of applications. In addition, foamed concrete can easily accommodate a wide range of RSA instead of primary materials. Assuming an annual market size of 250,000 m³ for foamed concrete in the UK, the use of RSA in foamed concrete alone could result in primary aggregate savings of up to 1,300,000 tonnes a year (i.e. 1.4% of the aggregate used by the concrete industry or 0.6% of the total aggregate market), with concomitant cost and environmental benefits. However, in order to maximise the uptake of foamed concrete with RSA, both foamed concrete and secondary aggregates would need to be incorporated in existing National Standards/Guideline documents.
5 Environmental Assessment of RSA Foamed Concretes

5.1 Introduction

The Concrete Technology Unit (CTU), University of Dundee commissioned BRE’s Centre for Sustainable Construction to undertake a study to assess the environmental performance of foamed concrete containing recycled and secondary aggregates (RSA). This study uses the BRE Environmental Profiles methodology to quantify the overall effect of RSA in foamed concrete.

Foamed concrete containing the following types of RSA have been assessed within this study:

- Glass
- China clay sand

The RSA foamed concretes have been compared with the environmental performance of a foamed concrete containing virgin aggregate; sand.

The methodology followed to establish the environmental profiles of all foamed concretes is described in Appendix B.

5.2 Project Description and Methodology

BRE have provided an assessment of the impacts on the environment associated with foamed concrete containing different RSA. The mix proportions of each foamed concrete mix assessed in this study are tabulated below (Table 14). For each 1000 kg/m³ plastic density foamed concrete, mixes with different amounts of Portland cement (CEM I), 300 kg/m³ and 400 kg/m³, were modelled. All mixes were provided by the CTU and reflect those examined in the laboratory study.

Table 14  Concrete Mix Proportions

<table>
<thead>
<tr>
<th>Foamed Concrete Type</th>
<th>CEM I</th>
<th>Sand</th>
<th>Primary Aggregate/ RSA</th>
<th>Water</th>
<th>Air, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 kg/m³ foamed concrete with sand</td>
<td>300</td>
<td>550</td>
<td>-</td>
<td>150</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>400</td>
<td></td>
<td>200</td>
<td>52</td>
</tr>
<tr>
<td>1000 kg/m³ foamed concrete with recycled glass</td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
<td>400</td>
<td>200</td>
<td>51</td>
</tr>
<tr>
<td>1000 kg/m³ foamed concrete with china clay sand</td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>-</td>
<td>400</td>
<td>200</td>
<td>53</td>
</tr>
</tbody>
</table>

The assessment was undertaken using the BRE Environmental Profiles Methodology, which uses a 'level playing field' approach to assess environmental impacts over the whole life cycle. The assessments therefore take account of any environmental impacts associated with transport, manufacturing, processing,
maintenance, replacement and disposal at the end of life. These are based on typical UK scenarios. For this study, the concrete mixes were modelled as a domestic house foundation.

For recycled and reclaimed items, environmental impacts are measured from the point at which the item becomes available for processing into its second function. Burdens from its previous manufacture are carried forward to its next use according to the relative value of the waste stream and primary product. If a recycled material has no value at any point in the process, e.g. during demolition, then no burdens are carried forward.

In the case of the recycled glass, the environmental impact was based on the manufacture of flat glass. The glass burden was allocated using a cost ratio of 20% of recycled glass compared to virgin glass. Therefore, it is important to note that variations in the price ratio between recycled glass and virgin glass will have a direct effect on the environmental impact of the glass.

In the case of china clay sand, the figures for the environmental impact were derived from a study into china clay production at the quarry, where china clay dust is a by-product of this process (Simapro LCA database v5.1).

The assessment uses BRE's Ecopoints single scoring system for environmental impact. Ecopoints are a single score rating taking into account total contribution to, and relative importance of, a range of 12 environmental impacts. The total contribution is measured by the BRE's approach to LCA, the Environmental Profiles Methodology for construction materials and components. The relative importance of each environmental impact has been assessed by undertaking a consultation with stakeholders in the construction industry. Further information on Ecopoints and the BRE Environmental Profiles methodology is provided in Appendix B.

5.3 Findings of the Environmental Assessment

This report provides an assessment for each foamed concrete type as follows:

- Ecopoint Score
- Contribution of RSA foamed concrete to environmental issues
- Analysis of the major and minor environmental impact categories.

5.3.1 Ecopoint score

The Ecopoint scores for each foamed concrete considered are shown in Figure 20. The results show that the cement (rather than the aggregate) is accountable for the largest proportion of environmental impact associated with the foamed concretes. The influence of the cement content is demonstrated by the fact that the foamed concretes containing the lower cement content (300 kg/m³) have lower Ecopoint score and hence, environmental impact, than the corresponding higher cement content (400 kg/m³) concretes.

The glass foamed concretes have the highest environmental performance of the foamed concretes assessed. As noted within the methodology of this report, recycled materials carry forward with them environmental impacts associated with their previous manufacture. In the case of glass, the environmental impacts of the manufacture of virgin glass are relatively high compared to that of quarrying for china clay or primary sands. The impact of preparing the recyclate is also greater for glass than for china clay sand, as it must be crushed. The crushing impact in our study represented 26% of the total impact of the recycled glass.

5.3.2 Influence of reference and RSA foamed concretes on environmental issues

For the lower cement content foamed concrete mixes (300 kg/m³), the overall environmental impact has been broken-down by environmental issue. Figures 21 to 23 identify that the most significant environmental impacts for the foamed concretes are climate change, minerals extraction and waste disposal. These results are tabulated in Table 15. These major impacts are discussed in detail below.
Figure 20  Ecopoint scores for concrete within a domestic house foundation (Note: the impacts for water and electricity were calculated but were negligible compared to those of aggregate and cement)

Figure 21  Influence of sand foamed concrete on environmental issues
Figure 22  Influence of china clay foamed concrete on environmental issues

Figure 23  Influence of glass foamed concrete on environmental issues
Table 15  Environmental impact results

<table>
<thead>
<tr>
<th>Foamed Concrete Type</th>
<th>Minerals Extraction</th>
<th>Climate Change</th>
<th>Waste Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 kg/m³ foamed concrete with sand</td>
<td>22%</td>
<td>33%</td>
<td>18%</td>
</tr>
<tr>
<td>1000 kg/m³ foamed concrete with china clay sand</td>
<td>13%</td>
<td>37%</td>
<td>21%</td>
</tr>
<tr>
<td>1000 kg/m³ foamed concrete with glass</td>
<td>10%</td>
<td>33%</td>
<td>25%</td>
</tr>
</tbody>
</table>

5.3.3 Influence of mix constituents on Ecopoint scores

The major environmental impacts associated with the foamed concretes assessed within this study were found to be on climate change, minerals extraction and waste disposal. These environmental issues are most significantly influenced by the cement content. Figure 24 shows that the higher cement content foamed concretes all have a poorer environmental performance with regard to these issues.

The cement content has a significant influence on climate change due to the energy-intensive nature of the manufacturing process, in particular the very high temperatures needed within the kiln. It can be seen that the impact on minerals extraction is highest for the sand, which is a virgin material and so incurs all of the burdens for its production process. In the case of the RSA, because they are by-products of a process, only a portion of the full impact is attributed and hence their impact is lower. The climate change and waste disposal figures are highest for foamed concrete with glass. As previously mentioned, this is due to the impact carried over from the energy and waste-intensive glass production process from which the recycled glass is sourced.

![Figure 24](image)

Figure 24  Environmental issues that the foamed concretes had a major impact on

The RSA foamed concretes assessed in this study exhibited comparatively minor impacts on issues such as transport pollution & congestion (freight), fossil fuel depletion and pollution to air (human toxicity), as shown in Figure 25.
Figure 25  Environmental issues that the foamed concretes had a minor impact on

Although the Ecopoint scores in Figure 25 are lower than those in Figure 24, it can be seen that there is a direct relationship to the level of cement content. In each case, the impact is greatest for the foamed concrete with the higher cement content.

5.4 Summary of Environmental Impact of RSA in Foamed Concrete

The results of this study have shown the following:

- Foamed concrete containing china clay sand has the lowest overall environmental impact of the RSA foamed concretes assessed
- Foamed concrete containing recycled glass had the highest overall environmental impact, greater than that of foamed concrete containing primary sand
- The overall environmental impact associated with the aggregate content of foamed concretes is comparatively low, when compared to the impact associated with the cement content
- There was a significant difference in the environmental performance of the two RSA types assessed within this report.

This study has shown that the key environmental drawback of foamed concrete is its rather high content of CEM I. This results in poorer ratings, in particular for climate change, which could be improved by:

- choosing a concrete with a lower cement content
- substituting a proportion of the Portland cement (CEM I) with a cementitious material of lower environmental impact, eg fly ash.

The choice of RSA used in the foamed concrete can have a significant effect on its environmental impact. The environmental impact of the RSA can be reduced by selecting one which:

- has a low monetary value, thus reducing the burden carried over from the virgin aggregate
- requires little or no secondary processing
Finally, it must be noted that, since no environmental data was available to the BRE on the remaining RSA materials (IBA, crumb rubber, foundry sand), their environmental impact, when used in foamed concrete, could not be assessed. It is apparent that, in order to promote the use of these materials in construction, further work in this area (i.e. environmental database and life cycle assessment of a wider range of RSA products) would be required.

6 Cost Benefit Assessment of Using RSA in Foamed Concrete

6.1 Introduction

The cost benefit assessment of using RSA in foamed concrete was carried out on mixes containing incinerator bottom ash, fine crushed glass, crumb rubber, foundry sand and china clay sand. The assessment was based on the following:

- cost of RSA compared to that of primary aggregates (as delivered)
- savings from avoiding disposal of RSA to landfill
- minimising costs due to Aggregate Levy
- lighter RSA (e.g. crumb rubber, incinerator bottom ash) replacing heavier primary aggregates by volume result in additional saving of the latter.

The cost comparison was carried out assuming that handling of the RSA was comparable to that of the primary fine aggregate. It was also assumed that no additional costs were incurred in using RSA.

6.2 Range of RSA Foamed Concretes Compared

The range of RSA foamed concretes compared on a cost benefit basis are summarised in Table 16. All foamed concretes comprised 300 kg/m³ CEM I content (as this is the level typically used by the construction industry) at a 0.50 w/c ratio (again, this is typical for foamed concrete) with 100% RSA (incinerator bottom ash, fine crushed glass, crumb rubber, foundry sand and china clay sand) at a 1000 kg/m³ target plastic density. In addition, a 1400 kg/m³ density foamed concrete with 300 kg/m³ CEM I and 100% IBA was used in an example calculation of indicative monetary savings.

6.3 Direct Savings

Given that the costs of sand and RSA materials change with time and vary with location across the UK, an indicative comparison between sand and RSA 1000 kg/m³ foamed concretes was carried out in percentage terms. The comparative values reported are an average of those given by material suppliers, RSA end-users and those reported in several case studies on the AggRegain website. As can be seen in Table 17, there is scope for significant material cost savings when incinerator bottom ash, recycled glass, foundry and china clay sand are used instead of primary aggregates (by weight replacement, i.e. 550 kg of RSA used instead of 550 kg of sand per m³ of 1000 kg/m³ plastic density foamed concrete) in foamed concrete. In addition, despite its initial higher unit cost, the very low apparent particle density of crumb rubber (around 1075 kg/m³) compared to that of sand (2630 kg/m³) or any other RSA (2265 - 2795 kg/m³) examined could also result in cost savings when the replacement of sand is carried out in volume terms instead (i.e. 225 kg of crumb rubber required instead of 550 kg of sand per m³ of 1000 kg/m³ plastic density foamed concrete).
Table 16  Mix proportions of RSA foamed concretes studied in cost comparison

<table>
<thead>
<tr>
<th>Fine Aggr. Type</th>
<th>Target Plastic Density, kg/m³</th>
<th>Mix Constituent Proportions, kg/m³</th>
<th>CEM I</th>
<th>Sand</th>
<th>RSA</th>
<th>Water</th>
<th>Air, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>550</td>
<td>-</td>
<td>150</td>
<td>55</td>
</tr>
<tr>
<td>b) Recycled and secondary aggregates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incinerator bottom ash</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>51</td>
</tr>
<tr>
<td>Recycled glass</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>54</td>
</tr>
<tr>
<td>Crumb rubber</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>Foundry sand</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>51</td>
</tr>
<tr>
<td>China clay sand</td>
<td>1000</td>
<td></td>
<td>300</td>
<td>-</td>
<td>550</td>
<td>150</td>
<td>56</td>
</tr>
<tr>
<td>Example calculation with IBA</td>
<td>1400</td>
<td></td>
<td>300</td>
<td>-</td>
<td>950</td>
<td>150</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 17  Indicative comparative costs of sand and RSA

<table>
<thead>
<tr>
<th>Fine Aggregate Type</th>
<th>Range of Material Costs, units per unit weight</th>
<th>Potential Material Cost Savings1, % per unit weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Primary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>b) Recycled and secondary aggregates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incinerator bottom ash</td>
<td>45-133</td>
<td>up to 55%</td>
</tr>
<tr>
<td>Recycled glass</td>
<td>37-133</td>
<td>up to 63%</td>
</tr>
<tr>
<td>Crumb rubber</td>
<td>1185-1333</td>
<td></td>
</tr>
<tr>
<td>Foundry sand</td>
<td>&lt;&lt; 1002</td>
<td>Not established2</td>
</tr>
<tr>
<td>China clay sand</td>
<td>&lt;&lt; 1002</td>
<td>Not established2</td>
</tr>
</tbody>
</table>

1 The potential material cost savings are applicable when sand is replaced with RSA by weight. However, these savings would be significantly higher for the RSA examined, if the replacement was carried out in volume terms, as the above RSA (except china clay sand) are lighter than sand.
2 Although exact material costs could not be obtained, several reports suggested significant material cost savings with both foundry and china clay sand, compared to primary sand.
6.4 Indirect Savings

In addition to the direct material cost savings outlined above, there are additional (indirect) cost savings when RSA are used instead of primary aggregates in foamed concrete. More specifically, for every tonne of primary aggregates that is replaced with RSA, there is a Landfill Tax saving of £15 (2004 rate), Landfill Gate fee saving of approximately £10 (although this varies significantly across the UK) and an Aggregate Levy saving of £1.60. As regards the foamed concretes examined (see Section 6.2), the use of 100% RSA as fine aggregate would result in a total saving of £14.63 per m³ of the 1000 kg/m³ plastic density RSA foamed concrete produced. Furthermore, assuming an annual industry market size for foamed concrete in the UK of around 250,000m³ (Pickford and Crompton, 1996), the total indirect savings could potentially exceed £3.5m.

6.5 Indirect Benefits

In addition to the direct and indirect cost savings described above, there are a number of additional benefits that result from the use of RSA in foamed concrete:

- potential reduction of up to 137.5 million tonnes of primary materials (assuming annual market for foamed concrete in the UK of 250,000m³ and 1000 kg/m³ density foamed concrete)
- avoiding disposal of potentially up to 137.5 million tonnes of RSA to landfill (assuming annual market for foamed concrete in the UK of 250,000m³ and 1000 kg/m³ density foamed concrete)
- increased performance of all RSA foamed concretes, particularly those with incinerator bottom ash and recycled glass, compared to primary aggregate mixes (see Sections 2.4 and 2.5)
- if primary sand was being replaced by RSA in terms of volume rather than weight, the use of lighter (compared to sand) RSA, i.e. incinerator bottom ash, recycled glass, crumb rubber and foundry sand, would result in reduced quantities of RSA required (savings up to 75 kg, 26 kg, 325 kg and 76 kg respectively per m³ of RSA foamed concrete produced).

6.6 Example Calculation of Cost Benefits Using RSA in Foamed Concrete

The example calculation of cost savings with IBA in a 1400 kg/m³ foamed concrete is summarised in Table 18. The 1400 kg/m³ density foamed concrete used in this example comprises 950 kg/m³ fine aggregate (see Table 16).

<table>
<thead>
<tr>
<th></th>
<th>Primary Sand</th>
<th>Incinerator Bottom Ash</th>
<th>Savings with IBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material cost</td>
<td>£ 13.50 / tonne</td>
<td>£ 6.00 / tonne</td>
<td>£ 7.50 / tonne</td>
</tr>
<tr>
<td>Aggregate Levy</td>
<td>£ 1.60 / tonne</td>
<td>-</td>
<td>£ 1.60 / tonne</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>£ 15.10 / tonne</strong></td>
<td><strong>£ 6.00 / tonne</strong></td>
<td><strong>£ 9.10 / tonne</strong></td>
</tr>
</tbody>
</table>

As can be seen, assuming a cost of £13.50/tonne for primary sand and £6.00/tonne for IBA, the direct material cost saving for this specific mix amounts to £7.13 per m³ of 1400 kg/m³ plastic density IBA foamed concrete produced. The indirect savings from the Aggregate Levy (£1.52 per m³ of IBA foamed concrete produced) increase the potential cost benefits to foamed concrete manufacturers to a total of £8.65/m³ with this mix.

In addition, for every m³ of 1400 kg/m³ foamed concrete produced with IBA (instead of the IBA being sent to landfill), savings from Landfill Tax and Landfill Gate fee (assuming rates given in Section 6.4) are £14.25 and £9.50 respectively.

However, it must be noted that these cost savings are indicative, as the material costs assumed above vary significantly with location and change with time. Similar differences in the price of the Landfill Gate fee are noted across the UK.
6.7 Summary of Cost Benefits Using RSA in Foamed Concrete

Overall, this study has shown that using RSA in foamed concrete instead of primary aggregates could lead to significant cost savings. Indeed, the majority of RSA materials examined in the study are currently available at prices lower than those of the primary aggregates. In addition, the use of RSA instead of primary aggregate results in reduced expenditure towards Landfill Tax, Landfill Gate fee and Aggregate Levy. Finally, there are several indirect benefits with using RSA in foamed concrete, including reduction of primary aggregate consumption, decrease in RSA sent to landfill and enhanced foamed concrete performance.

7 Tentative Specification and Quality Control Test Framework for RSA Foamed Concrete

7.1 Introduction

RSA foamed concrete is currently not covered within any existing National Specification/Guidance documents and there is no guidance on how to specify it. In addition, there are limited publications in both RSA and foamed concrete subject areas, which, in combination with the lack of guidance (in terms of materials, requirements, production, testing etc), would probably result in reduced uptake of RSA foamed concrete.

It would be useful if foamed concrete was included (even as a standardized prescribed foamed concrete mix, FC1) in BS 8500 and RSA in BS EN 12620 (Note: the special nature of the former and the wide range and variability of the latter preclude this). However, the findings of this study have been used to prepare a tentative specification and quality control framework for RSA foamed concrete. A summary of this is given in Section 7.2, whilst the document is included in Appendix C.

7.2 Summary of Tentative Specification and Quality Control Test Framework for RSA Foamed Concrete

Given that it is not possible to specify foamed concrete using the existing Standards framework for normal weight concrete, the basic methods, clauses and format of BS 8500 were used as a guideline to produce a specification and quality control test framework for RSA foamed concrete. This is included in Appendix C and gives a range of terms and definitions, considers the constituent materials (cements and combinations, recycled and secondary aggregates, admixtures and mixing water) and reviews the requirements for the material. The latter comprises mix stability, consistence, plastic density, composition and concrete temperature for the fresh, and difference in values between oven-dry and target plastic densities and cube strength (where required) for the hardened foamed concrete. In addition, production control (production procedures, responsibility of the producer) and transport issues are also addressed.

Annex A of the proposed specification considers the method for specifying RSA foamed concrete. This includes requirements for conformity to a published document, specification of a ‘target’ water/cement ratio, target plastic density and target slump-flow spread. The requirement for ‘target’ water/cement (w/c) ratio was included to cover (i) the need for a minimum w/c ratio to ensure adequate consistence of the base mix, foam stability and to prevent ‘balling’ of constituents in the free-fall mixer and (ii) a need for a maximum w/c ratio, to ensure that the RSA foamed concrete achieves the expected strength. Annex B provides the test methodology for the slump flow spread of RSA foamed concrete.
8 Overall Conclusions and Recommendations for Further Work

Overall, this study has shown that foamed concrete can easily accommodate a wide range of RSA materials to replace primary aggregates. The performance of the RSA concretes (in terms of consistence and strength development) was comparable with or, in some cases better than, that of equivalent primary aggregate foamed concretes. However, further work is required to examine the effect of RSA on a wider range of RSA foamed concrete properties, including permeation, thermal and durability.

The full- and smaller-scale demonstration projects carried out with four different RSA types demonstrated the ease of production and placement of RSA foamed concretes and their free-flowing and self-compacting ability and mix stability in the fresh state.

The market analysis revealed that there is significant scope for primary aggregate savings (up to 1,300,000 tonnes a year, which is 1.4% of the aggregate used by the concrete industry or 0.6% of the total aggregate market annually) with RSA in foamed concrete. However, in order to maximise the uptake of foamed concrete with RSA, both foamed concrete and secondary aggregates would need to be incorporated in existing National Standards/Guideline documents.

The high air content of foamed concrete (in excess of 20% by volume) and lack of use of coarse aggregate in its matrix makes it environmentally friendly. The reduced impact of foamed concrete on the environment can be further enhanced by the replacement of sand with RSA (preferably with low monetary value and requiring little or no secondary processing), and the use of lower cement contents. However, in order to promote the use of these materials in construction, further work in this area (i.e. environmental database and life cycle assessment of a wider range of RSA products) would be required.

Finally, the cost benefit assessment has shown that using RSA in foamed concrete instead of primary aggregates could lead to significant cost savings. The majority of RSA materials examined in the study are currently available at prices lower than those of the primary aggregates, whilst additional savings are made by avoiding Landfill Tax, Landfill Gate fee and Aggregate Levy. In addition, there are several indirect benefits with using RSA in foamed concrete, including reduction of primary aggregate consumption, decrease in RSA sent to landfill and enhanced foamed concrete performance.

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Appendix A: Programme of the Demonstration Seminar

DEMONSTRATION SEMINAR

Using Recycled and Secondary Aggregates in Foamed Concrete

26 November 2004

Building Research Establishment

Garston, Watford

In partnership with:
Introduction

Reducing the consumption of primary aggregates is a major environmental concern of the UK Government and a major challenge for the concrete industry. In response to this challenge, initiatives have focused on the use of alternative, recycled and secondary aggregates (RSA). This study found that a concrete formulation/technology that can easily accommodate a wide range of RSA is foamed concrete.

This demonstration seminar will look at the use of RSA in foamed concrete to partially or fully replace primary aggregate. The range of materials examined, production methods and performance of RSA foamed concrete for a variety of end-uses will be described. A market analysis for the use of RSA in foamed concrete and an environmental assessment of the material will also be reported.

Full-scale demonstrations

The afternoon session will offer demonstrations of in-line foaming and mixing using the latest developments in truck-based mobile systems. These will provide an ideal opportunity to show how foamed concrete with RSA can be mixed and placed for both large and smaller-scale projects. The demonstrations will finish with a Question and Answer session with the materials suppliers and there will then be an opportunity to discuss general and more specific foamed concrete project applications.

Range of foamed concrete applications (courtesy of Propump Engineering Ltd)

Coffees and lunch

Refreshments and a buffet lunch will be provided during the course of the seminar.

CPD certificates

Certificates of attendance will be issued upon request. Our courses are intended to assist members of Professional Institutions meet their CPD obligations.
Seminar Programme

9:30  Coffee / Tea

9:50  Welcome & Introduction

Professor R K Dhir OBE, Director,
Concrete Technology Unit, University of Dundee

Professor G Hammersley, Operations Director,
Building Research Establishment

10:00  Recycled and Secondary Aggregates (RSA) in Construction

Mr J Barritt, Aggregates Technical Advisor,
Waste & Resources Action Programme (WRAP)

- Definition of recycled and secondary aggregates
- Range of RSA materials
- WRAP's objectives for uptake of recycled and secondary aggregates
- Case studies illustrating use of RSA in a range of construction projects.

10:20  Foamed Concrete Applications

Dr M R Jones, Associate Director
Concrete Technology Unit, University of Dundee

- Trench reinstatement
- Large-scale void fill
- Bridge abutment
- Bridge arch infill
- Soil stabilisation
- Thermal insulation
- Screeds
- Precast units
- Sewers, storage tanks, wells, cellars, basements, tunnels, shafts and culverts
- Blinding, raft foundations, road sub-base.

10:50  Foamed Concrete with Recycled and Secondary Aggregates (RSA)

Dr A McCarthy, Research Fellow
Concrete Technology Unit, University of Dundee

- Use of incinerator bottom ash, recycled glass, crumb rubber, foundry sand, china clay sand, quarry fines, GRP in foamed concrete as partial/total replacement for sand
- Characterisation of RSA
- Consistence and strength development of RSA foamed concretes
- Effect of RSA variability on foamed concrete.

11:15  Coffee / Tea

11:40  Market Analysis for the Use of RSA in Foamed Concrete

Dr C A Clear, Research Manager,
British Cement Association

- Potential for the use of foamed concrete in mainstream construction applications
- Effect of lack of National Specification in the uptake of foamed concrete in the building and infrastructure market
- Benefits of using RSA to replace primary aggregates.
12:00 Environmental Assessment of RSA Foamed Concretes

Mr P Thistlethwaite, Consultant, Building Research Establishment

- Effect of RSA in foamed concrete on climate change (e.g. greenhouse gas emissions)
- Effect of RSA in foamed concrete on fossil fuel depletion (e.g. use of coal)
- Effect of RSA in foamed concrete on minerals extraction (e.g. quarrying resulting in noise)
- Ecopoints of RSA foamed concretes.

Demonstration Programme

The delegates will be split into two groups for the RSA foamed concrete demonstrations and lunch.

12:30-14:00 Lunch and Small-Scale Demonstrations with RSA Foamed Concrete - Groups 1 and 2

Mr D Aldridge and Mr T Ansell, Directors, Propump Engineering Ltd

- Production of foamed concrete with RSA in-situ
- Foamed concrete trench reinstatement with demolition arisings fines
- Foamed concrete slab with demolition arisings fines
- Small-scale production of foamed concrete with incinerator bottom ash, crumb rubber, recycled glass and quarry fines.

14:30 Discussion and Closing Remarks

15:00 Close
Appendix B: Methodology for Assessing the Environmental Impact of RSA Foamed Concretes

B.1 Life Cycle Analysis Methodology

BRE life cycle assessments (LCA) can be divided into three distinct phases (see below), although in practice, the life cycle assessment is an iterative process.

B.1.1 Inventory data

During this phase, data on all the inputs and outputs of the product system under study are calculated for all appropriate life cycle stages. This list of inputs and outputs is known as Inventory data. Once the process boundaries have been defined, and the data allocated to the relevant product, the inputs and outputs are processed to refer to 1 tonne of product.

B.1.3 Impact assessment

The impact assessment phase is aimed at evaluating the data calculated in the inventory analysis in terms of their environmental impact. The BRE Methodology breaks this phase into a further 3 stages:

**Classification**

The impact categories are selected and the inputs and outputs from the inventory are then assigned to the appropriate impact category. Each input or output can contribute to one or more impact category (e.g. methane contributes to climate change and photochemical ozone creation).

A list of the 13 following impact categories considered in BRE LCA methodology:

1. Climate change
2. Fossil fuel depletion and extraction
3. Ozone depletion
4. Transport pollution and congestion: Freight
5. Pollution to air: Human toxicity
6. Pollution to water: Human toxicity
7. Waste disposal
8. Water extraction
9. Acid deposition
10. Pollution to water: Ecotoxicity
11. Pollution to water: Eutrophication
12. Pollution to air: Low level ozone depletion
13. Minerals extraction

**Characterisation**

The characterisation step evaluates the relative importance of the different burdens under each impact category compared to a reference unit (e.g. for climate change the reference unit is 'one kg of CO₂ equivalent emitted over 100 years'). The characterisation stage results in the contributions to each impact category being expressed as equivalent amounts of emitted reference unit; these contributions can then be summed to give a final category score. For example, for global warming, 1 tonne of CO₂ is considered to have an impact score of 1 whereas 1 tonne of methane has 21 times more global warming potential than CO₂, and therefore has an impact score of 21.
**Normalisation**

A comparison between impact categories is still difficult because the data are represented in different units. One solution to this problem is ‘normalisation’. In the BRE Environmental Methodology, this relates the amount of environmental impact arising from the product to the impacts arising from activity associated with an average UK citizen over the period of 1 year.

As a result, the environmental impact for each category becomes a dimensionless ratio, and because the different impacts become dimensionless, they can be added together. This is useful to show how important the impacts of a product are compared to the reference point of one person (whose total impact is, therefore, 1). Normalising the data may allow its addition (sum), but it does not distinguish the most important impacts from the least. To do this, it is necessary to ‘weigh’ the impacts. BRE has created a single score system for environmental impacts that takes into account the relative importance of different impacts. This is known as Ecopoints (further details provided in Section B.2 below).

**B.2 Ecopoints: a Single Score Environmental Assessment**

The environmental impacts of construction encompass a wide range of issues, including climate change, mineral extraction, ozone depletion and waste generation. Assessing such different issues in combination requires subjective judgements about their relative importance. For example, is a product with a high global warming impact that does not pollute water resources giving less overall environmental impact than a product that has a low global warming impact but produces significant water pollution? To enable such assessments, BRE has developed Ecopoints.

**B.2.1 Normalised environmental impacts**

Each environmental issue is measured using its own unit, for example BRE measure mineral extraction using tonnes of mineral extracted and climate change in mass of CO₂ equivalent. Using these ‘characterised’ impacts, it is hard to make any useful comparisons. However, by comparing each environmental impact to a ‘norm’, each impact can be measured on the same scale. BRE have taken as their norm the impacts of a typical UK citizen, calculated by dividing the impacts of the UK by its population.

**B.2.2 Weightings**

Expert panels from across the industry’s stakeholder groups were used to judge the importance of many sustainability issues, covering environmental, social and economic issues. The results showed a surprising degree of consensus about the relative importance of different environmental issues across a broad range of interest groups. Currently, only data for environmental issues measured by BRE have been used to weight the normalised environmental impacts to provide the Ecopoints score.

**B.2.3 UK Ecopoints**

A UK Ecopoint score is a measure of the overall environmental impact of a particular product or process covering the same environmental impacts as listed on an Environmental Profile:

- Climate change
- Fossil fuel depletion
- Ozone depletion
- Freight transport
- Human toxicity to air
- Human toxicity to water
- Waste disposal
- Water extraction
- Acid deposition
- Ecotoxicity
- Eutrophication
- Summer smog
- Minerals extraction
UK Ecopoints are derived by adding together the score for each issue, calculated by multiplying the normalised impact with its percentage weighting. The annual environmental impact caused by a typical UK citizen therefore creates 100 Ecopoints. A higher Ecopoints score is indicative of greater environmental impact.

Ecopoints are calculated in the following manner:

First, the impact for each issue must be measured in an appropriate unit. For example, for fossil fuel depletion, the impact is measured in tonnes of oil equivalent (toe). This is known as a characterised impact.

Next, the characterised impacts are compared to the characterised impacts of a typical UK Citizen. These have been calculated by dividing the impacts of the UK by its population. This process produces normalised impacts.

Lastly, the normalised impacts are weighted. Weighting factors for each environmental issue have been determined by BRE from an extensive research exercise that included consultation with more than seven different interest groups including environmental campaigners, local and national government and manufacturers.

The weighted normalised impacts are called Ecopoints, and they can be added to provide a total Ecopoint score for the system under examination. The weightings (in descending order) and characterised impacts associated with a typical UK Citizen are provided in the Table below:

<table>
<thead>
<tr>
<th>Issue</th>
<th>% weighting</th>
<th>Characterised Impact associated with a typical UK Citizen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Change</td>
<td>37.8</td>
<td>12,300 kg CO₂ eq. (100 yr)</td>
</tr>
<tr>
<td>Fossil Fuel Depletion</td>
<td>12.0</td>
<td>4.09 tonnes oil eq.</td>
</tr>
<tr>
<td>Ozone Depletion</td>
<td>8.2</td>
<td>0.286 kg CFC11 eq.</td>
</tr>
<tr>
<td>Human Toxicity to Air</td>
<td>7.0</td>
<td>90.7 kg toxicity</td>
</tr>
<tr>
<td>Waste Disposal</td>
<td>6.1</td>
<td>7.19 tonnes</td>
</tr>
<tr>
<td>Water Extraction</td>
<td>5.4</td>
<td>418,000 litres</td>
</tr>
<tr>
<td>Acid Deposition</td>
<td>5.1</td>
<td>58.9 kg SO₂ eq.</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>4.3</td>
<td>178,000 m³ toxicity</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>4.3</td>
<td>8.01 kg PO₄ eq.</td>
</tr>
<tr>
<td>Photochemical Ozone Creation</td>
<td>3.8</td>
<td>32.2 kg ethene eq.</td>
</tr>
<tr>
<td>Minerals Extraction</td>
<td>3.5</td>
<td>5.04 tonnes</td>
</tr>
<tr>
<td>Human Toxicity to Water</td>
<td>2.6</td>
<td>0.0275 kg toxicity</td>
</tr>
</tbody>
</table>

1 percentages may not add up to 100% due to rounding

**B.2.4 Examples**

To calculate the Ecopoints for 1 tonne of mineral extraction:

- Characterised impact = 1 tonne mineral extraction
- Characterised impact for 1 typical UK citizen = 5.04 tonnes mineral extraction
- Normalised impact = 1/5.04 = 0.198
- Weighting = 3.5%
- Ecopoints = 0.198 x 3.5 = 0.693 Ecopoints.

To calculate the Ecopoints for 1000 kg of CO₂ emission:

- Characterised impact = 1000 kg CO₂ eq
- Characterised impact for 1 typical UK citizen = 12300 kg CO₂ eq
- Normalised impact = 1000/12300 = 0.0813
- Weighting = 37.8%
- Ecopoints = 0.0813 * 37.8 = 3.07 Ecopoints
B.3 Environmental Issues

B.3.1 Climate change

‘Global warming’ is associated with problems of increased desertification, rising sea levels, climatic disturbance and spread in disease. It has been the subject of major international activity, and methods for measuring it have been presented by the Intergovernmental Panel on Climate Change (IPCC).

Gases recognised as having a ‘greenhouse’ or global warming effect include CFCs, HCFCs, HFCs, methane and carbon dioxide. Their relative global warming potential (GWP) is calculated by comparing their global warming effect after 100 years to the simultaneous emission of the same mass of carbon dioxide.

B.3.2 Fossil fuel depletion

This issue reflects the depletion of the limited resource that fossil fuels represent. It is measured in terms of the primary fossil fuel energy needed for each fuel.

B.3.3 Ozone depletion

Ozone depleting gases cause damage to stratospheric ozone or the ‘ozone layer’. There is great uncertainty about the combined effects of different gases in the stratosphere and all chlorinated and brominated compounds that are stable enough to reach the stratosphere can have an effect. CFCs, Halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth’s atmosphere, increasing the amount of harmful UVB light hitting the earth’s surface.

B.3.4 Human toxicity to air and water

The emission of some substances such as heavy metals can have impacts on human health. Assessment of toxicity has been based on tolerable concentrations in air, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity.

B.3.5 Waste disposal

This issue reflects the depletion of landfill capacity, the noise, dust and odour from landfill (and other disposal) sites, the gaseous emissions and leachate pollution from incineration and landfill, the loss of resources from economic use and risk of underground fires etc.

B.3.6 Water extraction

This issue reflects the depletion, disruption or pollution of aquifers or disruption or pollution of rivers and their ecosystems due to over abstraction.

B.3.7 Acid deposition

Acidic gases such as sulphur dioxide (SO\textsubscript{2}) react with water in the atmosphere to form ‘acid rain’, a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem impairment of varying degree, depending upon the nature of the landscape ecosystems. Gases that cause acid deposition include Ammonia, Hydrochloric acid, Hydrogen, Fluoride, Nitrous Oxides and Sulphur Oxides.

B.3.8 Ecotoxicity

The emission of some substances such as heavy metals can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecotoxicity.

B.3.9 Eutrophication (or ‘over-enrichment of water courses’)

Nitrate and phosphates are essential for life, but in increased concentrations in water, they over-encourage the growth of algae, reducing the oxygen within the water leading to increasing mortality of aquatic fauna and flora and to loss of species dependent on low nutrient environments. Emissions of ammonia, nitrates, nitrous oxides and phosphorous to air or water all have an impact on Eutrophication.
B.3.10 ‘Low level ozone creation’

In atmospheres containing nitrogen oxides (a common pollutant) and volatile organic compounds (VOCs), ozone creation occurs under the influence of radiation from the sun. Different VOCs, such as solvents, methane or petrol, react to form ozone at different rates. Although ozone in the upper part of the atmosphere is essential to prevent ultraviolet light entering the atmosphere, increased ozone in the lower part of the atmosphere is implicated in impacts as diverse as crop damage and increased incidence of asthma and other respiratory complaints.

B.3.11 Minerals extraction

This issue reflects the total quantity of mineral resource extracted. This applies to all minerals, including metal ore, and applies to both UK and overseas extraction. The extraction of minerals for building in the UK is a high profile environmental topic but the minerals themselves are not considered to be scarce. Instead, this issue is a proxy for levels of local environmental impact from mineral extraction such as dust and noise. It assumes that all mineral extractions are equally disruptive of the local environment.
Appendix C: Tentative Specification and Quality Control Test Framework for RSA Foamed Concrete

All advice or information from the University of Dundee is intended for those who will evaluate the significance and limitations of its contents and take responsibility for its use and application. No liability (including that for negligence) for any loss resulting from such advice or information is accepted. Readers should note that this publication will be subject to revision from time to time and should therefore ensure that they are in possession of the latest version.

**Foreword**

This specification has been prepared under a Department of Trade and Industry and Waste and Resources Action Programme project undertaken by the Concrete Technology Unit of the University of Dundee. Representatives from the following organisations prepared this specification:

- Ballast Phoenix
- British Cement Association
- British Standards Institution
- Building Research Establishment
- Hydrock Consultants
- John Doyle Group plc
- Propump Engineering Ltd.
- Quarry Products Association
- Scott Wilson
- Transport Research Laboratory
- United Kingdom Quality Ash Association
- University of Dundee.

This specification was drafted on the assumption that the execution of its provisions is entrusted to appropriately qualified and competent people.

**Caution**

Where skin is in contact with fresh concrete, skin irritations are likely to occur owing to the alkaline nature of cement. The abrasive effects of sand and aggregate in the concrete can aggravate the condition. Potential effects range from dry skin, irritant contact dermatitis, to - in cases of prolonged exposure - severe burns. Take precautions to avoid dry cement entering the eyes, mouth and nose when mixing mortar or concrete by wearing suitable protective clothing. Take care to prevent fresh concrete from entering boots and use working methods that do not require personnel to kneel in fresh concrete. Unlike heat burns, cement burns may not be felt until some time after contact with fresh concrete, so there may be no warning of damage occurring. If cement or concrete enters the eye, immediately wash it out thoroughly with clean water and seek medical treatment without delay. Wash wet concrete off the skin immediately. Barrier creams may be used to supplement protective clothing but are not an alternative means of protection.

**Introduction**

This publication contains a specification for foamed concrete produced by injecting a grout or mortar containing recycled or secondary aggregates (RSA), with preformed foam.
C.1 Scope

This specification addresses the constituent materials, fresh and hardened concrete requirements, production control and transport issues of foamed concrete containing RSA. The material can be used in any construction application, where free-flowing and self-levelling consistence is required. If RSA foamed concrete is to be used in reinstatements, it shall additionally conform to the requirements of the ‘Specification for the Reinstatement of Openings in Highways’ issued by the Highway Authorities and Utilities Committee. If RSA foamed concrete is to be used in any other Highway Works, it shall additionally conform to the requirements of the ‘Specification for Highway Works’ Series 1000.

C.2 References

C.2.1 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this specification. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

AggRegain, Technical Note for use of RSA in foamed concrete road building construction projects.


BS EN 197-1, Cement. Part 1: Composition, specifications and conformity criteria for common cements.


BS EN 450, Fly ash for concrete - Definitions, requirements and quality control.

BS EN 934-2, Admixtures for concrete, mortar and grout. Part 2: Concrete admixtures - Definitions, requirements, conformity, marking and labelling.

BS EN 1008, Mixing water - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete.


BS EN 12390-1, Testing hardened concrete. Part 1: Shape, dimensions and other requirements for specimens and moulds.


BS EN 12620, Aggregates for concrete.

BS EN ISO 9001, Quality management systems - requirements.


BS 3892-2, Pulverized-fuel ash - Part 2: Specification for pulverized-fuel ash to be used as a Type I addition.
C.2.2 Informative references

The following informative documents contain information which, through reference in this text, constitute recommendations of this specification. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 8500-1, Concrete - Complementary British Standard to BS EN 206-1. Part 1: Method of specifying and guidance for the specifier.

C.3 Terms and Definitions, Symbols and Abbreviations

C.3.1 Terms and definitions

For the purposes of this Specification, the terms and definitions given in BS EN 206-1, BS EN 12620, BS 8500 and the following apply.

**foamed concrete (also known as aerated concrete and cellular concrete)**
highly aerated grout or mortar with uniformly distributed voids of 0.1mm to 1.0mm diameter, air content in excess of 20% by volume of material and densities of concrete in the fresh state typically between 400 kg/m³ and 1600 kg/m³.

**surfactant**
chemical admixture that, when in an aqueous solution, reduces the surface tension of water and enables the creation of foam.

**preformed foam**
foam prepared (using either wet or dry production methods) separately from the mortar or grout comprising one part of surfactant and 5 to 40 parts of water.

**base mix**
cementitious grout or mortar containing recycled and secondary aggregates (RSA), into which preformed foam is incorporated to produce foamed concrete.

**recycled aggregates**
aggregates derived from reprocessing materials previously used in construction.

**secondary aggregates**
by-products of industrial processes, not previously used in construction, either manufactured or natural.

**in-line mixer**
mixing unit into which the 'base' mix is discharged and blended with the foam.

**cement content**
mass of CEM I or other cement combinations in a cubic metre of fresh, free-flowing and self-levelling foamed concrete, expressed in kg/m³.

C.3.2 Symbols and abbreviations

For the purposes of this Specification Document, the symbols and abbreviations given in BS EN 206-1, BS EN 12620, BS 8500 apply.
C.4 Constituent Materials

C.4.1 Cements and combinations

General suitability is established for the cements and combinations given in BS 8500-2 in Table 1. However, compatibility of the cements and combinations with the surfactants used to produce the preformed foam needs to be established in small-scale trials.

C.4.2 Recycled and secondary aggregates

Recycled and secondary aggregates shall conform to the grading, physical and chemical property requirements described below. General suitability is established for the following aggregates:

- recycled aggregates and recycled concrete aggregates, resulting from reclamation or processing of concrete previously used in construction, which originate from appropriate identified structures with a known history of use.

NOTE: A Technical Note published by AggRegain (the sustainable aggregates information service from WRAP) allows the use of a few RSA (i.e. recycled concrete aggregate, china clay sand, slate aggregate, blastfurnace slag, recycled aggregate and pulverized-fuel ash) in foamed concrete road building projects (i.e. lower trench fill and reinstatement of openings in highways). However, in addition to the specific requirements for these RSA in the AggRegain Technical Note, reference should be made to the ‘Specification for Highway Works’ Series 1000, Clause 1043 for the application of foamed concrete in highway reinstatement works.

Whilst this tentative specification provides generic requirements for the use of recycled and secondary aggregates in foamed concrete, it is recognised that additional characteristics and requirements, specific to the type of RSA, may be specified on a case-by-case basis.

Composition requirements

The RSA allowed to be used in foamed concrete road building projects (i.e. lower trench fill and reinstatement of openings in highways) shall conform to the composition requirements in the AggRegain Technical Note.

No additional restrictions on the composition requirements of other RSA to be used in foamed concrete are specified.

Grading requirements

All RSA used in foamed concrete shall pass a 6.3mm sieve and shall conform to the MP and FP grading limits given in BS EN 12620. Larger or finer size RSA may be used, provided it can be shown to be practicable and non-detrimental to the mix stability.

Physical properties requirements

No restrictions on the physical properties of other RSA to be used in foamed concrete are specified. However, the compatibility of the RSA with the foamed base mix shall be checked in trials prior to use.

Chemical properties requirements

The RSA allowed to be used in foamed concrete road building projects (i.e. lower trench fill and reinstatement of openings in highways) shall conform to the requirements on alkali contribution, acid soluble and total sulfur contents stipulated in the AggRegain Technical Note.

No additional restrictions on the chemical properties of other RSA to be used in foamed concrete are specified. However, in certain circumstances, testing may be required to prove that the RSA foamed concrete will not lead to contamination of ground or surface waters due to leaching or spillages.

C.4.3 Admixtures

Suitable foaming agents shall conform to ASTM C 869-91 and ASTM C 796-97. When the foamed concrete contains one or more chemical admixtures in addition to a foaming agent, these shall conform to BS EN 934-2 and their compatibility with the foaming agent shall be checked prior to use.

C.4.4 Mixing water

Mixing water shall conform to BS EN 1008.
C.5  Requirements for RSA Foamed Concrete

C.5.1  General

The method for specifying RSA foamed concrete is given in Annex A.

The RSA foamed concrete shall comprise constituent materials described in Section C.4 proportioned to give the specified plastic density and consistence. The foamed concrete shall be designed to minimise segregation. Initial tests should verify that the difference in oven-dry hardened density, measured in accordance with BS EN 12390-7, between the top 25mm and bottom 25mm of a 100mm diameter by 300mm length cylinder is not more than 50 kg/m³.

NOTE: Oven drying shall be carried out at 30°C. The density of specimens around or below 1000 kg/m³ will be determined by weight measurement and calculation of their volume by geometric dimensions.

C.5.2  Requirements for fresh concrete

Consistence
When measured in accordance with Annex B, the slump flow spread shall be within 50mm of the specified target value.

Plastic density
The plastic density shall be measured in accordance with BS EN 12350-6. The as-received hardened density on any batch, measured in accordance with BS EN 12390-7, shall not be more than 50 kg/m³ above or 150 kg/m³ below the plastic density value.

Composition
The requirement for target water/cement ratio (to ensure an adequate consistence of the base mix and to prevent ‘balling’ of constituents in the free-fall mixer) applies to the grout, mortar or concrete prior to foam injection. The composition of the base mix fraction shall be within the tolerances given in BS EN 206-1, Table 21 and the target water/cement ratio shall be within the tolerance given in BS EN 206-1:2000, 8.3.

Concrete temperature
In order to minimise the risk of thermal strains and cracking of the RSA foamed concrete, the sustained core temperature of a pour shall not exceed 30°C above ambient temperature.

C.5.3  Requirements for hardened concrete

Oven-dry density
The oven-dry density (at 30°C) measured in accordance with BS EN 12390-7 shall be within 200 kg/m³ of the specified target plastic density.

Cube strength
Where a minimum cube strength is specified, the test shall be carried out on a minimum of three 150mm RSA foamed concrete cubes at each test age (cast in polystyrene moulds, with no mould release oil or cast in steel moulds lined with a non-stick plastic film) and the average shall be reported. The cubes shall be deemed to be representative of the whole volume of the RSA foamed concrete produced and shall have been made in accordance with BS EN 12390-1, except that the foamed concrete shall be placed in the mould without any tamping or vibration, other than gently rocking the mould on a firm base. The test cubes shall be sealed-cured (wrapped in cling film and placed in a sealed plastic bag at 20°C) and tested for cube strength in accordance with BS EN 12390-3.

Strength tests shall be carried out during trials to ensure that the minimum cube strength can be achieved at a given test age. If the RSA foamed concrete during the trials does not meet the minimum cube strength requirements, the mix design shall be modified and the tests repeated.

C.6  Non-Conformity of RSA Foamed Concrete

If any of the requirements for RSA foamed concrete described in Section C.5 are not satisfied, the Engineer shall decide what action shall be taken. Such action shall depend on the structural importance and location of the RSA foamed concrete concerned and shall be at the Contractor’s expense.
C.7 Production Control

C.7.1 General

The requirements in BS 8500-2, 11.1 and 11.2, apply to storage of materials and batching of constituent materials respectively. No water shall be added to the base mix after batching and prior to discharge into a hopper.

C.7.2 Production procedures

The foam shall be prepared and added to the base mix in the truck mixer, agitator or in-line mixer at the point of delivery to prevent foam collapse during transport. The foam shall be of density 50 ± 10 kg/m³ (unless required otherwise by the specifier) and shall be added to the base mix until the plastic density of the highly aerated grout/mortar (measured in accordance with BS EN 12350-6) is within ± 50 kg/m³ of the target plastic density.

C.7.3 Responsibility of the producer

The producer of the base mix shall hold current product conformity certification based on product testing and surveillance coupled with approval of the quality system to BS EN ISO 9001 by a certification body accredited by the Secretary of State (or equivalent) for the relevant areas of product and systems conformity certification. On request, the technical regulations of the accredited certification body shall be available for examination.

The producer shall inform the specifier of the status of the concrete production plant at the time of tender and immediately if any change in status occurs during the period between the time of tender and completion of supply.

C.8 Transport of Concrete

C.8.1 General

The base mix shall be transported from the mixer to the point of delivery as rapidly as practicable by methods that will maintain the required consistence and will minimise segregation and loss of any constituents or ingress of foreign matter or water.

C.8.2 Transport to the point of delivery

The base mix shall be transported to the point of delivery in a truck mixer, agitator, or in-line mixer.

C.8.3 Time of transport

The base mix shall be delivered within 2h after the time of loading unless a shorter time is specified or a longer time permitted by the specifier.

NOTE: A longer time after loading may be appropriate in cool, humid weather or where pfa or retarding admixtures have been used. A shorter time may be essential in hot weather with cement rich foamed concretes, or where accelerating admixtures have been used.

C.9 Delivery Ticket

With each batch of RSA foamed concrete, the producer shall supply a delivery ticket with the following information:

- RSA foamed concrete conforming to publication XXX;
- target water/cement ratio;
- target plastic density;
- target slump-flow spread;
- certification mark.

C.10 Placement of RSA Foamed Concrete

The free-flowing and self-levelling RSA foamed concrete shall be placed without tamping or any other form of compaction.
Annex A: Method of Specifying RSA Foamed Concrete

The specification shall contain the following:

- RSA foamed concrete conforming to publication XXX;
- target water/cement ratio;
- target plastic density;
- target slump-flow spread, mm;

The specification may also contain additional requirements, specific to the nature of the project.
Annex B: Method for Determination of Slump Flow Spread

B.1 General
This annex describes a test method for the determination of the slump flow spread of RSA foamed concrete.

B.2 Principle
The fresh RSA foamed concrete is placed into a mould in the shape of a frustum of a cone. When the cone is withdrawn upwards, the distance the foamed concrete has spread over a flat horizontal surface is measured.

B.3 Apparatus
B.3.1 Mould to form the test specimen, conforming to BS EN 12350-2, 4.1.

B.3.2 Funnel (optional), made of non-absorbent material not readily attacked by cement paste and having a collar to enable the funnel to be located on the mould.

B.3.3 Base plate/surface, non-absorbent, rigid, flat, plate or other surface at least 700mm by 700mm on which to place the mould.

B.3.4 Re-mixing container, flat tray of rigid construction and made from a non-absorbent material not readily attacked by cement paste. It shall be of appropriate dimensions such that the RSA foamed concrete can be thoroughly re-mixed, using the square-mouthed shovel. NOTE: The square-mouthed is required to ensure proper mixing of material on the re-mixing container.

B.3.5 Shovel, with square mouth.

B.3.6 Calipers and/or rule, graduated at intervals not exceeding 5 mm. NOTE: A jig may be used to aid the measurement of slump-flow.

B.4 Test sample
The sample of the RSA foamed concrete shall be obtained in accordance with BS EN 12350-1. The sample shall be re-mixed using the re-mixing container and the square-mouthed shovel before carrying out the test.

B.5 Procedure
Set the base plate so that it is horizontal and stable. Dampen the mould and base plate and place the mould on the base plate. During the filling of the mould hold it firmly against the base plate/surface by clamping in place, or by standing on the two foot pieces.

Fill the mould and remove spilled foamed concrete from the base plate. Remove the mould from the foamed concrete by raising it carefully in a vertical direction. As the mould is started to be raised, start the stop-watch. Perform the operation of raising the mould in 5s to 10s, by a steady upward lift, with no lateral or torsional motion being imparted to the foamed concrete. Carry out the entire operation from the start of filling to the removal of the mould without interruption and complete it within 150 s.

Measure the diameter of flow in the direction where it appears to be widest and in the direction that is at right angles to this measurement. Take the average of these two measurements, rounded to the nearest 5mm, as the slump-flow of the test sample.

B.6 Test Report
The test report shall include:

- identification of the test sample;
- location of performance of test;
- time and date of performance of the test;
- the slump flow spread result;
- any deviation from standard method;
- a declaration by the person carrying out the test that it was carried out in accordance with this standard, except if deviation from the standard method is reported.

The report may also include:

- the temperature of the concrete specimen at time of test;
- other comments.