**ABSTRACT.**
This paper outlines the social, legislative and technical reasons for recycling waste glass, with specific emphasis on its use in concrete as high-value decorative aggregate or cement replacement material, as well as low-value aggregate. The experiences of two major research efforts in the UK (Centre for Cement and Concrete, at the University of Sheffield) and the USA (Department of Civil Engineering and Engineering Mechanics, University of Colombia) are drawn upon. Current legislation in the UK and EU is forcing the packaging waste chain, glass collectors and reprocessors and concrete companies to reconsider the appropriateness of using glass in concrete and this effort has been supported by the Waste and Resources Action Programme (WRAP). Work in the USA and the UK indicates that, with appropriate ASR mitigation techniques and mix proportioning, high-value architectural products or normal concrete could be made with glass aggregates and also that finely-ground glass appears to have significant pozzolanic properties. A selection of products in current development and ASR research results are presented.

**Keywords:** glass, aggregate, pozzolan, ASR, waste legislation, recycling

**Ewan Byars** is the Director of the WRAP-funded ConGlassCrete I and II Projects and the Research and Industrial Development Manager at the Centre for Cement and Concrete, University of Sheffield. His research interests include binder technology, concrete durability and alternative concreting materials.

**Christian Meyer** is a Professor of Civil Engineering and Engineering Mechanics at Colombia University, New York, where he has conducted extensive research on the use of waste glass in concrete

**HuiYing Zhu** gained wide experience in the area of ceramics and concrete technology at the Architectural Research and Design Institute in GuangXi Province, China and is now the research assistant to the ConGlassCrete I Project and a PhD scholar at the University of Sheffield.

## INTRODUCTION

Post-consumer and waste plate, float and other glass types represent a major component of the solid waste disposal in many countries and currently, most is still landfilled [1]. The EU Landfill Directive 1999/31/EC [2] and the UK Landfill Tax Regulations [3] have been developed to divert such biodegradable waste away from landfill. In addition, the Packaging Waste Regulations [4] provide legislative pressures to recycle packaging glass and the UK PRN (Packaging Waste Recovery Notes) scheme provides financial incentives for recycling.

Glass has the virtue that it can be remelted in an infinite number of time without any degradation of physical properties and theoretically, the glass manufacturing sector could use 100 % recycled glass as a primary feedstock. However, due to tolerances on contamination, there is a practical limit [5]. Major current alternative uses for recycled glass are: fill, drainage, filtration, pipe bedding, road base, glasphalt, sandblasting, hydraulic cements, reflective beads and fish tanks.

The use of waste glass as an aggregate in concrete has been tried in the past, but suffered due to deleterious alkali-silica reaction. Thus, due to highly reactive silica content and amorphous structure, glass has traditionally been considered unsuitable for use in concrete. Numerous laboratory studies investigating the ASR phenomenon in glass concrete have been documented elsewhere [6, 7, 8]. There are, however, a variety of possible measures available to mitigate ASR as follows:

- Grinding glass to a particle size less than 300 μm;
- Mineral admixtures (e.g., Metakaolin or fly ash) are known to effectively reduce ASR expansion;
- Using alkali-resistant glass;
- Modifying the glass chemistry;
- Sealing the concrete to keep it dry;
- Low-alkali cements;

## SOCIAL AND ECONOMIC DRIVERS

In modern civilizations, technological developments take place if driven by one or more of the following forces:

1. Economical, i.e. the incentive of monetary gain
2. Progress, i.e. the prospect of novelty or improvement in quality or Performance
3. Governmental legislation
4. Good will, if everything else fails.

In the case of recycling and reusing waste glass, it is possible to recognize all four forces. The economic incentive is obviously one of the fundamental forces that drive human behavior. If it can be shown that the substitution of glass for natural aggregate in concrete saves the concrete producer money (assuming all other parameters are equal), then the producer will not hesitate to implement such a substitution.

If the substitution of one natural aggregate by another one promises certain advantages, such as an increase in strength or durability, then such substitution is likely to happen, even if the economic advantage is not immediately apparent. This could continue until the market figures out whether the improved properties or novelty aspect translate into an added value, which in turn will fetch a higher price. If the substitution leads to unique properties, which cannot be achieved any other way, then the economic success is likely to be preprogrammed.

In modern market-based economies, it is possible that the profit incentive, which is so powerful in controlling individual behavior, does not result in the common good of society. Environmental protection and sustainable development are the most striking examples. In these cases, governmental bodies have to establish rules of conduct in the interest of the common good. They can achieve these goals either by coercive legislation, or by offering fiscal incentives and disincentives.

Then there is a fourth force, which sometimes leads individuals to act against their own personal advantage if they perceive a common good or higher purpose. This force is clearly visible in the environmental movement, whose participants are often willing to pay more for goods that they know are environmentally friendly.

## LEGISLATIVE AND FISCAL DRIVERS

Table 1 summarises the legislative and fiscal directives responsible for the growth in EU and UK recycling of packaging waste.

Table 1. Summary of Legislative and Fiscal Drivers in Europe and the UK

| Legislation | Region | Action | Date |
|---|---|---|---|
| Packaging & Packaging Waste Directive 94/62/EC | Europe | To enforce increased packaging waste recycling | 1994 |
| The Producer Responsibility Obligations (Packaging Waste) Regulations 1997 | UK | To comply with Directive 94/62/EC | 1997 |
| Packaging Waste Recovery Notes | UK | To increase packaging waste recycling | 1996 |
| Landfill Directive 1999/31/EC | Europe | To reduce waste dumped in landfill | 1999 |
| Landfill Tax Regulations | UK | To divert waste away from landfill | 1999 |
| Aggregate Levy | UK | To reduce demand for virgin aggregates | 2000 |

### Packaging Waste Legislation

#### *3.1.1 EC Directive 94/62/EC on Packaging and Packaging Waste*

This directive defines packaging as "all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer, …". The seven material categories of packaging waste listed include glass, paper, aluminium, metal, plastic, wood and incineration. The Directive's targets to be met by 2001 are to recover 50-65% by weight of packaging waste and recycle 25-45% by weight of packaging materials, with a minimum of 15% by weight of each material. It also requires member states to establish return, collection and recovery system.

***3.1.2 The Producer Responsibility Obligations (Packaging Waste) Regulations 1997***
The UK government complies with EC Directive 94/62/EC through the Producer Responsibility Obligations (Packaging Waste) Regulations 1997. Under these regulations UK businesses have a recycling and recovery obligation if they manufacture, fill or sell packaging waste materials in excess of 50 tonnes/year and have a turnover in excess of £2m pounds (reduced to £1m with effect from 2000). The targets are 50%, 25% and 16% for recovery, recycling and minimum recycling for each of the packaging materials identified by Directive 94/62/EC.

***3.1.3 Packaging Waste Recovery Notes (PRNs)***
PRNs are a UK Government scheme designed to provide incentives to increase packaging waste recycling and reuse. The parties responsible for the waste pay a cash input to the chain of collectors, processors, re-users and recyclers. Approximately £20-35 (depending on market availability of Recovery Notes) per tonne is available to the reprocessing chain.

**Landfill Legislation**

**EU landfill directive**
From July 1999, Directive 1999/31/EC set out increasingly stringent targets for reducing waste dumped in landfill and also required Member States to set up national strategies to meet these targets. Waste landfills must be reduced to 75 % of the 1995 baseline by 2010, 50% by 2013 and 35% by 2020.

**The UK landfill tax regulations**
Introduced in 1999, the UK Landfill Tax Regulations were aimed at diverting waste away from landfill by taxing the disposal of waste in landfill. The tax in 2002 was £2/tonne for inactive waste and £12/tonne for active waste. This is set to rise by £1/tonne each year to 2004 when it will be reviewed.

**Aggregate Levy (Tax)**
Introduced in April 2002, the Aggregate Levy[10] was aimed at reducing the demand for virgin aggregates, encouraging the use of recycled materials and addressing the environmental costs associated with quarrying, e.g. noise, dust, visual intrusion. The tax applies to sand, gravel and crushed rock and is charged at £2/tonne.

## GLASS RECYCLING

**The UK**

Glass has always been recycled throughout its history and the first reported recycling company in the UK was set up in 1922 [11]. Bottle banks were introduced in the mid 1970s in several European countries to recycle post-consumer glass cullet. In 2000 there were eight companies in the UK with 14 sites producing 1.7 million tonnes of container glass plus 500,555 tonnes of imported glass containers, giving a total consumption of 2.2 million tonnes of which 33% was recycled. Figure 1 [6] shows container glass arising and recycling in UK in recent years.

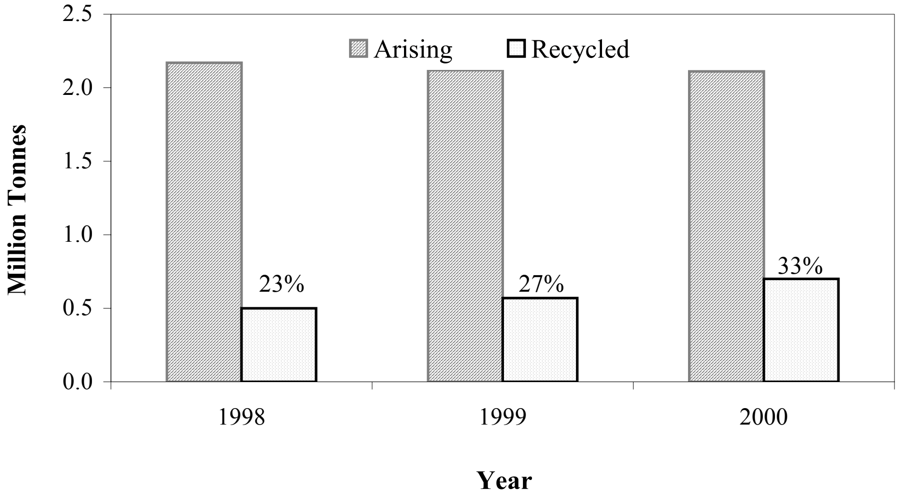


**Figure 1 UK container glass waste arising and recycled**

69% of UK production is flint (clear) glass, but 52% of collected glass is green and over 70% is green and amber for which there is lower demand in the UK. There has been some debate over the surplus of green glass collected, mainly due to imported wine bottles, with talk of a "green mountain" of glass. Therefore there has been a lot of interest in developing alternative uses (other than making containers) for recycled coloured glass. In line with this, one of the targets set by the Waste and Resources Action Programme (WRAP) is to divert an additional 0.2 million tonnes of glass cullet for use in construction industry.

**The USA**

The goals of sustainability in general and recycling in particular are directly related to the solid waste disposal problem faced by municipalities nationwide, especially in New York City – the largest American Metropolis. It is estimated that the disposal of their solid waste costs New Yorkers approximately $1billion per year. Aside from this fiscal burden, the very idea of landfilling large amounts of solid waste runs counter to the widely accepted principles of sustainability. Therefore, many local and State governments have mandated increased recycling efforts. Waste glass constitutes approximately 6% of New York's solid waste, and because it is filthy, of mixed color,
and partially broken, secondary markets for it are virtually nonexistent. Its beneficial use as concrete aggregate could save New Yorkers theoretically some $60 million, aside from the environmental benefits and other opportunities derived from the value to added concrete products.

## USE OF WASTE GLASS CULLET IN CONCRETE

### Technical Background

As a material glass offers several advantages that can be exploited in concrete products:

- It has zero water absorption and is one of the most durable materials known to man.
- The hardness of glass may give the concrete enhanced abrasion resistance.
- Glass aggregates may improve the flow properties of fresh concrete.

- The esthetic potential of color-sorted post-consumer glass has barely been explored and offers numerous novel opportunities for architectural purposes.
- Very finely ground glass has been shown to be an excellent filler and may have sufficient pozzolanic properties to serve as partial cement replacement.

With ground cullet as a cement replacement material:
- Distinct strength increases above the control are noted after 28 days, particularly with very finely ground cullet and replacement levels up to 30% of the cement.
- The effects of ASR appear to be reduced with ground cullet, with the reduction increasing with replacement level.

As an aggregate:
- A pessimum aggregate size of around 0.6-2.36 mm exists for maximum ASR susceptibility in cementitious systems for clear and amber glass. With smaller sizes ASR expansion reduces [7].

## UK Research Effort

### The ConGlassCrete projects
The University of Sheffield, in collaboration with 26 industrial and governmental partners are conducting two major investigations (ConGlassCrete Projects I and II) – with a total value of around £1.2m – into the potential for using waste glass as a high-value ingredient in concrete.

It is hoped the projects, ConGlassCrete I and ConGlassCrete II – will lead to waste glass being used in a wide range of concrete products. The projects are especially focused on developing cullet as a decorative, exposed or polished aggregate finish in bespoke concrete products and as a high-value cementitious material that will reduce consumption of Portland cement. Other potential applications being explored include waste glass fibre-reinforcement and general low-value aggregate.

### ASR testing and suppression
A wide range of laboratory studies is investigating the ASR reactivity of various colours and particle size ranges of waste glass cullet as coarse and fine aggregates and as pozzolan in concrete. The testing method adopted at this stage is ASTM C 1260-94[12] in order to yield quick results.

Initial results show that there exists a pessimum size of glass for ASR reactivity, Figure 2. Figure 3 shows that the rate of reaction also varies with glass colour. As can be seen from Figure 3, for 6-12 mm glass aggregates, amber and clear glasses are worse than green and blue.

A range of ASR mitigating-suppressants have also been studied. These include white cement, PFA, Super-classified PFA (SPFA), GGBS, MS (micro silica), MK (Metakaolin) and various colours and fineness of glass pozzolan. The effectiveness of these is shown in Figure 4. Up to a test age of 63 days (well beyond the 14-day ASTM C 1260 limit) whilst a 3-6 mm flint glass with PC alone shows strong ASR effects, the same aggregate in a PC/MK blended cement causes no reaction. With 20% green glass pozzolan (sub 40 micron fineness) as a cement replacement material in the same mix, the ASR expansion is reduced significantly, but not totally eliminated.

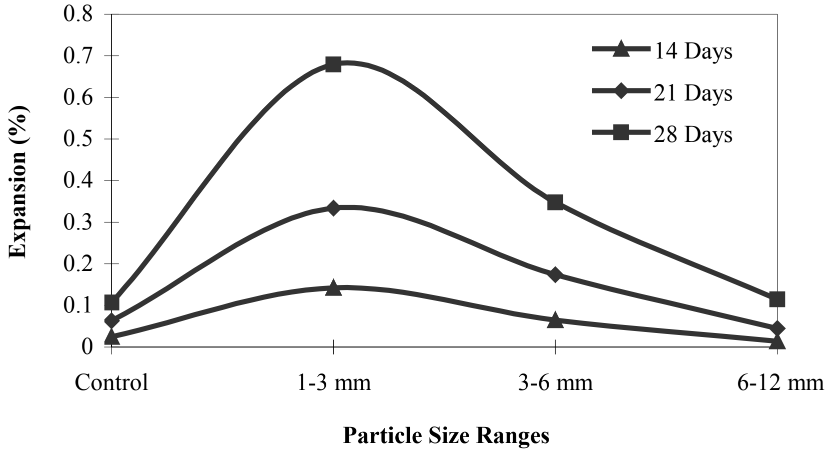


**Figure 2 Pessimum size of blue glass (30 % replacement of total normal aggregate)**

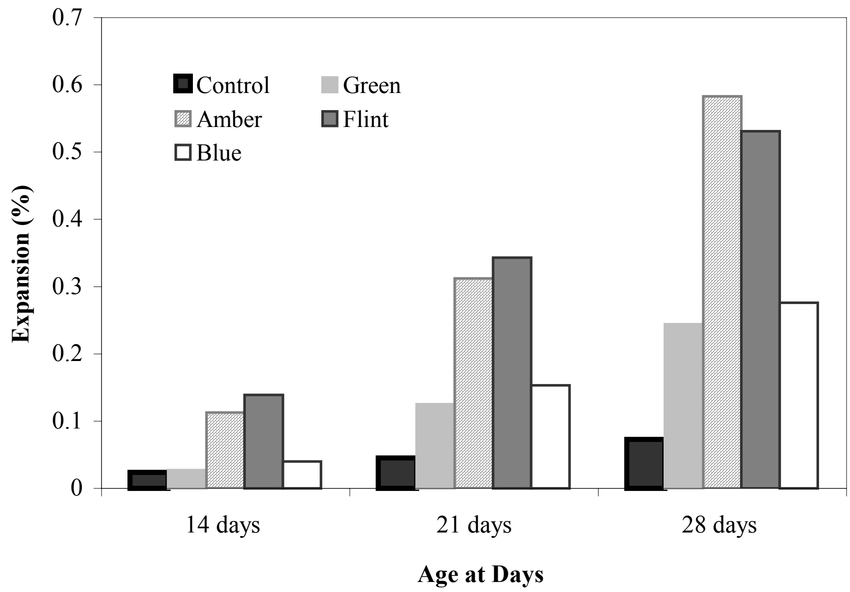


**Figure 3. Relative reactivity of 6-12 mm glass aggregate of different colours (100% replacement of normal coarse aggregate)**

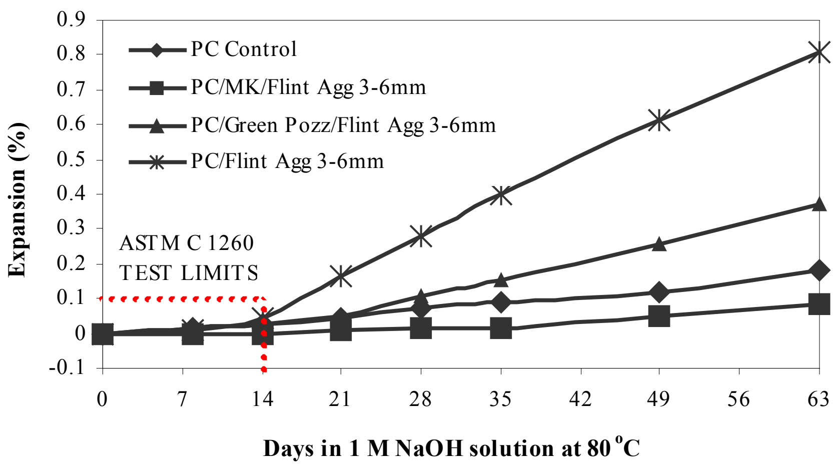

**Figure 4. Effect of green glass pozzolan and MK in suppressing ASR**

**Development of pre-cast concrete products**

A wide range of pre-cast concrete products using container glass cullet as coarse and fine aggregates as well as cement replacement have been made in collaboration with pre-cast concrete companies including Aggregate Industries UK, Mashalls Mono, CRH Forticrete Group, Conways Concrete Products, Stowells Concrete and Trent Concrete. The products include semi-dry cast blocks, pavers, slabs, hydraulic wet press flags, kerbs, cast stone, cast concrete feet and roof tiles, Figure 5. Most of the products have met product-specific compliance criteria at first pass and some have exceeded the performance of the currently marketed products.

Parallel long-term ASR samples are currently being tested at Sheffield University, with encouraging results to date.

**Premium products**

The ConGlassCrete Projects are also seeking to identify the highest possible values for waste glass in high value concrete products. Figure 6 shows two examples from a range of exposed aggregate finish made with low-alkali white cement and sorted-colour waste glass aggregates (Trent Concrete).

Semi-dry cast blocks (Conways)

Cast stone (CRH Forticrete Group)


Semi-dry cast blocks (Stowell)


Wet-pressing kerbs (Agg. Industries UK)

**Figure 5a Selected full-scale trial concrete products using container glass aggregates and pozzolan**

Wet-pressing flags (Marshalls)

Roof-tiles (CRH Forticrete Group)

**Figure 5b Selected full-scale trial concrete products using container glass aggregates and pozzolan**

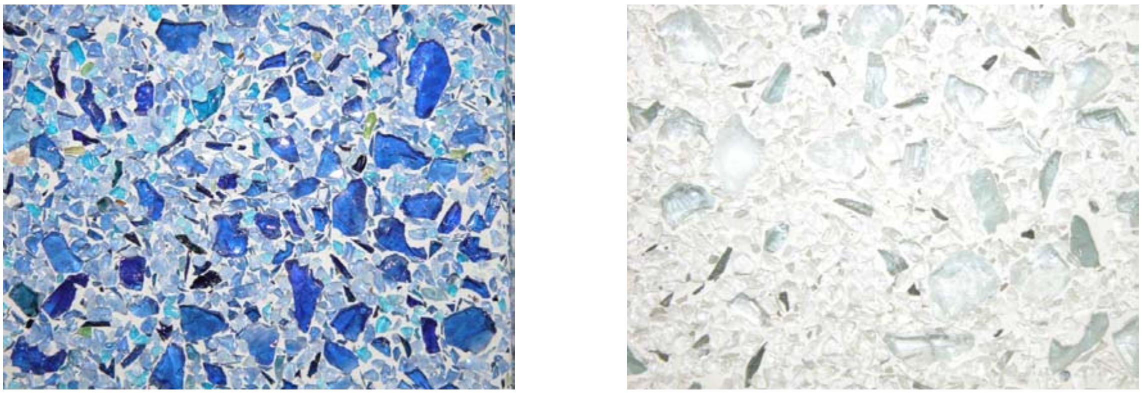

**Figure 6 Exposed glass aggregate finishes made with white cement**

## USA Research Effort

### Glass research at Columbia University

In 1995, a major research project was initiated at Columbia University with support from the New York State Energy Research and Development Authority (NYSERDA) to investigate the feasibility of using waste glass in concrete products.

### Commodity products

The first commodity product to be developed for commercial production was a concrete masonry block unit, for which a rather modest 10% of fine aggregate was replaced by finely ground glass, or 10% of the cement by glass powder. In view of such small amounts of material substitution, no major effects on strength or other block properties were observed, as expected.

### Value-added products

Figure 7 shows some of the value-added products produced by Columbia University in New York. In these applications, glass substitution is used to exploit the special properties that can add value to a material supposed to be a waste product. With appropriate surface treatments, glass can be used to make terrazzo tiles or tabletop counters, or as exposed aggregate surfaces for building facade elements. Glass concrete terrazzo tiles and roof deck pavers are already being manufactured commercially.

**Figure 7 Value-added products produced in New York**

There are numerous other promising applications in the architectural and decorative fields. It is not only possible to engineer the material's mechanical and other physical properties to satisfy any reasonable set of specifications. Surface textures and appearances can be created using techniques that are well known in the field of architectural concrete, while fully utilizing the esthetic potential of coloured glass. The number of potential applications is limited only by one's imagination. To name just a few:

- Building facade elements
- Pre-cast wall panels
- Partitions
- Floor tiles
- Wall tiles and panels
- Elevator paneling
- Table top counters
- Park benches
- Planters
- Trash receptacles

## CONCLUSIONS

Although the technical know-how to suppress the detrimental effects due to ASR has existed for some time, the use of crushed glass as aggregate is a relatively novel concept. By identifying the special properties of crushed glass and exploiting these in the design of concrete products, it is possible to add value to a material that otherwise would simply be added to the solid waste stream and disposed of in landfills. Such beneficial use of recycled glass offers three important advantages:

1. The targeted exploitation of glass properties results in concrete products with properties that are superior to those produced with natural aggregates;

2. The removal of the glass from the solid waste stream preserves sparse landfill capacity and saves taxpayers the cost of its disposal; moreover, such beneficiation of a waste product is compatible with the requirements of sustainable development;

3. By adding value to a waste product, both the waste management and concrete industries stand to benefit financially. Developers may also be able to benefit from tax write-offs by using building materials with recycled material content.

4. The beneficial use of glass as concrete aggregate and pozzolan in concrete is concurrently being proven in the UK and USA. However, until and unless long-term test results and robust specifications are available, potential users are advised to exercise normal engineering caution and ensure that proposed products are thoroughly tested prior to use.

**References**

[1] Yixin Shao, et, al, Studies on concrete containing ground waste glass, Cement and Concrete Research, 30(2000), pp 91-100.
[2] European Parliament and Council Directive 1999/31/EC on the landfill of waste, Official Journal L 182/1, 16.7.1999.
[3] The Landfill Tax Regulations 1996, The Stationery Office Limited, Statutory Instrument 1996 No. 1527, **http://www.hmso.gov.uk/si/si1996/Uksi_19961527_en_2.htm**, 18/06/2003.
[4] The Producer Responsibility Obligations (Packaging Waste) Regulations 1997, The Stationery Office Limited, Statutory Instrument 1997 No. 648, **http://www.legislation.hmso.gov.uk/si/si1997/1970648.htm**, 18/06/2003
[5] Enviros, Recycled Glass Market Study & Standards Review, www.wrap.org.uk, May 2002.
[6] Meyer C. and Baxter, S. "Use of Recycled Glass for Concrete Masonry and Blocks", Final Report to New York State Energy Research and Development Authority, Rep. No. 97-15, Albany, NY, Nov. 1997.
[7] Jin, W, "Alkali-Silica Reaction in Concrete with Glass Aggregate – A Chemo-Physico-Mechanical Approach", PhD Dissertation, Columbia University, New York, NY, 1998.
[8] Jin, W, C. Meyer and S. Baxter, "Glasscrete – Concrete with Glass Aggregate", ACI Materials Journal, Mar - April, 2000.
[9] European Parliament and Council Directive 94/62/EC on packaging and packaging waste, Official Journal L 365, 31.12.94.
[10] Aggregate Levy, **http://www.sepa.org.uk/wastemin/legis/aggregates.htm**, 28/03/ 2003
[11] J. C. Smith & C. Roberts, R&D Interim Report 2 to WRAP, GLASS GOES GREEN, Centre for Environmental Studies, December 2002.
[12] ASTM C 1260 – 94, "Standard Test Method for Potential Alkali Reactivity of Aggregate (Mortar-Bar Method)", Annual Book of ASTM Standards, Vol. 04.02, 1994.