Int. Symposium on Recycling and Reuse of Glass Cullet
19-20 March, 2001
University of Dundee, Scotland

Recycled Glass – From Waste Material to Valuable Resource

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ABSTRACT. The United States is a country blessed with enormous riches in natural materials. This explains their wasteful exploitation in the past. Only recently, the American public has become aware that even in North America, these resources are finite. This awareness, coupled with the scarcity of suitable landfills, has led to the increasing acceptance of the need for recycling. Glass constitutes a major component of solid waste both in the US and other highly developed countries. Relatively easy to separate from the general solid waste stream and owing to its physical and chemical properties, it is a prime candidate for recycling. A serious obstacle to its use in concrete has been the alkali-silica reaction (ASR). But with recent advances in research, this problem has basically been solved. This success opens up a wide spectrum of potential applications of as yet unfathomed breadth. At the one end of the spectrum, low-level commodity products such as concrete masonry blocks or paving stones are subject to severe economic constraints dictated by tight commodity markets. At the other end of the spectrum, high-value specialty products are subject to much less market pressure. The material's value derives from the uniqueness of its esthetic appearance, mechanical properties and the novelty aspect, for which customers are prepared to pay a premium. Seen in a broader context, the success of waste glass in opening new markets may serve as a model for other solid waste materials, such as wood, carpets, tires, and even plastics and metals, which already have enjoyed comparably long histories of successful recycling and reuse.

Keywords: Recycling, Waste Glass, Mixed-Color Cullet, Glass Concrete™, Paving Stones, Precast Concrete, Architectural Concrete.

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INTRODUCTION

The United States is the wealthiest nation on earth. It did not become this by chance, but rather owes it to the concurrence of several propitious circumstances. First there is its size and the wealth of natural riches, although many other countries are similarly blessed. Then there is the unique makeup of its population, derived from immigrants from all over the world. Most of these constitute self-selected groups characterized by exemplary adventurism and a drive to succeed, as well as hard work. Finally, "Yankee ingenuity" deserves some credit, that is, the readiness to tinker and try something new, especially where conventional wisdom has it that "it can't be done". But we should not forget that, except for a disastrous civil war, the United States has enjoyed almost 200 years of relative peace on its own soil. Instead of having experienced the devastations of two world wars, its economy has rather benefited from these turbulent conflicts. These are, in very simplistic terms, some of the factors that made this country the world power it is today.

Inseparable from this historic development was a comparably wasteful exploitation of natural resources. If the concepts of built-in obsolescence and single-use containers had not been invented in America, they should have been. Having grown up in thrifty post-war Germany, experiencing first-hand the wasteful use of resources in the United States came as something of a cultural shock to me.

Recycling and the reuse of natural materials have traditionally been of low priority and often nonexistent in the U.S. This is no longer the case. A dramatic change in attitude can be felt today throughout the country, although more so in some parts than in others. This change came relatively suddenly, gaining significant momentum in the early 1970s. A key event was the celebration of Earth Day in 1970, when a large part of the American public became aware of the limits of the nation's resources and grew concerned about the deteriorating environment, whether soil, water, or air. If any single picture could symbolize this awakening, it was the famous photo taken by our astronauts of "Spaceship Earth", which not only was well suited to put to rest any lingering remnants of Flat-Earth theories. It dramatically illustrated the fact that our planet is indeed finite in size and in resources, and that we had better learn how to live within our means.

One other reason why the American public was so slow in realizing the finiteness of its resources was the size of the country. Unlike in many countries in Europe, for example, there was plenty of space to dump its refuse and waste material. Or at least this seemed to be the case. And this perception has definitely changed, when reality needed to be faced. Not only did the physical space available for landfills become sparse. Also legislation on the federal, state, and local levels imposed severe environmental restrictions on them. As a result, many existing landfills had to be closed, with costly cleanup measures needed for some, and it is now becoming increasingly difficult to open up new landfills.

These developments are nowhere as dramatic as in New York City. This largest American metropolis, with almost 8 million people in the five boroughs of the City proper, probably generates more solid waste than any other city in the world, including those with much larger populations. The Freshkill Landfill on Staten Island is the world's largest. In fact, the Space Shuttle astronauts reported that it is the largest man-made object on earth. This is an achievement New Yorkers have no particular cause to be proud of. Moreover, the Freshkill Landfill, already filled well beyond its original design capacity, will have to be closed next year, which will make a bad situation worse. And it does not reflect positively on the City's administration that the main alternate option pursued so far is to ask for the lowest bids from states as far as Texas and Utah to take the City's garbage.

WASTE GLASS

It is beyond anyone's capacity to solve the solid waste disposal problem of the country or even of New York City. Therefore the remaining discussion shall be restricted to the one solid waste component, which is the subject of this Symposium, namely glass. Most of it finds its way into the solid waste stream in the form of containers. The use of container glass has its own special history. It is not that long ago, also in the U.S., that the milkman would deliver the day's supplies in refill bottles. But today's container glass is almost exclusively used just once. The glass industry is able to produce containers at such low cost that it can argue forcefully against any reuse, based strictly on economical terms – but terms that ignore the cost of disposal. The reasons for the industry's current difficulties lie elsewhere: the plastics and carton industries can produce their containers at even lower cost.

Here are some statistics to illustrate the order of magnitude of the problem we are facing [1]. In the U.S., 41 billion glass containers are manufactured annually, or almost 150 for every man, woman, and child. About 33% of these are food containers, 31% beer bottles, 9% wine and liquor bottles, 22% bottles for other beverages, and the remaining 5% are containers for cosmetics, pharmaceuticals, and other materials. Categorized by color, over 65% of domestic bottles are clear, 25% are brown or "amber", and 10% come in different shades of green and occasional blue and other colors. In addition, 2 to 4 billion containers are imported into the U.S. each year (primarily beer, wine, and liquor bottles). Most of these are green. In 1995, 12.9 million tons of glass were discarded nationwide. This constitutes about 6% by weight of municipal solid waste, and only about 27% of glass containers are recycled nationwide.

In New York City, the Department of Sanitation estimates that approximately 150,000 tons of glass were recycled in 2000, which accounts for well less than half of all consumer glass. An analysis of a representative sample gave the following color breakdown: 62% clear, 19% green, 14% amber, and 5% other colors.

The special nature of the recycling industry in the United States is a result of the public's attitude towards recycling. The public awareness and the recognition of the need for recycling are not as widespread as in some European countries. Households in Germany and the Netherlands, for example, have developed long ago the habit of cleaning the bottles before depositing them in special containers, neatly sorted by color. This kind of discipline cannot be expected in the United States, at least not uniformly. Whereas in suburban areas, strict separation of glass can be encountered not only from other recyclables, but also sorted by color, the most that one can expect at present in large metropolitan areas like New York City is that the mixed-color glass be collected commingled with plastics and metals. However, simple separate measures such as "bottle bills" showed rather dramatic results. Such legislation, passed in New York as well as in several other states, requires a deposit of typically 5 cent per container. Since that law was passed, New York's streets and parks became noticeably cleaner, thanks to an army of mostly unemployed and homeless people who pick them clean of bottles and cans. Yet, even the grocery chains, which are required to redeem the bottles, normally just crush them in order to reduce their volume and then dispose of the resulting cullet, for want of a better use.

In suburban areas, considerably more sophisticated methods of collection, separation and recycling can be encountered. But sometimes a lowest common denominator needs to be established, which means that communities with more sophisticated collection and recycling methods have to revert to simpler methods for the sake of state- or countywide uniformity.

PRIOR ATTEMPTS AT RECYCLING AND REUSE

The most common method of disposal of crushed mixed-color glass is still deposition in landfills. This is a relatively expensive solution. With tipping fees as high as $65 per ton, it is not only economically the least desirable option. It also violates the fundamental environmental principle that natural resources should be recycled or reused rather than simply deposed of.

Glass may be pulverized into a sand-like product, for which there are limited applications as fill material and for drainage. Studies have shown that the engineering properties of waste glass are adequate for certain fill applications. An interesting example is the R&D Pak, developed by the Glass Aggregate Corporation. This is a geotextile fabric sleeve filled with crushed glass that can be used in place of perforated plastic pipe for drainage. The use of mixed-color glass as road fill has been proposed, and preliminary studies such as the Glass Feedstock Evaluation Project are encouraging [2].

The use of recycled glass to produce fiberglass products has been widely discussed [3-5]. Present manufacturing techniques, however, call for specifications that cannot be met by post-consumer glass without major investments. Therefore, the fiberglass industry is resisting pressure from the recycling community to become a major user of waste glass.

An important use of crushed glass is as an aggregate for asphalt, or “glasphalt”. Up to 10% processed glass may be blended with natural aggregate, provided it has the proper grading and is free from contaminants such as paper.

More recently, other uses have been proposed or are under consideration. A number of these will be heard of in detail during the course of this Symposium.

All of these prior applications have to contend with the economics of post-consumer glass recycling. In an open market governed by supply and demand, any commodity is subject to several influence factors, which are difficult to predict. The costs of collecting, crushing, transporting and possibly cleaning can be estimated with confidence. The price that the end product can fetch from the end user is governed by competing materials. For example, the user is not expected to pay more for glass sand than for the natural sand it replaces. An important variable is the price that a municipality may pay for disposal of recyclables. The New York City Department of Sanitation, for examples, is at present paying Materials Recovery Facilities (MRF) $45 per ton to dispose of the waste glass, commingled with plastics and metals. Whereas the MRFs can sell the metals and plastics, after separating them from the glass, they generally incur expenses for the disposal of the crushed mixed-color cullet. Thus, the economics for the MRFs is governed by the balance between income from the City and from the sale of the metals and plastics on the one hand and processing expenses on the other hand. If major new markets for mixed-color cullet should open up, municipalities can be expected to respond by reducing the amount they are willing to pay for the disposal of the recyclables, provided a competitive market provides safeguards. In addition, legislative bodies may intervene with mandated incentives or disincentives in order to correct the situation determined by supply and demand. For example, New York State has recently passed legislation to provide tax benefits for construction that utilizes recycled materials.

The key for a marked improvement of the situation lies in the fact that glass is a very special material. Not only is it very inexpensive to produce, requiring only raw materials that are widely available and abundant. Also its chemical and physical properties are so unique that they define glass as a separate material category of its own. It is these special properties of glass that need to be exploited optimally, if it is to cease to be a waste material and become a valuable resource. One such use is as an aggregate for concrete.

USE OF GLASS IN CONCRETE

It has been known for some time that glass and cement are chemically incompatible. The alkali in the cement paste and the silica in the glass react in the presence of moisture. This reaction, ASR for short, produces a gel, which swells, thereby causing severe damage to the concrete. For this reason, earlier attempts at using glass as an aggregate for concrete have not been successful [4,6]. Conventional wisdom therefore dictated that glass cannot be used to produce concrete. Rather than following that standard maxim, we decided to study the ASR phenomenon instead to determine whether the reaction can be checked or its detrimental consequences mitigated. The research conducted at Columbia University during the last six years proved to be successful to the point that we are now confident that the problem can be solved. Results of that research are reported elsewhere [7-11]. The main lesson learned from this experience is that it pays at times to ignore conventional wisdom and, rather than being intimidated by an obstacle, to look for a solution to the problem instead. In our case, the result is nothing less than the potential opening of a new dimension to the world of concrete.

The repercussions of this development are far-reaching and have not yet been explored or felt. It can be expected that because of the potential volumes of material involved, the entire economics of glass recycling will be affected. For example, a manufacturer of paving stones is currently planning to convert his production from natural to glass aggregate, requiring all by himself up to 1000 tons of glass a day. This is more glass than the entire City of New York is collecting at this time. Once the City realizes that a new market has been created for cullet, it can be anticipated that it will renegotiate its contacts with the MRFs, thereby saving millions of dollars to taxpayers.

The prospects of potential developments are exciting indeed, because the spectrum of possible applications is as wide as those of concrete itself, spanning from low-value commodity items to high-end decorative concrete products. What makes glass such a special ingredient for concrete becomes apparent by summarizing its special properties:

- Because it has basically zero water absorption, it is one of the most durable materials known to man. With the current emphasis on durability of high-performance concrete, it is only natural to rely on extremely durable ingredients.
- The excellent hardness of glass gives the concrete an abrasion resistance that can be reached only with few natural stone aggregates.
- For a number of reasons, glass aggregate improves the flow properties of fresh concrete so that very high strengths can be obtained even without the use of superplasticizers.

- The esthetic potential of color-sorted post-consumer glass, not to mention specialty glass, has barely been explored at all and offers numerous novel applications for design professionals.
- Very finely ground glass has pozzolanic properties and therefore can serve both as partial cement replacement and filler.

For balance, we have to list also the negative attributes:

- The aforementioned ASR problem calls for effective countermeasures. The effectiveness can be assessed with confidence only by reliable accelerated tests. Current tests such as the one of ASTM C 1260 [12] all have some drawbacks.
- The smooth surfaces of crushed glass particles affect the mechanical (as well as chemical) properties of the interfacial transition zone. It was expected that this reduces an already low ductility (or increases brittleness). Experimental evidence obtained so far does not support this prediction [13]. Even if that were the case, fiber reinforcement, whether in the form of randomly distributed short fibers or continuous fiber mesh or textile reinforcement, can provide the material with about any desired degree of ductility and fracture toughness.

Below, some of the glass concrete* products are listed that are at various stages of development.

Concrete Masonry Block Unit. The first product to be developed for commercial production was a concrete masonry block unit [7,11]. Because of the uncertainty at the time of project conception whether the solution of the ASR problem would be possible, a rather modest goal was set to replace just 10% of the fine aggregate with finely ground glass. By grinding the glass fine enough, no serious ASR related problems are anticipated. But glass particles of such small size are not visible. Thus, this application is a typical example of a *commodity* product, which has only one objective, namely to utilize as much waste glass as possible. More detailed information about this product can be found in the quoted references and in a companion paper.

Paving Stone. The next product, also close to commercialization, is a paving stone, which contains up to 100% glass aggregate. The idea is to create a paver with novel colors and surface texture effects that are made possible by the reflective properties of the glass and cannot be obtained with regular natural aggregate. Other advantages are the greatly reduced water absorption and excellent abrasion resistance due to the high hardness of glass. As an option, the paver may be reinforced with randomly distributed short fibers for improved ductility and fracture toughness. As mentioned earlier, a single paving block manufacturer can absorb exorbitant amounts of waste glass that have the potential of completely changing the local economy of glass recycling. We are content to refer to the paving stone, like the concrete masonry unit, as a commodity product, because the market is not very likely to support a much higher price than what can be charged at present for standard paving stones. For this reason, production costs have to be controlled tightly, as the net cost of the glass aggregate should be comparable to that of natural aggregate.

Façade Element with Exposed Aggregate. Architects are quite excited about the many possibilities of achieving novel surface textures and color effects with glass aggregate. This is

* Glass Concrete™ is a trademark of Echo Environmental, Inc., New York City, which has an exclusive license to the technology to produce concrete products with glass aggregate.

particularly true for exposed aggregate technologies, which have been known in the architectural concrete community for some time. One well-known architectural firm in Manhattan, strongly committed to "green building technology", is seriously considering the use of exposed aggregate glascrete façade elements for a number of upcoming projects. The novelty aspect of this application renders this a *value-added* product. The new material does not attempt to compete with a low-cost alternative. Also, it is not necessary to simulate other materials such as natural stone. It may turn out to look like marble or granite, but in the end it still is Glass Concrete™ and easily recognizable as such. The added value derives from the fact that both regular concrete and waste glass are very inexpensive, but used in combination, these two component materials can fetch a price that is only marginally controlled by the costs of producing it. Since alternative materials (to avoid the term "competing") are much more costly, the producer of Glass Concrete™ façade elements has considerable latitude in satisfying the architect's or other design professional's specific requests. It is also contemplated to develop a sandwich façade element, with a face layer of architectural glass aggregate concrete, backed by an insulation layer and a regular structural concrete layer.

Terrazzo Tiles. Some precast concrete manufacturers and architectural concrete producers are offering terrazzo tiles that utilize rather expensive specialty aggregates such as marble chips. Crushed glass constitutes a relatively low-cost alternative to such materials, even if the glass needs to be sorted by color. Efforts are now under way to mass-manufacture Glass Concrete™ terrazzo tiles. Because of the relatively high cost of the specialty aggregates and the premium prices fetched by terrazzo tiles, this application qualifies as a value-added product. Although it does not utilize as large quantities as the commodity products, it has the potential of impacting the local glass recycling economy.

Architectural Concrete Block. This application has not yet progressed beyond the conceptual stage. But it is expected that a qualified block manufacturer will be able to manufacture a palette of novel products that exploit the color, surface texture, or reflective properties of the glass aggregate. Again, such blocks will be no more expensive to manufacture than standard concrete blocks. By offering creative possibilities to design professionals that result directly from the special properties of the glass, the block can be expected to command prices in the open market that bear no correlation with the manufacturing cost. Therefore, this is another example of a value-added product.

Decorative Applications. Other exciting applications exist in the architectural and decorative fields. We can create surface textures and appearances using techniques well known in the architectural concrete industry, while fully utilizing the esthetic potential of colored glass. The results can be stunning, and the number of potential applications are limited only by one's imagination. To name just a few: precast wall panels, partition walls, elevator paneling, tabletop counters, park benches, planters, trash receptacles, etc. All of these applications have in common that they are relatively inexpensive to produce, yet because of their unique and novel appearance and esthetic effects, they have the potential of creating value way beyond the cost of the ingredients. In addition, they may benefit from the goodwill of environmentally conscious consumers, who are willing to pay a premium for products with recycled material content.

Conclusion

Concrete is a marvelous construction material. It can be very durable, is wonderfully moldable and adaptable to myriad applications, its ingredients are readily available and inexpensive. We have the technical knowhow to engineer its mechanical and other properties to fulfill almost any set of reasonable specifications. Concrete is also an excellent medium to recycle solid waste, which is welcome news to municipalities that are hard-pressed by the scarcity of suitable landfills.

In developing concrete products with crushed waste glass aggregate, the economics is controlled by the price the product can fetch on the open market. Commodity products, by definition, are characterized by low values, which exert strong pressures on the production and manufacturing technology. The value added by the glass is marginal to nonexistent in those cases. But by utilizing the special properties of glass, chemical, physical, or esthetic, novel products can be developed, for which the prices fetched in the open market are much less exposed to competitive pressures. A beautiful tabletop counter made of polished glass aggregate concrete has the potential to stand on its own and does not need to compete with other materials, many of which are likely to be much more expensive to produce. After all, this is an engineered material. Prudent application of technical knowhow all but guarantees a cost-effective satisfaction of all reasonable material specifications. In conventional concrete, we are more likely to be concerned with strength, durability, and workability. Crushed glass aggregate adds a new dimension to the possibilities for architectural concrete applications. This is truly a case where a waste material is turned into a valuable commodity. This is independent of any bonus the consumer may be willing to pay for products made with recycled materials.

We do not have to limit ourselves to waste glass. Although this Symposium is dedicated to the recycling and reuse of glass cullet, there are other solid waste components that are good candidates for being turned into valuable commodities. The various ashes and microsilica that are byproducts of industrial processes or combustion and are already widely utilized in the concrete industry. Other possibilities are offered by the reprocessing of carpets. The nylon fibers have interesting effects on the strength, workability and thermal properties of concrete. Also the reuse of tires has been successfully attempted. But we can go a step further. A major research project is currently under way at Columbia University to utilize highly toxic dredge material from New York Harbor in concrete products. The challenge here is to render the contaminants harmless by encapsulating them such that they cannot leach out under normal service conditions.

In conclusion, it is permissible to remind ourselves that concrete is a marvelous material. Not only can we engineer its mechanical and other properties to about any reasonable specifications. We also have the means to give it esthetic attributes with limits set only by our imagination. Even if we may be accused of a bit of Yankee hyperbole, with what we know today, we can honestly proclaim: Give us your solid waste – we shall turn it into a valuable commodity.

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