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CONCRETE WITH WASTE GLASS AS AGGREGATE

C Meyer
Columbia University
N Egosi
RRT Design and Construction
C Andela
Andela Products Ltd
United States of America

ABSTRACT. The reuse of waste glass poses a major problem in large municipal areas of the United States. Post-consumer glass is often mixed-color and commingled with plastics and metals, contaminated with other materials like ceramics and organic matter and partially broken. This reduces its value and complicates the ability to achieve the cullet specifications of bottle manufacturers or other markets such as the construction industry. Most of these markets make little use of the inherent chemical and physical properties of glass, therefore its market value is very low. A major research effort has been underway at Columbia University for a number of years, to develop new applications for waste glass as an aggregate for concrete. Extensive studies were undertaken to solve the alkali-silica reaction (ASR) problem. Specific products such as paving stones, concrete masonry blocks, terrazzo tiles, and precast concrete panels are close to commercial production. This paper discusses the various steps that need to be taken by recyclers to collect the glass, separate it from the other materials, clean it and crush it to obtain the appropriate grading to meet the specifications for specific applications.

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

Dr. C Meyer is a professor of civil engineering at Columbia University in New York. An expert in analysis and design of concrete structures and earthquake engineering, his interests have shifted in recent years to concrete materials science and technology and the use of waste materials to develop concrete products.

Mr. N Egosi is president and founder of RRT Design & Construction. He has led the construction of nearly 100 material recovery facilities throughout North America and has pioneered the development of advanced technologies for the recycling and solid waste industry. With direct responsibility for over $200 million of construction during RRT's past 10 years, Mr. Egosi's experience is recognized industry-wide.

Ms. C Andela has a mechanical engineering degree from the University of Michigan and a Master of Business Administration from Polytechnic University of New York. She is president of Andela Products, Ltd., a leading manufacturer of glass recycling equipment and systems.

INTRODUCTION

The passage of federal and state recycling regulations in the United States, the closing of more than half of the nation's landfills in the last ten years, and environmental concerns have raised among local governments a recycling consciousness that led to the development of nearly ten thousand municipal programs to collect recyclables. Just as there are numerous approaches for collecting recyclables, there are many approaches to planning and designing material processing facilities. These facilities, which number nearly 500 in the United States, are typically referred to as Material Recovery Facilities (MRF). Serving a large region or city, they share the common objective to sort and process the mixture of recyclables into separate products, which are marketable to the manufacturing industry as "alternate" raw materials competing with traditional virgin or natural materials.

It is the design goal of each MRF to effectively recover the maximum amount of recyclables from the incoming stream. A significant portion of the mixed-color container glass set out by the participating households is received broken. Glass breaks during the loading onto collection trucks, during transport, unloading at the MRF, and during processing. Although this breakage is unintentional, it is also inevitable due to the characteristics of glass. As much as 75% of the total glass may be broken, and at most MRFs the breakage percentage is typically 50%. Due to size and contamination, color sorting of this material into glass cullet suitable for glass bottle manufacturing can be costly. Therefore, MRFs are often forced to landfill this material as residue, unless alternative approaches are found.

Container glass represents about 65 to 70% of the total commingled container stream (i.e. inclusive of plastics and metals). There is consequently a significant amount of potential residue if the broken glass cannot be recovered as a marketable product. The solution is to develop an alternate product that could be marketed even if not color-sorted. A simple automatic mixed broken glass beneficiation system was developed by RRT in the early 90's to size, clean and sell the contaminated broken glass material as a construction aggregate product. While this material does not have a strong market value, it does contribute to overall plant performance by reducing residue disposal costs.

Many recycling operations realize that they gain little - or even have a loss of - income by processing glass. *Closed-loop recycling*, the process of collecting, sorting, transporting, beneficiating, and manufacturing glass back into bottles, is the most common form of glass recycling and has costs embedded in each step of the process.

The growth and evolution of recycling in the United States and in many other parts of the world has resulted in a number of different methods for the collection and sorting of glass. Some glass is collected and sorted by color at drop-off centers. This often requires labor at the center to assure that the glass is properly color-sorted and free of ceramic contamination. Glass may also be collected as part of the commingled curbside collection programs common in many communities. The color sorting is then done at the MRF. Both of these collection methods incur labor and transportation costs for color sorting and recycling of bottle glass.

Because the glass is of mixed color, and much of it is broken, it cannot be easily recovered for closed-loop recycling. The disposal of the mixed broken glass (MBG) as a residue from the recycling process causes a significant cost to recyclers. If they are getting paid $20.00 per ton to process the recyclables, but have to pay $40.00 per ton to dispose of residual material in landfills, the losses they incur for disposing of the MBG will exceed the entire income they receive for taking in the glass.

Also the labor cost for sorting the glass and transporting it to a glass recycler or beneficiator often equals or exceeds the price paid by the glass beneficiator. As the glass manufacturing industry consolidates and the number of glass beneficiators decreases, the cost of transportation increases, and the prices traditionally paid by the beneficiators decrease. Clearly, closed-loop glass recycling under such conditions is a break-even business at best and often results in financial losses for every bottle that is picked.

PAST EXPERIENCE

Alternative solutions for disposing of mixed-color glass have been sought in the past, but none of these have proven to be successful in an economic sense. In addition, the basic tenet of environmental consciousness is violated if a potentially valuable resource is simply wasted or underutilized, while using up increasingly scarce landfill capacity.

Andela Products, Ltd. manufactures equipment to pulverize waste glass into a sand-like product with smooth edges, but what does one do with the glass "sand" or glass "gravel", once it is produced? The cost savings associated with diverting the MBG from the landfill are significant and alone justify the investment in equipment to pulverize glass, but the marketing of the finished material needs to be addressed.

A number of different uses of such glass sand have been and are being tried. Local uses as a substitute for natural sand and gravel products may provide a local solution, but the income from the sale of glass sand is limited by the availability and prices of local aggregates. If natural sand and gravel are readily available at a low price, it is difficult to market a new product (glass sand) unless a significant benefit can be demonstrated. MRF operators are often removed from the local aggregate market and do not have access to the buyers in this market. But applications where the enhanced filtration or reflective properties of glass sand or gravel are beneficial, provide more promise for sustainable markets. Also the markets for glass as a pipe bedding material continues to increase.

Technical specifications by local and state Departments of Transportation or the Environment can create barriers to the substitution of glass sand or gravel for natural aggregates. Investments in time and effort for testing are required to secure approvals. The general fear of "glass...it must be sharp" needs to be overcome.

Through effective marketing efforts, the material is generally sold between U.S. $1.00 to $2.00 per ton versus $5.00 to $7.00 per ton for conventional aggregate. The most successful and predominant use is in the manufacture of asphalt, commonly referred to as "glasphalt". Depending on the customer, asphalt plants throughout the Northeast and other areas of the U.S. routinely blend the natural aggregate with up to 10% processed glass for making asphalt. The amount of glass is limited to 10% in order to avoid stripping (i.e. the separation of the glass component from the binders). This application also requires the proper sizing of the glass aggregate, but most importantly, the quantities of glass aggregate required for asphalt producers to continually incorporate the material into their product are often prohibitive.

In commercial and local public works applications, glasphalt is used for top courses, while for state applications it is used in the base and binder course. The grading for such applications is typically as follows:

Table 1. Typical Glass Aggregate Grading for Glasphalt

Sieve Size	½”	¼”	1/8”	No. 20	No. 40	No. 80	No. 200
% Passing	100.0	85.0	53.2	17.1	8.8	3.6	1.2

As more recycling facilities have come on-line with a steady supply of properly processed mixed glass in conjunction with increased acceptability of glass as an aggregate by the engineering community, the construction industry is increasingly utilizing recycled glass.

More recently, opportunities have developed to further improve the glass aggregate for higher end uses, such as concrete. Requirements to clean the glass aggregate are evident due to the high presence of sugars, liquids and other organics found in food/beverage containers. Additionally, the presence of foreign (deleterious) substances, including high percentage of fines, is unacceptable. By applying basic techniques used in the aggregate industry, a clean aggregate can be produced that would be suitable as an aggregate for concrete.

PROCESS DESCRIPTION

The incoming commingled recyclables, after passing an initial magnetic separation step, are conveyed typically to a screen designed to separate the broken glass through 2-inch openings. An Andela breaker may also be used to selectively reduce the glass so all the glass passes through the screen. Other items passing through this screen include significant amounts of contaminants such as flattened aluminum cans and plastic containers, tramp metals, caps, lids, tabs, etc. Such contaminated material is conveyed to a glass beneficiation system. This is typically a modular unit that automatically beneficiates the mixed broken glass with a 98% glass recovery rate.

A key factor in the design of such a system is the selection of a crusher to produce consistent glass particle sizes, while keeping the bottle caps, tabs, aluminum and plastic neck rings, and other contaminants intact. Other miscellaneous contaminants include flattened aluminum and plastics, which pass through the screens. Other factors to be considered in such designs are:

- Low maintenance: Glass is highly abrasive and as a consequence, careful attention must be given to this problem.
- Low noise: Typically these processes occur indoors, therefore the noise resulting from crushing must be limited.
- Ability to handle non-uniform feed rates: The incoming feed rate, due to its non-homogeneous characteristics, tends to impose significant surge loadings to the system.
- Ability to handle plastic, aluminum and gallon HDPE jugs: These contaminants must be able to be processed without causing crusher jams, while considering that these contaminants are not “crushable”.

GLASS AS AGGREGATE FOR CONCRETE

The use of waste glass as aggregate for concrete has been attempted decades ago. Those early efforts were thwarted by the problem of alkali-silica reaction (ASR), which was not well understood then. Therefore, a high priority was assigned to gaining such an understanding, when a major research effort was initiated at Columbia University some six years ago. It was also expected that the glass aggregate would affect the mechanical properties of the concrete. For example, it is known that the concrete strength is typically controlled by the bond strength between cement matrix and aggregate. If natural aggregate with relatively rough surfaces is replaced by crushed glass particles with relatively smooth surfaces, one would expect a drop in strength and in particular a reduction of an already low ductility. Finally, it was recognized early on that glass concrete is basically a new material that requires the development of appropriate production technologies, as well as answers to other questions that need to be addressed by basic research. Details of the pertinent studies have been documented elsewhere [1-5]. Therefore, only some of the most significant findings shall be summarized here.

The problem of ASR is not restricted to glass aggregate concrete. It can occur also in conventional concrete, if (according to the definition of ACI Committee 116) the aggregate contains "certain siliceous rocks and minerals, such as opaline chert, strained quartz, and acidic volcanic glass". The build-up of the ASR gel causes volume expansion and may cause the concrete to crack. As this is a long-term problem and may take years to manifest itself, it is in general difficult to predict the potential reactivity of natural aggregate, and a reliable accelerated test method is needed. If ASR in regular concrete is subject to this uncertainty, glass aggregate has the one "advantage" of no uncertainty in this regard. Also, the chemistry of soda-lime glass used for common consumer containers is quite simple compared to that of most natural aggregates. That makes glass almost an ideal aggregate to study the ASR phenomenon and to search for methods to avoid it or to mitigate its detrimental consequences.

Most of the ASR studies with glass concrete utilized the ASTM C1260 test [6]. This is the most popular accelerated test, because it lasts just a little over two weeks. It has been developed primarily to assess the potential reactivity of an aggregate. It calls for the preparation of 25 by 25 by 280 mm mortar bars containing the aggregate to be investigated, which are immersed in a 80^{o}C sodium-hydroxide solution for two weeks. Their expansions are interpreted as being indicative of the material's potential reactivity. Although a positive test result is not a guarantee that the material is innocuous, the ASTM C1260 test is of great value for comparative purposes.

There are a number of measures to avoid ASR or its damaging effects:

- grinding the glass to pass at least U.S. standard mesh size #50;
- adding mineral admixtures that can effectively suppress the reaction;
- making the glass alkali-resistant, for example, by coating it with zirconium (a solution chosen by the glass fiber industry, but impractical for post-consumer waste glass);
- modifying the glass chemistry, if that is an option, e.g. for specialty glasses;
- sealing the concrete to protect it from moisture, either on a micro- or component level, because ASR needs three factors to thrive: alkali, silica, and moisture;
- using a low-alkali cement, which is likely to be less effective, unless alkalies from the environment can be kept away;
- developing special ASR-resistant cements, some of which are already being offered commercially.

In spite of its potential reactivity in an alkaline environment, glass has a number of properties that make it a very attractive aggregate for a variety of concrete products.

- 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 or the addition of metallic fines typical of special floor toppings that exceed $15.00 per square foot per inch of thickness.
- 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 glass, not to mention specialty glass, has barely been explored at all and offers numerous novel applications.
- Very finely ground glass has pozzolanic properties and therefore can serve both as partial cement replacement and filler.

The use of recycled glass in concrete opens a vast new market for mixed as well as color-sorted broken glass in a variety of specialty products or in local concrete operations. Recent research findings will make it possible to utilize glass also in regular concrete applications, thereby expanding and developing markets for recycled glass.

GLASS CONCRETE PRODUCTS

Glass concrete[*] products can be categorized as *commodity products* and *value-added products*. For simple commodity products, the primary objective is to utilize as much waste glass as possible. Whether the glass can be seen is a secondary issue. For value-added products, on the other hand, the esthetic potential of the glass is utilized, because glass can be very attractive. In order to be visible, glass particles of a certain minimum size must be present, for example, mesh size #8 or #4. But glass particles of this size are also most vulnerable to ASR and therefore require effective countermeasures.

Commercial production of both commodity and value-added products requires a reliable supply of glass that is cleaned, crushed, and graded according to specifications. The crushing and grading operations ought to be coordinated such as to result in preferably zero wastage. The crushing operation can be quite dusty. But collection of the dust is not only mandated by air pollution control. The glass powder turns out to be the most valuable product of the crushing operation, both because of its pozzolanic potential and filler effect.

Special esthetic effects can be achieved with color-sorted glass. Architects or designers can help coordinate the colors of glass aggregate and cement matrix. Also the choice of surface texture and treatment may benefit from specialists trained in the visual arts.

The development of an appropriate production technology should recognize the differences between glass and natural aggregates. For example, the basically zero water absorption of glass improves the mix rheology and calls for quite different mix designs, including the choice of admixtures, which also depends on whether a dry or wet technology is used.

Since plain Glass Concrete™ is quite brittle, just like conventional concrete, it is advantageous to reinforce glass concrete products with either randomly distributed short fibers or, in the case of thin sheets or panels, with fibermesh or textile reinforcement [7].

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[*] 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.

Concrete Masonry Block Unit

The first product to be developed for commercial production was a concrete masonry block unit [1]. 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. Prototype blocks were made using the facilities of a block manufacturer in Long Island, New York. Four batches were produced, Table 2. Batch A served as the control mix with no glass content. In Batch B, 10% of the fine aggregate was replaced by glass passing mesh #30. In Batch C, 10% of the cement was replaced by finely ground glass powder, passing mesh size #400. And Batch D contained both, 10% fine aggregate and 10% glass powder as cement replacement. As seen in Table 2, the 28-day strength results were barely affected by the glass substitutions. This result was not surprising, because a 10% substitution was not expected to have much of an effect.

Table 2. Concrete Block Test Program

Batch	A	B	C	D
	Control: 3010 lbs gravel 5600 lbs sand 1000 lbs cement 174 lbs water	Replace 10% of aggregate by glass of size -#30	Replace 10% of cement by glass of size -#400	Replace 10% of aggregate by -#30 glass and 10% of cement by -#400 glass
28d strength (ksi)	4.68	4.26	4.63	4.26

In order to get the new block approved, a number of requirements need to be fulfilled. First of all, it will have to be shown that damage due to ASR expansion is not likely to impair the strength of the block. Research has shown that this problem can be controlled. Also achieving strength is no problem at all, because glass is an extremely strong aggregate. Concrete mixes with 100% glass aggregate and 28-day compressive strengths exceeding 15,000 psi have already been made using standard procedures. Linear shrinkage and water absorption pose no problems because of the non-existing water absorption of glass. The resolution of the final issue, fire rating, requires additional testing. But it is fair to predict that the substitution of one siliceous material by another one should not cause much of a problem.

The economics of concrete masonry block production is promising, but depends strongly on a reliable supply of glass, that is cleaned, crushed, and graded according to specifications. Whereas replacing just the sand by finely ground glass may be of modest economic benefit, replacing also part of the cement by glass powder, which is obtained during crushing anyway, improves the economical outlook. Finally, the test run revealed that the improved flow property of the mix caused an increase of block machine throughput of about 6%. Given the tight economics of concrete block production, such an increase in productivity is not negligible.

Paving Stone

The next product, also close to being commercialized, is a paving stone, which contains up to 100% glass aggregate. The idea was to create a paver with novel colors and surface texture effects, such as special light reflections, that 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 to offset the inherent brittleness of concrete in general and glass concrete in particular. Fiber reinforcement improves the paver's mechanical properties, especially its energy absorption capacity or fracture toughness. A fiber-reinforced paver will also crack like any other paver under impact loading. However, fibers will keep such cracks so small as to be basically invisible. Initial tests have shown that the freeze-thaw cycle resistance is excellent. An initial batch of samples survived 300 cycles with about one quarter of a percent weight loss.

A major test production run is in the planning stage, therefore definite statements about the economics of glass concrete paver production cannot be made at this time. If the retail value is conservatively assumed to be no higher than that of a standard paver, it will be essential that the glass be processed within tight economical constraints. In addition, the potentially large volumes of waste glass required (one manufacturer is contemplating to process as much as 1000 tons of glass a day) will have a major effect on the entire economics of waste glass.

Architectural and Decorative Applications

The most exciting applications appear to be in the architectural and decorative fields. Not only can we engineer the material's mechanical and other properties to about any reasonable specifications. We also can create surface textures and appearances using techniques well known in the field of architectural concrete, 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:

- Building façade elements
- Precast wall panels
- Partition walls
- Floor tiles
- Wall tiles and panels
- Elevator paneling
- Table top counters
- Park benches
- Planters
- Trash receptacles
- Ashtrays

A well-known architectural firm in Manhattan is considering Glass Concrete™ façade elements for a new building in Manhattan, and efforts are under way to identify a precast concrete manufacturer with the capability to produce the required 100,000 sqft of façade elements with an exposed aggregate finish. Studies are also underway to incorporate into the concrete mix recycled carpet fibers, because hollow-core nylon fibers effectively improve the R-value of the concrete, in addition to the mechanical properties. Photographic reproductions of sample tiles could be provided here. However, these would not do the material justice. One has to see the real material to appreciate its esthetic potential.

CONCLUSIONS

For many years, the recycling and waste management industry has struggled with the problem of identifying or developing reliable markets for mixed-color broken glass. To date, only low-value applications are available, which do not utilize the physical and other inherent properties of the glass. Recent research has made it possible to use such glass as aggregate in concrete, either in commodity products, with the only objective being to utilize as much glass as possible, or in value-added products that make full use of the physical and esthetic properties of color-sorted crushed glass. The potential applications are basically limitless, and it is expected that commercial production of specialty glass concrete products will have a major impact on the economics of glass recycling throughout the United States.

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