Cracking an ASR Barrier

By Christian Meyer, Columbia University

As university researchers, we get great satisfaction from seeing aspects of our work transferred from the lab to commercial production. Our recent research to find ways to use waste glass as an aggregate for concrete is a good case in point.

It began as our attempt to help improve a bad situation before it gets worse. New York City's Freshkill Landfill, the world's largest, will soon close. This will force the City to come up with alternative ways to dispose of its solid waste. Although the Material Recycling Facilities under contract with the City can sell at a profit much of the metal and plastic it recycles, glass presents a different problem. New York City alone generated more than 150,000 tons of waste glass last year. Without a market for this material, the City has few alternatives to crushing it and trucking it to faraway landfills.

Substituting waste glass for natural aggregates in concrete has so far been unsuccessful because of the problem of alkali-silica reaction (ASR). This problem was foremost on our minds when we started our research. We also expected that glass aggregate would affect the mechanical properties of concrete. For example, the bond strength between cement paste and aggregate typically controls the compressive strength of concrete. If natural aggregate shaped with relatively rough surfaces is replaced by crushed glass particles with relatively smooth surfaces, one would expect a drop in strength.

Our fundamental understanding of ASR in Glass Concrete emerged from studying glass chemistry. Strictly speaking, the ASR problem should be considered a so-called *coupled field problem*. On one hand, both cement hydration and the ASR reaction are chemical processes that can be described by the laws of diffusion. On the other hand, when the quasi-liquid ASR gel swells and causes internal pressure, it attempts to permeate the pore structure of the cement matrix. This is a transport problem. The elastic behaviors of both the cement matrix and the aggregate particles couple these two processes. This is an extremely complex problem, which requires the simultaneous solution of three coupled differential equations.

ASR occurs in ordinary concrete if the "wrong" kind of aggregate is used. However, whether such aggregate is reactive or not or is prone to cause damage is often subject to a vexing uncertainty. Compared to that, glass aggregate has one advantage (if we may want to call it that): ASR occurs in glass aggregate with much more certainty. Also, the chemistry of soda-lime glass (used for common consumer containers) is quite simple compared with that of natural aggregate. That makes glass almost the ideal aggregate with which to study the ASR phenomenon and search for methods to prevent it or to mitigate its effects, and with which to perform parameter studies.

Mindful that both sand and glass consist mostly of silica, it might be interesting to raise the following question. Why is regular sand not likely to cause ASR damage, whereas glass typically is highly reactive? The main reason for this difference in behavior is that the silica in sand has a regular crystal structure, which is relatively stable and resistant to chemical influences, whereas the same silica in the amorphous form of glass is not.

Different glasses cause different expansions

One way to detect the existence of ASR gel is to treat a sample with uranyl acetate solution. The ASR gel will fluoresce under ultraviolet light, as shown in Figure 1, which was taken with an optical microscope. In the photo in Figure 2, taken with an electron microscope, the ASR gel is not readily visible, but its detrimental effect is, namely the cracks in the cement paste propagating away from the surface of the glass particle.

Glass particles produced by an impact crusher are quite harmless. They feel and handle like regular sand, allaying our original worry that masons would get bloody hands when handling glass concrete masonry units. If such glass particles are submerged in a sodium hydroxide solution for 14 days, they appear as shown in Figure 3. A strongly alkaline environment literally eats up the glass.

Most of our ASR studies used the ASTM C 1260 test. This is the most popular accelerated test because it lasts just a little more than 2 weeks. It has been developed primarily to gauge the potential reactivity of a certain aggregate. To make 25 by 25 by 280-millimeter mortar bars, aggregate is graded as follows: 10% of mesh size #8, 25% each of #16, #30, and #50, and 15% of #100. The water-cement ratio is 0.47 and the cement-to-aggregate ratio is 0.44.

Figure 4 illustrates mortar bar expansion as a function of time and glass content. Mortar bars without glass show basically no expansion. Bars with 10% aggregate replaced by clear glass have a 14-day expansion that is twice the ASTM limit of 0.1%, and bars with 100% glass aggregate exhibit the extraordinary expansion of 1.4%.

To study the effect of glass particle size on mortar bar expansion, we replaced 10% of the aggregate with an equal amount of crushed clear glass of a specific size (Figure 5). On the vertical axis, the reference values for mortar bars without any glass indicate a 14-day expansion of slightly above 0.1%, indicating that the Long Island sand used may be slightly reactive. But replacing 10% of this sand by #4 glass more than triples that expansion, with even worse results for #8 and #16 glass. However, for smaller glass particle sizes, the expansions clearly decrease. Mesh size #16 appears to be the size that causes the most expansion for clear soda-lime glass, and bars containing glass particles of size #100 produced expansions smaller than those of the reference material.

This result suggests the first solution to the ASR problem. If glass is ground finely enough it appears that the ASR-induced damage is minimized. It is possible that in the case of very finely ground glass, the reaction takes place so quickly that much of the expansion occurs during the first 2 days before measurements are taken.

In studying whether glass color has any effect on the expansion as measured in the ASTM C 1260 test, we analyzed samples of New York City waste glass with different colors (see Figure 6). The curve for clear container glass is identical to the one in Figure 5. For one type of colored glass a clear reduction in expansion was noticeable. But bars made with glass of a different color displayed less expansion than even the reference bars. This finding indicates that finely ground glass powder of that particular color may have a beneficial effect on the ASR expansion of the slightly reactive Long Island sand. Columbia University has obtained a patent for this discovery.

To find out what makes this type of glass so special, we focused our attention on the pigment that the manufacturer added to the glass. For this purpose, we manufactured our own glass by adding different amounts of that pigment to clear glass and found a strong correlation between the amount of pigment and mortar bar expansion.

In sum, there are several ways to avoid ASR and its damaging effects in concrete with glass aggregate.

- Glass may be ground to pass at least mesh size #50.

- Certain admixtures can effectively suppress expansion.
- Glass can be made alkali-resistant, for example, by coating it with zirconium—a solution chosen by the glass fiber industry, but impractical for post-consumer waste glass unless an inexpensive method becomes available.
- Similarly, the glass chemistry can be successfully modified, as indicated by the colored glass studies. Again, cost is a key consideration.
- Because ASR needs three factors to thrive (alkali, silica, and moisture), sealing the concrete—either individual particles or an entire element such as a block—to protect it from moisture can be effective.
- Using a low-alkali cement is probably less effective because the alkalies can still come from somewhere else. However, special ASR-resistant cements are available, and others may be developed.

A word of caution is in order, though. ASR is an extremely complex phenomenon. As we found out, even small changes in the glass chemistry can make large differences. For this reason, each product and glass source need to be evaluated and tested thoroughly to ensure an acceptable quality and durability. Also, replacing natural aggregate with glass aggregate has significant repercussions on the mix design, required admixtures, and concrete production technology.

Product development

The aesthetic potential of waste glass, which can be very attractive, can be useful in producing value-added products. Special aesthetic effects are achievable by sorting the glass by color. To be visible, glass particles of a minimum size—for example, size #8 or #4—must be present. But as shown earlier, glass particles of this size are most vulnerable to ASR and therefore require appropriate countermeasures. That said, three applications with immediate commercial potential have already been pursued.

Example 1: concrete masonry block. As this was our first application, we were not sure of whether we would succeed in controlling ASR. Therefore we set a modest goal of replacing just 10% of the fine aggregate with finely ground glass.

Barrasso & Sons, Islip Terrace, N.Y., produced prototype units using four different batches (Table 1). Batch A served as the control mix with no glass. In Batch B, 10% of the aggregate was replaced with 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 glass aggregate and 10% glass powder as a cement replacement. As shown, the glass substitutions barely affected 28-day strength results. This result was not surprising, because a mere 10% substitution was not expected to have much of an effect on strength.

For the new block to be approved by any building department, it is necessary to fulfill a number of requirements. First, it needs to be shown that damage due to ASR expansion is not likely to impair the strength of the block. Our research gives rise to optimism that this problem is controllable. Also, achieving strength is no problem at all, because glass is an extremely strong aggregate. We have made glass concrete mixes with 28-day compressive strengths exceeding 17,000 psi. Linear shrinkage and water absorption pose no problems because glass does not absorb water. The resolution of the final issue, fire resistance, requires additional research, including an actual fire test. But it is safe to predict that the substitution of one siliceous material by another should not cause a great difference in fire resistance.

The economics of concrete masonry block production is promising, but it depends strongly on a reliable supply of glass that will be washed, crushed, and graded according to specifications. Replacing just the sand may be of marginal economic benefit. When part of the cement is also replaced by glass powder, which is obtained during crushing anyway, then the economics is more promising. Finally, the test run revealed that the improved flowability of the mix caused an increase of block machine productivity of about 6%._____

Example 2: paving stone. A paving stone, which also is close to commercial availability, can be made with up to 100% glass aggregate. Grinnell Pavingstones, Sparta, N.J., has produced several prototypes. The idea is to create a paver with novel colors and surface texture effects such as special light reflections, which are not possible using natural aggregate. Other advantages are greatly reduced water absorption and excellent abrasion resistance due to the high hardness of glass. We may want to reinforce the paver with fibers to improve its energy absorption capacity and fracture toughness. Initial tests have shown that the paver's freeze-thaw resistance is excellent. Some samples were tested 3 years ago and survived 300 cycles with about a 0.0025% weight loss. Our most recent mixes are expected to perform even better.

A major test production run is in the planning stage, which will allow us to quantify the economics of glass concrete paver production. It should be noted that the technology to produce paving stones is readily used to produce architectural blocks, bricks, and segmental retaining walls as well.

Example 3: 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 properties to about any reasonable specifications, but by using colored glass we also can create surface textures and appearances using techniques well-known in the field of architectural concrete. The number of potential applications are limited only by one's imagination and include:

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

A noted architectural firm, Fox & Fowle Architects, New York, N.Y., 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 its 100,000 square feet of façade elements with an exposed-aggregate finish. We are also investigating the use of recycled carpet fibers, which can improve the mechanical properties and R-value of the concrete.

Negotiations are currently underway with Wausau Tile, Wausau, Wis., to license the technology to mass-produce decorative Glass Concrete™ tiles. We are now exploring ways to use this material to produce thin sheet products with textile reinforcement.

Conclusion

We have the technical knowhow to control potential ASR damage in Glass Concrete™. However, because of the complexity of this chemical phenomenon, each product mix design and source of glass aggregate must be carefully studied to ensure adequate concrete durability. On the other hand, the vast number of possible applications and the overwhelming reception of our lab-produced samples make such studies worthwhile.

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[graphics]

Table 1. 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

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engineering practice before joining the faculty of Columbia University. His current research interests are directed primarily towards concrete materials science and technology as well as structural engineering. He has authored over 130 technical publications, including a textbook on design of concrete structures.