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"Glascrete"—Concrete with Glass Aggregate

by Weihua Jin, Christian Meyer, and Stephen Baxter

Post-consumer glass represents a major component of solid waste, yet its use as an aggregate in concrete is problematic because of the strong alkali-silica reaction (ASR) between the cement paste and the glass aggregate. In a research project at Columbia University, the use of crushed waste glass as aggregate for concrete products was investigated. Fundamental aspects of ASR in concrete with glass aggregate were studied. It was shown that waste glass ground to U.S. standard sieve size No. 50 or smaller causes mortar bar expansions in the ASTM C 1260 test of less than 0.1%, which is less than that of reference bars without any glass. Also, green glass does not cause any expansion to speak of, and finely ground green glass has the potential of an inexpensive ASR suppressant. Specific concrete products with glass aggregate are currently under development. These include concrete masonry blocks with 10% mixed-color waste glass aggregate and "glascrete" products with 100% color-sorted glass aggregate for numerous architectural and decorative applications.

Keywords: alkali-aggregate reactions; architectural concrete; glass aggregates.

INTRODUCTION

The recycling of mixed-color waste glass poses major problems because glass producers have no easy way for its economical reuse. Therefore, the need for its disposal contributes to the solid waste problem faced by municipalities worldwide. For example, New York City alone collects more than 100,000 tons of mixed-color waste glass annually. It has several material recycling facilities (MRFs) under contract and pays them substantial sums to accept the glass, comingled with plastics and metals. While the MRFs are able to sell the plastics and metals, there are virtually no takers for the glass.¹⁻⁴ Some limited applications have been found in asphalt (glasphalt)⁵ and roadway fill. In addition, its use as aggregate in concrete has been attempted in the past,^{6,7} but without success. The main problem was caused by the alkali-silica reaction (ASR) between the highly alkaline pore solution of the cement paste and the silica in the glass, which results in the degradation of the concrete micro- and macrostructure. For this reason, glass is usually considered unsuitable as aggregate in concrete.

There exists a considerable body of knowledge on ASR in general.⁸⁻¹¹ However, while the reactivity of many natural aggregates is often subject to uncertainty, the high reactivity of soda-lime glass has been known for a long time and therefore attracted relatively little attention in the literature.¹²

The solid waste disposal problem in the State of New York prompted a re-evaluation of this situation. A comprehensive research effort has been underway at Columbia University since 1994 to study the suitability of mixed-color cullet in concrete masonry blocks,¹³ as well as other precast concrete products.¹⁴ Fundamental aspects of ASR in concrete with glass aggregate were studied experimentally, using the ASTM C 1260 standard test,¹⁵ and the most practical methods to suppress the harmful effects caused by ASR were sought. This paper reports the important results of those studies and discusses the practical implications of commercially producing concrete masonry blocks and decorative precast concrete elements with waste glass as aggregate.

RESEARCH SIGNIFICANCE

ASR causes major concerns throughout the concrete industry because of the potential reactivity of some natural aggregates and the resulting long-term deterioration of the affected concrete products. The relatively simple chemistry and amorphous structure of soda-lime glass makes it an ideal aggregate for the study of fundamental aspects of ASR. The theory behind ASR suppression and the techniques derived from such studies may be of relevance to concrete with reactive natural aggregates as well. Perhaps more important, any large-scale utilization of waste glass as concrete aggregate will be an important step towards the reduction of solid waste and should therefore be considered a contribution towards environmentally friendly construction.

MATERIALS AND TEST METHOD

The main obstacle to the study of ASR, specifically, the potential reactivity of certain aggregates, is the long-term nature of ASR. The resulting damage can take many years to manifest itself. Therefore, accelerated test methods are needed that either compress the material's service life into a reasonable time frame or exaggerate certain reactions in such a way as to enable efficient comparative studies.

Around the time when the research reported herein was initiated, ASTM standardized one such accelerated test method, now known as ASTM C 1260.¹⁵ For this test, the aggregate in question is crushed and graded as follows: 10% of mesh size No. 8; 25% each of No. 16, 30, and 50; and 15% of No. 100. Mortar bars with water-cement ratio (w/c) of 0.47 and aggregate-cement ratio 2.25 are made, with metal pins embedded at both ends. The bars are demolded after 24 h, stored in water at 80°C for another 24 h and then placed in a 1 N NaOH solution at 80°C for 14 days. Their lengths are measured daily, and their expansion is assumed to be an indicator of the aggregate's reactivity. According to ASTM C 1260, material with a 14-day expansion of less than 0.1% should be considered innocuous in most cases, but the 0.1% value is not to be taken as an absolute limit.

The ASTM C 1260 test, in contrast to the ASTM C 227 test,¹⁶ is usually considered to be overly severe due to the harsh test conditions with the highly alkaline NaOH solution and elevated temperature, which are not representative of the service life encountered by actual concrete structures. Tests with such strict criteria for potential ASR reactivity, however, are gaining in popularity for their relatively high reliability and especially for the short time needed to detect the ASR potential of reactive aggregate, which makes them highly suitable for comparative and parameter studies. It is for this reason that the ASTM C 1260 test was used for the study reported herein. However, the authors are well aware of its limitations and cognizant of the need for additional tests (such as ASTM C 227¹⁶

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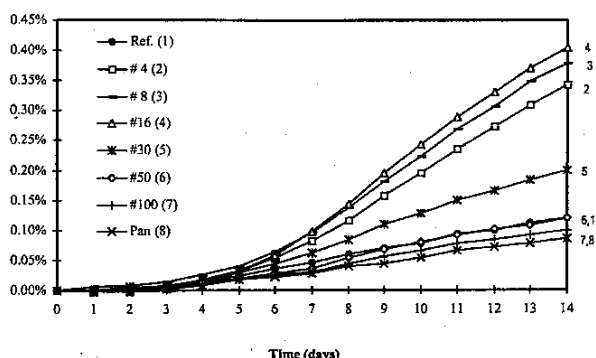


Fig. 1—Expansion time histories for mortar bars containing 10% clear soda-lime glass of different particle sizes.

and ASTM C 441¹⁷), before any ASR mitigating techniques are proposed to be applied to concrete with glass aggregate subjected to actual service conditions.

A local Long Island sand was used in the initial experiments. Mortar bars made with this sand exhibited expansions of approximately 0.1%. In all subsequent studies, the Long Island sand was replaced by a manufactured sand that caused mortar bar expansions of approximately 0.027%. Type I low-alkali cement containing 0.23% Na₂O-equivalent was used throughout the study.

The glass aggregate was obtained from beverage bottles collected locally. The bottles were washed and crushed with a crushing machine. In one test, Pyrex glass of Type 7740 borosilicate and fused silica were used. The chemical compositions of these glasses are summarized in Table 1.

ASR TEST RESULTS

Effect of particle size

ASR processes involve a solid (the reactive aggregate) and a liquid (the pore solution) and are properly classified as heterogeneous solid-liquid chemical reactions.¹⁸ As a result, the surface area of the aggregate, as related to its particle size distribution, is a primary factor for the reaction rate. To study the effect of particle size on the reactivity of glass aggregate, 10% of the total graded sand aggregate (Long Island sand) by weight was replaced with clear soda-lime glass aggregate of one particular size at a time.

The individual expansion time histories for different aggregate sizes are plotted in Fig. 1, showing the typical evolution of mortar bar expansions. The expansion is usually not noticeable until after 3 to 4 days when the rate clearly accelerates. The mortar bar expansions are replotted in Fig. 2, where the sizes of the glass particles substituted for sand are noted on the horizontal axis by U.S. standard sieve numbers. The values

Table 1—Chemical compositions of soda-lime container glass,* Pyrex glass, and fused silica (%)

	Clear glass	Amber glass	Green glass	Pyrex glass	Fused silica
SiO ₂	73.2 to 73.5	71.9 to 72.4	71.27	81.0	99.97
Al ₂ O ₃	1.7 to 1.9	1.7 to 1.8	2.22	2.0	—
Na ₂ O + K ₂ O	13.6 to 14.1	13.8 to 14.4	13.06	4.0	—
CaO + MgO	10.7 to 10.8	11.6	12.17	—	—
SO ₃	0.20 to 0.24	0.12 to 0.14	0.052	—	—
Fe ₂ O ₃	0.04 to 0.05	0.30	0.599	3.72	—
Cr ₂ O ₃	—	0.01	0.43	12.0 to 13.0	—

*Clear, amber, and green glass.

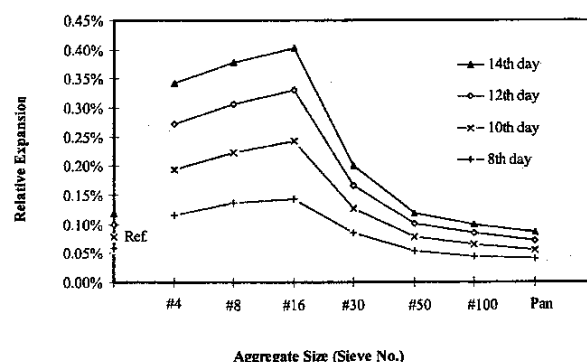


Fig. 2—Particle size effect on ASR expansion (10% clear soda-lime glass).

marked "Ref." are for reference mortar bars containing no glass. All results are the means of values obtained for three identical bars.

The graph shows that for clear soda-lime glass, maximum expansion (the "pessimum") occurs for sieve size No. 16, that is, particles retained on sieve No. 16 (1.18 to 2.36 mm). Mortar bars containing 10% of size No. 50 glass aggregate exhibit approximately the same expansion as the reference bars, while mortar bars with 10% of either size No. 100 or pan (glass particles passing sieve No. 100) show less expansion than the reference bars. The intrinsic shape of the distribution curve barely changes during the 14-day test period.

A pessimum effect with respect to either aggregate content or size has been reported by many researchers. While the pessimum content effect has been studied extensively and several mechanisms have been postulated, literature on the pessimum size effect is relatively scarce and in fact not quite consistent. In tests using opaline silica as the reactive constituent, it was found that expansion increases as the reactive particle size is reduced to 50 μ m,^{19,20} but below that particle size, no abnormal expansion was observed. However, based on a test with opal aggregate in which large expansions were detected for particles as fine as 20 to 30 μ m, Diamond and Thaulow²¹ suggested that fineness of aggregate size is no guarantee against expansion.

The chemical composition of the ASR gel is a critical factor in determining expansion. The classical theories to explain the pessimum behavior have been based mostly on mechanisms related to the Na₂O/SiO₂ ratio of the ASR gel products. Hansen²² and later Pike et al.²³ attributed the pessimum content effect to variation in the alkali to silica ratio of the reaction product. They argued that a gel of a particular Na₂O/SiO₂ ratio would generate a maximum swell pressure. This hypothesis was later supported by some experimental

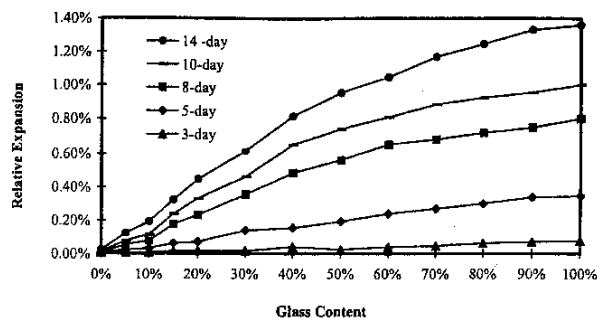


Fig. 3—Effect of glass content on ASR expansion (clear soda-lime glass).

work. Dent Glasser and Kataoka²⁴ suggested that the maximum amount of dissolved silica occurred at an intermediate $\text{Na}_2\text{O}/\text{SiO}_2$ ratio. By preparing a series of synthetic sodium-silicate gels, Struble and Diamond^{25,26} observed the maximum swelling pressure for gels with intermediate sodium contents.

The theory based on the $\text{Na}_2\text{O}/\text{SiO}_2$ ratio explains reasonably well the pessimum content effect observed in the early tests using a standard test method, such as ASTM C 227, with a fixed supply of alkalis. Assuming that the accessible SiO_2 extends a certain distance below the original particle surface, Zhang and Groves²⁷ were also able to further relate the pessimum particle size effect of silica glass to an effective $\text{Na}_2\text{O}/\text{SiO}_2$ ratio. This hypothesis, however, is challenged by both the current test results for glass aggregate using ASTM C 1260 and by results from Shayan²⁸ who used accelerated mortar bar tests that exhibited a pessimum content that was unexpected, since the supply of alkali in a 1 N NaOH solution is basically unlimited, and no pessimum effect is supposed to exist in such an accelerated test. This means that a better theory is needed to explain the experimental evidence. During the search for such a theory, a number of factors involved in the ASR expansion and damage process were studied, with the ultimate objective to develop a unified model capable of accounting for all observed phenomena.²⁹

Effect of glass content

To study the effect of glass content and to determine whether there exists a pessimum content, 13 sets of mortar bar specimens with glass contents varying from 0 to 100% were tested for ASR expansions according to ASTM C 1260. In this test, the nonreactive Blue Circle sand was used as aggregate, different percentages of which were replaced by clear soda-lime glass such that the same aggregate grading was maintained.

The 14-day expansions of the mortar bars are plotted against glass content in Fig. 3. As can be seen, the expansion increases consistently with increasing glass content, so that no pessimum content is detected.

Effect of glass type

To further study the pessimum particle size effect, a test was performed with mortar bars containing nonreactive Blue Circle sand, 10% of the graded sand was replaced by either Pyrex glass or fused silica of one single particle size at a time. The 14-day expansions are shown in Fig. 4, together with those already seen in Fig. 2 for clear soda-lime glass. The expansion caused by Pyrex glass and fused silica are multiples of those exhibited by clear soda-lime glass. Moreover, a pessimum size is seen to exist for all three types of glass tested: size No. 16 for clear soda-lime glass, No. 200 for Pyrex glass, and No. 400 for fused silica. Fused silica is the most reactive glass among the three, followed by Pyrex and soda-lime glass.

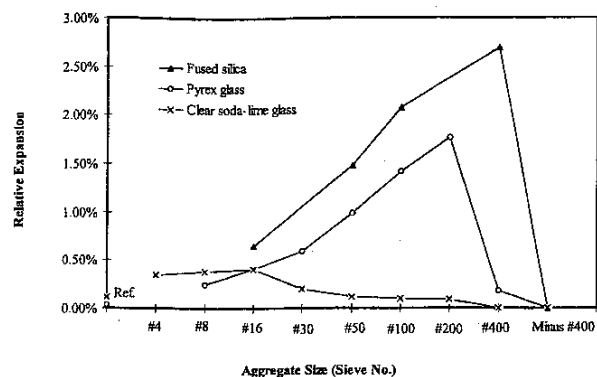


Fig. 4—Particle size of clear soda-lime glass, Pyrex, and fused silica.

The reactivity of aggregate has been attributed to the amount of amorphous silica it contains. It also depends on other factors such as CaO content. Tang et al.³⁰ correlated the reactivity of the glass to the reactivity index defined as $K = (\text{CaO} + \text{Al}_2\text{O}_3)/(\text{SiO}_2 + \text{Na}_2\text{O})$. It was shown that for decreasing CaO and Al_2O_3 contents (with corresponding increases in Na_2O and SiO_2 contents), the reactivity increases.

Fused silica is an almost 100% amorphous silica glass. Pyrex is a two-phase borosilicate that contains 80% silica glass and 20% sodium-borate glass. The second phase creates greater microporosity, and the two phases are expected to react at different rates in the highly alkaline pore solution. Soda-lime glass has a silica content ranging from 65 to 80%, depending on compositions. It also contains a variety of alkali and alkali earth oxides, as well as alumina. It is thought of as a single-phase material, even though some opaque glasses contain a second phase that can cause different reaction rates.

The results of Fig. 4 indicate that the pessimum size depends strongly on the reactivity of the aggregate. As the aggregate becomes more reactive, the pessimum size decreases. Because the expansions of the three types of glass tested cover quite a large range, it can be postulated that a pessimum size exists for all reactive aggregates, although the pessimum size of some highly reactive aggregates might be too small to be detectable in the size range normally tested. This might explain why Diamond and Thaulow²¹ observed increasing expansions for particle sizes as fine as 20 μm . Another example is the paradox described by Diamond³¹ about silica fume: silica fume with coarse particles or undispersed agglomerates can induce ASR rather than mitigate it. Thus, even the highly pozzolanic material cannot be guaranteed to be free of ASR, unless the particles are fine enough.

Effect of glass color

Most postconsumer glass is recycled as mixed-color cullet. A fairly representative sample of New York City waste glass contained 62% clear glass, 19% green glass, 14% amber glass, and the balance of 5% contained other colors, as well as various foreign materials such as ceramics. When determining the particle size effect on ASR expansion for different color glass, the results of Fig. 5 were obtained, in which the 14-day mortar bar expansions are plotted for various colors as a function of particle size. As can be seen, clear glass causes the most expansion. Amber glass is considerably less reactive, and its pessimum size is No. 8 rather than No. 16. Green glass, on the other hand, appears not only to be not reactive, but to also reduce the expansion of the slightly reactive (Long Island) sand. Based on this surprising finding, finely ground green glass seems to have the potential of an inexpensive ASR suppressant, with its effectiveness increasing with particle fineness.

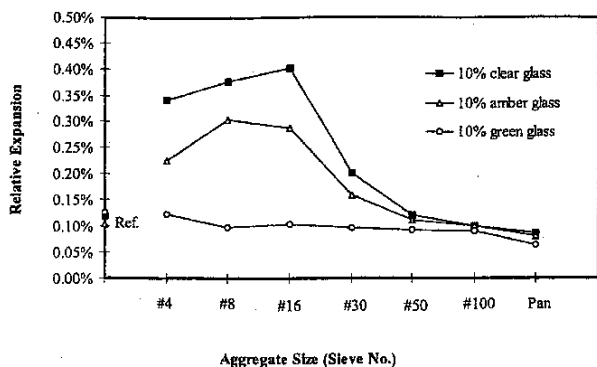


Fig. 5—Particle size effect for different glass colors.

The color of glass is normally obtained by adding certain oxides to the glass melt, such as Fe_2O_3 for amber color and Cr_2O_3 for green color. The effectiveness of green glass as an ASR suppressant was found to strongly correlate with the amount of Cr_2O_3 in the glass (Fig. 6).³² Cr_2O_3 , added straight to the concrete mixture, was found to increase the expansion considerably, as has been observed earlier.³³ But if added as chemically bound frit, it can serve as an ASR inhibitor. This ASR suppressing mechanism of Cr_2O_3 seems to support the hypothesis of Prezzi et al.³⁴ that the expansive pressure resulting from electrical double-layer repulsion is inversely proportional to the ionic valence. Thus the gel containing Cr^{3+} appears to be less expansive.

GENERAL COMMENTS ON ASR

ASR is a chemophysical process that may result in mechanical damage. If the aggregate contains reactive silica, it will be dissolved in the highly alkaline pore solution of the cement paste and react with (or absorb) Na^+ , K^+ , Ca^{2+} , and other ions to form ASR gel. Depending on the composition, the gel can be swelling or expansive in nature. If one considers concrete or mortar as a three-phase composite consisting of cement or mortar matrix, interfacial transition zone (ITZ), and aggregate, and further assume the reactive aggregate to be relatively dense, as in the case of glass, the gel that results from the reaction between the aggregate and cement pore solution will form initially on the surface of the aggregate; some gel will probably form within the aggregate as well, if this is porous. Under confinement by the cement matrix and aggregate, the swelling of the ASR gel generates hydrostatic pressure. Viscous in nature, the ASR gel is able to permeate into the surrounding porous ITZ and cement matrix, thereby relieving the pressure caused by the gel expansion. The observed expansion is therefore the result of the elastic and inelastic deformations caused by the net hydrostatic pressure, which depends on the elastic moduli of the matrix and aggregate, the viscosity of the ASR gel, the permeability of the matrix, and the aggregate size and content. If the reaction continues and the internal pressure exceeds the tensile strength of the matrix, cracks will form around the reacting aggregate particles. This microcracking decreases the effective elastic modulus and increases the material's effective permeability, and marked expansion will result.

The gel formation and gel permeation are the chemical and physical processes that affect the internal pressure, which causes the expansion and microcracking of concrete. The gel formation builds up the internal pressure, while the gel permeation tends to relieve it. The net pressure thus reflects the difference between gel formation and permeation rates. These two rates are different functions of the aggregate surface area, such that there exists a certain particle size at which the two processes balance each other. In other words, there exists a size at which maximum expansion occurs. This pessimum

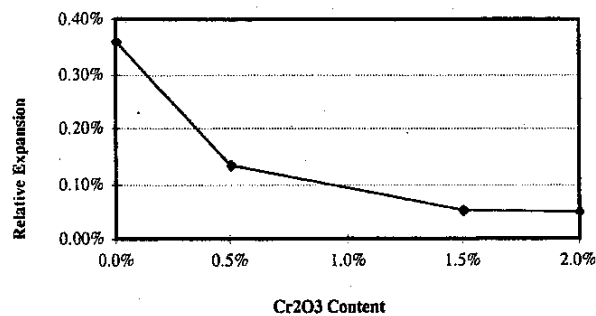


Fig. 6—Effect of Cr_2O_3 content in green glass on expansion.

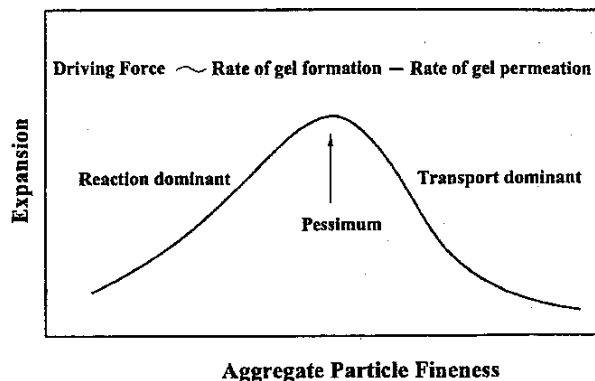


Fig. 7—Illustration of pessimum size effect as result of two processes.

size is a function of the aggregate reactivity and the transport property of the matrix. Figure 7 illustrates schematically how these two processes contribute to the pessimum size effect. For the left branch of the curve, the process is reaction dominant, while for the right branch it is transport dominant. The pessimum size will be shifted to the right as the aggregate reactivity increases and to the left as the matrix permeability increases. This analysis is consistent with the experimental evidence at early ages, when the expansions are mainly elastic. Using the approach previously outlined, which takes into account the coupling effect of chemical, physical, and mechanical processes, a chemo-physico-mechanical model has been developed to predict the ASR expansion of concrete. This model consists of three parts. First, a micromechanical multiphase composite model is formulated to calculate the overall expansion caused by the expanding phase due to ASR and the pressure generated thereafter, both depending on the rates of gel formation and gel permeation. Next, the rate of gel formation is determined by Fick's law of ionic diffusion. Finally, the rate of gel permeation is described by Darcy's law of steady-state viscous flow. By solving the three coupled equations, together with proper calibration of material parameters, the kinetic expansion process of concrete undergoing ASR can be simulated. Details of the theoretical formulation of this model can be found in Reference 29, together with first analytical results.

CONCRETE MASONRY BLOCKS

Concrete masonry blocks are suitable for absorbing large quantities of waste glass. Such blocks are manufactured by relatively few producers with good quality control in often highly automated facilities. By initially limiting the goal of aggregate replacement by glass to 10%, the problems of ASR and potential strength loss, as crushed glass particles with smooth sur-

faces are substituted for regular aggregate, seemed to be manageable. As the preceding results show, it is indeed possible to keep the negative effects associated with ASR expansion under control, by grinding the glass fine enough. Novel crushing techniques have been developed by which the required fineness can be achieved with relatively low energy consumption.

Prototype concrete blocks were produced. A batch for the standard blocks consists of 3010 lb gravel, 5600 lb sand, 1000 lb cement, and 174 lb (20.8 gal.) water and is good for approximately 250 blocks. In the test described herein, four different batches were mixed, using as a basis the quantities for 1/2-standard batch. Batch A served as control and contained exactly the same mixture proportions as the standard batch listed previously. The mixture proportions for Batches B, C, and D were identical to those of Batch A, except that in Batch B, 430 lb of sand (that is, 10% of the total aggregate) were replaced by an equal amount of mixed-color crushed waste glass of size No. 30; in Batch C, 10% of the cement was substituted by No. 400 glass; and in Batch D, the substitutions of Batches B and C were combined. The fully automated system moved the blocks from the block machine into a curing chamber, where they were steam-cured for approximately 42 h at 140 F.

Strength tests after 28 days gave the following results for the four batches, respectively: 4.68, 4.26, 4.63, and 4.26 ksi (32.2, 29.4, 31.9, and 29.4 MPa). These results indicate a maximum strength drop of 9%, which is mostly attributable to statistical scatter, as paving blocks with 100% glass aggregate have already been produced with strengths in excess of 10 ksi (69 MPa).^{3,5} Because the strength of the control block exceeded the required strength considerably, such small strength variations were felt to be acceptable.

The drying linear shrinkage values measured for the four batches were with 0.017, 0.0286, 0.0300, and 0.0260%, respectively, well below the limit of 0.065% specified in ASTM C 90.³⁶ The absorption test results showed negligible variation among the four batches, and all results stayed well below the maximum acceptable limit of ASTM C 90 for normalweight blocks.

Whether concrete masonry blocks with waste glass aggregate can be manufactured economically depends on both technical and economical feasibility. The technical feasibility has been demonstrated,¹³ but concrete block manufacturing is a highly competitive business with very small profit margins. A small profit margin, however, is also the cause for optimism in that a few cents of additional profit realized through the use of waste glass may offer a sufficient economical incentive for a block manufacturer to use it. In analyzing the economic viability of glass-containing concrete block, it was apparent that using crushed waste glass as substitute for aggregate alone is of marginal cost advantage, because sand is simply too inexpensive, whereas replacing both sand and cement by glass and finely ground glass powder (as in Batch D) can offer a slight economic advantage. The block machine output was found, however, for as yet inexplicable reasons, to be almost 8% higher for the three batches with glass than for the reference batch. This productivity increase has the potential of a 5 to 6% reduction in cost. There are other, mostly intangible and less quantifiable potential benefits. Although the U.S. lags behind many European countries in some aspects of environmental consciousness, environmentally friendly products are gaining in popularity nationwide, and anecdotal evidence suggests that consumers are willing to pay a premium for products that are shown to save our natural resources by using recycled materials.

The concrete block described herein can be referred to as a commodity product. Although the partial glass substitution for sand and cement has only a marginal economic effect at best, it offers the opportunity of absorbing large amounts of waste glass, thereby easing the solid waste disposal problem of municipalities. For example, if a single manufacturer with an annual

output of 5 million blocks were to use 10% glass aggregate, he could absorb about 10,000 tons of waste glass, or 10% of what New York City currently collects annually.

ARCHITECTURAL CONCRETE PRODUCTS

If the waste glass is sorted by color, carefully graded by size, mixed with cement paste and expertly polished, a value-added material, glasscrete is obtained with unlimited decorative and architectural applications. The added value of such a material derives from the fact that it can serve as a substitute for expensive natural stone products, like polished marble or granite, at a fraction of the cost. Effective color coordination may call for white cement and cement colors. Because aggregate particles larger than No. 30 are needed to enhance the visual effect, ASR suppressing admixtures are necessary to control potential ASR damage. This is particularly true for outdoors applications that are exposed to the elements, where the moisture required to perpetuate the chemical reaction is available. Some of the applications that are being considered are: tiles for floors or walls, wall panels, curtain walls, table top counters, benches and other furniture, tree planters, vases, and paving blocks. The compressive strength properties are generally adequate, as a strength of 6000 psi (40 MPa) is easily achievable.^{14,55} If tensile strength, impact resistance, and fracture toughness are essential, the material can be reinforced with appropriate fibers, either continuous fiber mesh or randomly oriented discontinuous fibers. Efforts are currently underway to set up manufacturing facilities in New York State to produce various prototype

products containing 100% glass aggregate. The response by architects, builders, and the public at large has been overwhelmingly positive.

CONCLUSIONS

Using the relatively new accelerated ASR expansion test, ASTM C 1260, hundreds of mortar bars containing various amounts of crushed waste glass particles of different sizes were tested. These studies resulted in the following findings.

1. A pronounced particle size effect was identified. The pessimum size (particle size that causes maximum expansion) is a function of glass type and color. With increasing reactivity of the glass, the pessimum shifts towards smaller particle sizes;
 2. The expansion of mortar bars is directly proportional to the glass content. No pessimum content was found in this accelerated test;
 3. The expansions of mortar bars are strongly dependent on the color of the glass. Clear soda-lime glass was most reactive, followed by amber glass. Green glass caused no expansion to speak of. A strong correlation was found between expansion and Cr_2O_3 content, which is typically added to the glass for the green color; and
 4. It has been shown that finely ground green glass powder has the potential of an inexpensive ASR suppressing admixture.
- The use of crushed waste glass as an aggregate in concrete has several advantages. If used in large quantities in commodity products such as concrete masonry blocks, the solid waste disposal problem faced by municipalities nationwide can noticeably be reduced. The studies reported herein indicate that the detrimental consequences of alkali-silica reaction can be avoided by grinding the glass fine enough, (that is, to the size passing U.S. standard sieve No. 50).

For value-added concrete products made of glasscrete, particles of color-sorted glass have to be large enough to be seen by the eye. In this case, the potential for ASR induced damage can be eliminated by using appropriate ASR-suppressing admixtures. By careful coordination of glass color and colored cement, and proper surface treatment such as polishing, stunning aesthetic effects can be achieved, which can be exploited for decorative and architectural applications limited only by one's imagination.

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