

# **FIELD INVESTIGATION OF CONCRETE INCORPORATING MILLED WASTE GLASS**

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## **ABSTRACT**

About 12.5 million tons of waste glass is generated annually in the U.S., 77% of which is disposed of in landfills. Waste glass can be cost-effectively collected in mixed colors, but has limited markets. Mixed-color waste glass offers desired chemical composition and reactivity for use as a supplementary cementitious material for enhancing the chemical stability, moisture resistance and durability of concrete. To realize this potential, waste glass needs to be milled to micro-scale particle size for accelerating its beneficial chemical reactions in concrete. In this investigation, recycled glass concrete was produced by partial replacement of cement with milled waste glass. Recycled glass concretes with 15, 20 and 23 wt.% of cement replaced with milled glass were investigated in field (pavement) construction projects. The compatibility of recycled glass concrete with conventional construction techniques was evaluated, and the field performance of recycled glass concrete under weathering effects (in mid-Michigan) was monitored over a two-year period. Compressive strength, water sorption, chloride permeability, and abrasion resistance tests of recycled glass concretes were performed on cores drilled from the experimental pavements, and the results were compared with those obtained with normal concrete. Flexural strength tests were carried out on concrete specimens at various ages. Test results indicated that recycled glass concrete incorporating milled waste glass as partial replacement for cement offers excellent strength and durability attributes when compared with normal concrete. The pozzolanic reactions of milled waste glass with cement hydrates improve the microstructure and chemical composition of concrete. Use of milled waste glass in concrete as partial replacement of cement represents an important step towards development of sustainable (environmentally friendly, energy-efficient and economical) concrete-based infrastructure systems.

**Keywords:** Waste glass; recycling; supplementary cementitious material; concrete; energy saving; environmentally friendly; economics

## **INTRODUCTION**

Each year about 12.5 million tons of waste glass is generated in the U.S., 77% of which is disposed of in landfills, accounting for 6 wt.% of the total municipal solid waste stream [1]. Globally, about 5 wt.% of the 2.02 billion tons/yr of municipal solid waste generated is glass [2]. Post-consumer waste glass can be cost-effectively collected in

mixed color; there are, however, limited markets for mixed-color waste glass [3]. Disposal of waste glass in landfills is costly, considering increasing tipping fees; the non-biodegradable nature of glass further complicates the environmental impact of its disposal in landfills [4]. Stricter environmental regulations and the scarcity of landfill space are other factors encouraging diversion of waste glass from landfills for value-added use in new applications.

Manufacturing of cement, a key ingredient used for the production of concrete, is a major source of greenhouse gas emissions. Fabrication of a ton of cement results in emission of one ton of carbon dioxide (CO<sub>2</sub>) to the atmosphere [5-13]. Globally, cement production contributes 5-8% of anthropogenic CO<sub>2</sub> emissions [5, 8, 10-12, 14-16]. In 2007, the total cement production in the United States was close to 100 million tons, which contributed about 100 million tons of CO<sub>2</sub> to the atmosphere [17]. The 1995 CO<sub>2</sub> emissions by the cement industry was equivalent to the emissions from 300 million automobiles [18]. This highlights the large carbon footprint of the cement industry [19-20]. Cement production also involves emission of moderate quantities of NO<sub>x</sub>, SO<sub>x</sub>, and particulates [8].

Manufacturing of cement is also an energy-intensive process, which ranks third after aluminum and steel manufacture in terms of energy consumption. Close to 5.5 million BTU of energy is consumed for production of a ton of cement [21]. The cement industry accounts for about 2% of the global primary energy consumption (or ~5% of the total global industrial energy consumption) [22]. The energy used for production of cement accounts for more than 90% of the total energy required for production of concrete [23]. In spite of major efforts in recent decades, significant gains in fuel-efficiency of cement production plants has not been realized [9]. This situation warrants decisive measures to be taken to reduce the carbon contribution of the cement and concrete industries.

The use of solid waste materials or industrial by-products as partial replacement for cement in concrete is a viable strategy for reducing the use of Portland cement and hence making concrete production environmentally friendly and energy-efficient [24]. Glass, which is rich in amorphous silica (Table 1 compares the chemical compositions of glass and cement), has the proper chemistry and reactivity to enter pozzolanic reactions with the lime released during hydration of cement;

these reactions can yield highly stable end products with desired binding qualities.

Past efforts to recycle waste glass in concrete have focused on the use of crushed glass as replacement for aggregate in concrete [25-26]. These efforts neglected the reactive nature of glass in concrete, which was slowed down due to the relatively large (millimeter-scale) size of glass particles [26-27]. Such long-term reactions proved to be detrimental to the long-term stability of concrete incorporating relatively large (crushed) glass particles. Milling of glass to micrometer-scale particle size, for accelerating the reactions between glass and cement hydrates, can bring about major energy, environmental and cost benefits when cement is partially replaced with milled waste glass for production of concrete. It has been reported that recycling of each ton of glass saves over one ton of natural resources, and recycling of every six tons of container glass results in the reduction of one tone of carbon dioxide emission [28].

This paper reports on field investigations of concrete materials incorporating milled waste glass as partial replacement for cement. Two field projects covered here involved construction of: (i) Pavement sections used as sidewalk and maintenance vehicle access route on the Michigan State University campus (constructed in May 2008); and (ii) concrete driveway, sidewalks and curbs at the Michigan State University Recycling Center (constructed in May 2009). These projects evaluated commercial production (in ready-mixed plants) of concrete incorporating milled waste glass as partial replacement for cement, and its large-scale use in concrete pavement (and curb) construction. The field performance of recycled glass concrete under weathering effects and traffic is subject of long-term monitoring. Recycled glass concrete has performed satisfactorily in these field studies. The field projects have played key roles in introducing the value of waste glass as partial replacement for cement to concrete producers and contractors.

**TABLE 1**  
**Typical chemical compositions of waste glass and Portland cement**

<i>Chemical</i>	<i>Glass</i>	<i>Cement</i>
SiO <sub>2</sub>	73.5%	20.2%
Al <sub>2</sub> O <sub>3</sub>	0.4%	4.7%
CaO	9.2%	61.9%
Fe <sub>2</sub> O <sub>3</sub>	0.2%	3.0%
MgO	3.3%	2.6%
Na <sub>2</sub> O	13.2%	0.19%
K <sub>2</sub> O	0.1%	0.82%
SO <sub>3</sub>	-	3.9%
Loss on ignition	-	1.9%

In field projects, milled waste glass with 25 µm average particle size was used as replacement for 15%, 20% and 23% of Type I Portland cement in concrete. Cores were taken from sections of concrete pavements at different ages, and were tested for evaluation of the compressive strength, water sorption, chloride permeability, and abrasion resistance of field recycled glass concrete versus normal concrete. Microstructural analysis of the recycled glass concretes were carried out using SEM and EDX analysis of the concrete cores. Compression and flexure tests were also performed on recycled glass and control concrete specimens prepared from field concrete during construction.

## MATERIALS, MIX DESIGNS, AND FRESH MIX PROPERTIES

Table 1 shows the chemical composition of the milled waste glass and ordinary Portland cement used in field projects. Table 2 presents some physical properties of the milled

waste glass used here, and Figure 1 shows a scanning electron microscope image of the milled waste glass.

Three mix designs containing milled waste glass as replacement for 15%, 20% and 23% of cement (by weight) were prepared at ready-mix concrete plants for use in the two field projects. Pavement and driveway sections were also constructed with control concrete for comparative evaluation against recycled glass concrete. Table 3 shows the mix designs and fresh concrete properties for recycled glass and control concrete mixtures used in field projects.

Crushed limestone coarse aggregate with maximum size of 19 mm (¾ in) and non-reactive river sand were used in all concrete mixtures. All batches of concrete were manufactured in ready-mix concrete plants. Representative concrete cylinders with 6 in. (152 mm) diameter and 12 in (305 mm) height were prepared and tested in compression following ASTM C 39 procedures after 7, 14, 28, 90 and 270 days of moist curing (in lime-saturated water). Similarly, concrete beams were prepared from all concrete mixtures, and were tested for flex-

TABLE 2  
Physical properties of milled glass

<i>% Passing # 325 Mesh</i>	93%
Specific Gravity	2.46 gm/cc
Median Particle Size	25 µm
Moisture content	0.1%
Brightness	80%
Specific Surface Area	4280 cm <sup>2</sup> /gm

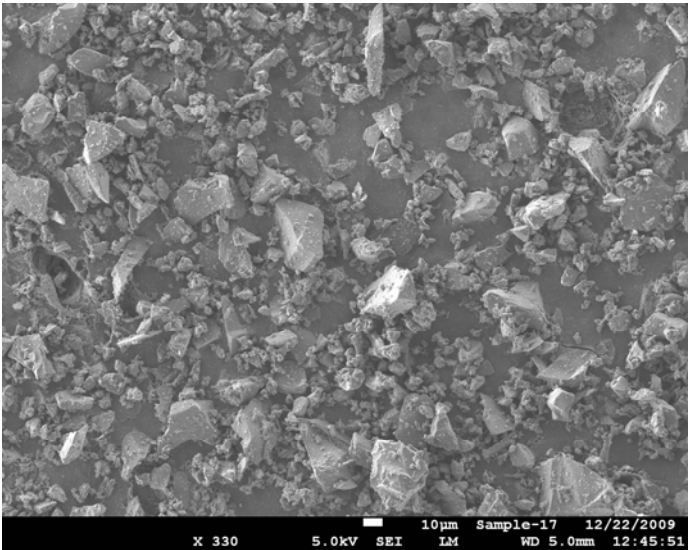


FIGURE 1  
SEM micrograph of milled waste glass

**TABLE 3**  
**Concrete Mix Designs and fresh mix properties**

Ingredient	Mix Designs			
	<i>Control</i>	<i>15% Glass</i>	<i>20% Glass</i>	<i>23% Glass</i>
Cement Type I, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	312 (526)	265 (447)	250 (421)	240 (405)
Milled Glass, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	-	47 (79)	62 (105)	72 (121)
Fine aggregate, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	799 (1347)	799 (1347)	799 (1347)	799 (1347)
Coarse aggregate, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1063 (1792)	1063 (1792)	1063 (1792)	1063 (1792)
Water content, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	141 (237)	141 (237)	141 (237)	141 (237)
Air entraining agent (ml/100 lb of cement)	60	60	60	60
Water/Cement ratio	0.45	0.45	0.45	0.45
Slump, cm (inch)	9 (3.5)	9 (3.5)	7.5 (3)	7.5 (3)
Air content (%)	4.5	4.5	4.0	4.0

ural strength following ASTM C 78 procedures after 7, 28, 90 and 270 days of moist curing. In addition, 90 days and 450 days after construction of the Recycling Center and the sidewalk/maintenance vehicle pavement projects, respectively, cores were drilled from the constructed pavement sections, and tested for evaluation of the compressive strength, water sorption (ASTM C1585), chloride permeability (ASTM C 1202) and abrasion resistance (ASTM C 944) of field concrete.

The slump test results presented in Table 3 indicate that, at equal water/cement ratios, the recycled glass concrete mixtures have slightly lower fresh mix workability (with the exception of the concrete mix with 15% replacement of cement with milled waste glass). This trend may be attributed to the non-spherical and rough geometry of the milled waste glass particles (see Figure 1). Unlike fly ash, the introduction of milled waste glass did not significantly affect the entrained air content of concrete mixtures prepared with similar dosages of air entraining agent.

### Construction of Sidewalk / Maintenance Vehicle Pavement Sections

Concrete pavement sections with 0.18 m (7 in) thickness, which were 2.4 m (8 ft) in width and 3 m (10 ft) in length between construction joints, were constructed in May 2008 over a compacted base using three recycled glass and one control concrete mixtures. Two pavement slabs were constructed using each concrete mix. Figure 2 shows pictures taken during construction of pavement slabs. During pouring, compaction, and finishing operations, recycled glass and control concretes performed similarly. The pavement sections have performed satisfactorily over two years of exposure to

the mid-Michigan climate and light maintenance vehicle traffic.

### Construction of the Recycling Center External Concrete Pavements and Curbs

This project involved construction of driveways, heated pavement slabs, sidewalks, gutters, curbs, and parking stands at the MSU Recycling Center in May 2009 using recycled glass concrete with 20% of cement replaced with milled waste glass. Mix designs were slightly different in the case of heated pavement and curbs in comparison to other components. Pump-grade flowing recycled glass concrete was produced for the heated pavement, and low-slump concrete was produced for curb construction by the extrusion method. Other components were made using more conventional concrete mixtures (with milled waste glass partially replacing cement). A control concrete was also used in construction of an approach driveway. Figure 3 presents pictures taken during construction of the driveway and curb in this project.

## TEST RESULTS AND DISCUSSION

This section presents the test results produced in the two field projects. Various test results at different ages were generated for the three recycled glass concrete mixtures as well as the control concrete. Tests were performed on concrete specimens prepared at the time of pouring concrete in field, and also on cores drilled at different ages from field concrete sections.





(a)



(b)

**FIGURE 2**

Construction of the sidewalk/maintenance vehicle pavement with recycled glass concrete: (a) pouring of concrete; (b) finishing of concrete



(a)



(b)

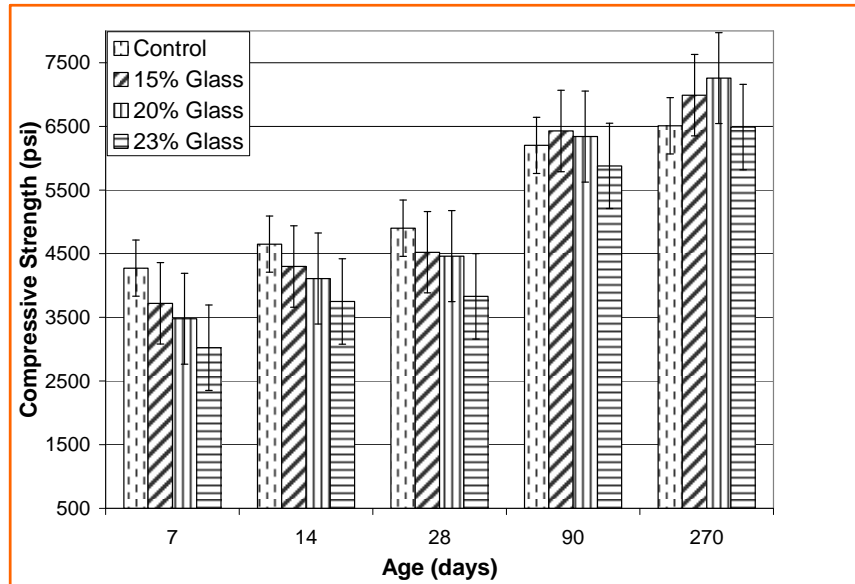
**FIGURE 3**

Construction with recycled glass concrete at the Michigan State University Recycling Center: (a) concrete curb; (b) concrete driveway

## Compressive and Flexural Strengths of Concrete Specimens

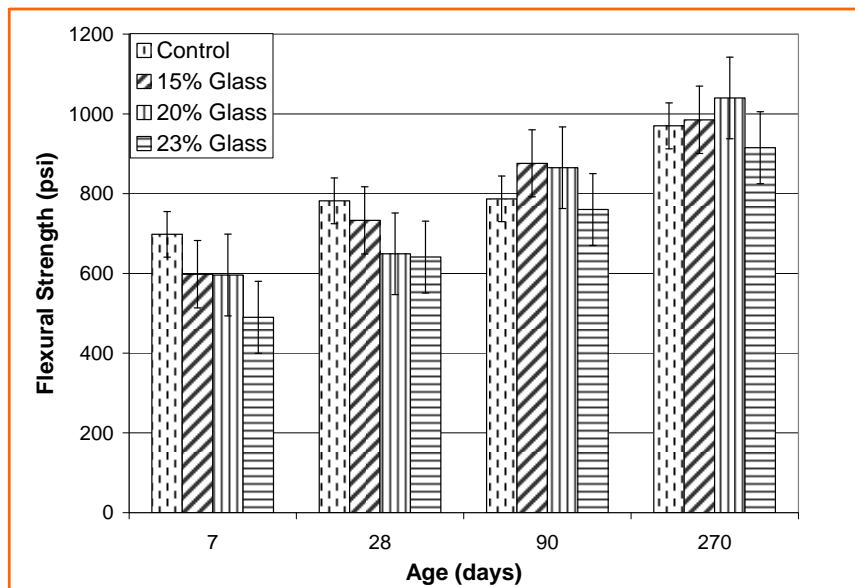
Figures 4 and 5 shows the compressive and flexural strength test results, respectively, for representative concrete specimens molded during construction. Recycled glass concretes are observed in Figure 4 to offer lower mean compressive strengths at 7, 14 and 28 days of age when compared with the control concrete. Statistical analysis (of variance) followed by pair-wise comparison of test results indicated that only the recycled glass concrete mix with 23% cement replacement with milled waste glass produced compressive

strengths that were lower than those of control concrete (at 0.05 significance level). At the age of 90 days, recycled glass concretes with 15% and 20% of cement replaced with milled waste glass provide mean compressive strengths exceeding that of control concrete; while the 90-day compressive strength of the recycled glass concrete with 23% of cement replaced with milled waste glass was lower than that of control concrete. Statistical analysis (of variance) of the 90-day test results indicated that the differences between the compressive strength test results of recycled glass and normal concretes were not statistically significant (at 0.05 significance level). At 270 days, recycled glass concretes with 15% and 20% of cement replaced with milled waste glass provided



**FIGURE 4**

**Compressive strength test results at different ages for concrete specimens prepared using field concrete materials (means & standard errors)**



**FIGURE 5**

**Flexural strength test results at different ages for concrete specimens prepared using field concrete materials (means & standard errors)**

higher mean compressive strengths when compared with control concrete; the mean compressive strength with 23% of cement replaced with milled waste glass was comparable to that of concrete. Statistical analysis (of variance) of the 270-day compressive strength test results indicated that, at 0.05 significance level, the recycled glass and normal concrete materials provided statistically comparable levels of 270-day compressive strength.

Flexural strength test results shown in Figure 5 follow trends comparable to those of compressive strength. Mean flexural strengths of recycled glass concrete at 7 and 28 days of age were less than those of control concrete. Statistical analysis (of variance) indicated that the mean flexural strengths of recycled glass concrete with 23% of cement replaced with milled glass were lower than those of control concrete at all ages. At the age of 90 days, the difference be-

tween mean flexural strengths of recycled glass concretes (with the exception of the 23% replacement level) and control concrete were not statistically significant (at 0.05 significance level). At the age of 270 days, recycled glass concretes with 15% and 20% of cement replaced with milled waste glass produced flexural strengths exceeding that of control concrete. Statistical analysis (of variance), however, showed that the flexural strengths of recycled glass concrete with 15% and 20% of cement replaced with milled waste were statistically comparable (at 0.05 significance level) with that of control concrete at the same age.

The above test results indicate that strength gain in recycled glass concrete occurs at a somewhat lower rate than that in normal concrete, but recycled glass concrete has the potential to reach long-term strengths surpassing those of normal concrete. The slower rate of strength gain in recycled glass concrete reflects the rate of pozzolanic reactions of glass with the calcium hydroxide in cement hydrates. The long-term advantages of recycled glass concrete over normal concrete can be attributed to the enhanced binding qualities of the calcium silicate hydrate which results from pozzolanic reaction of glass with calcium hydroxide, and also to the refinement and partial blocking of capillary pores in cementitious binders undergoing pozzolanic reactions involving milled waste glass. These test results also suggest that there is an upper limit on the cement replacement level with milled waste glass if one desires to produce recycled glass concretes with long-term strengths that are equivalent to or greater than those of normal concrete.

## Compressive Strength of Concrete Cores

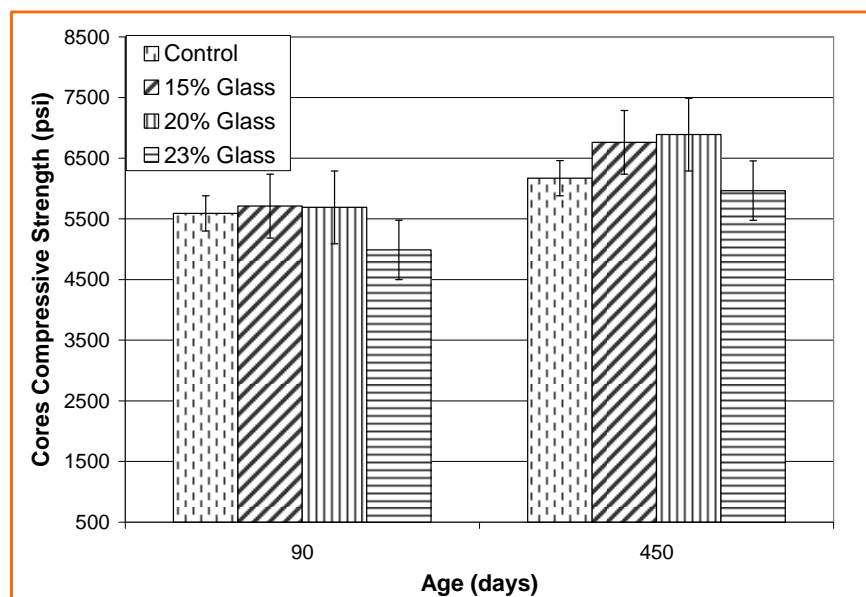
Cores with 102 mm (4 in.) diameter and heights varying from 178 to 203 mm (7 to 8 in.) were drilled from the recycled glass and normal concrete pavements at 90 and 450 days

of age. Figure 6 shows the compressive strength test results produced using these cores. Generally, the strengths of cores exposed to field environment are less than those obtained using continuously moist-cured cylindrical specimens produced using the same concrete (see Figure 4). This finding was found to be statistically significant at 0.05 significance level. The higher strength of specimens prepared in molds and subsequently cured in laboratory, when compared with that of specimens cored from field concrete, is due to the improved curing and probably better preparation of molded specimens.

The strength gain with time for cores follows trends similar to those for molded specimens. At the ages of 90 and 450 days, the core compressive strength with 23% milled waste glass is less than that of control. With 15% and 20% recycled glass content, concrete materials provided higher core compressive strengths when compared with control concrete at both ages. Statistical analysis (of variance) of the test results, however, showed that the differences in core compressive strengths of recycled glass and control concretes were not statistically significant (at 0.05 significance level) at both ages. The compressive strength test results for molded and cored specimens provide strong evidence for the occurrence of pozzolanic reactions between milled waste glass and cement hydrates. These pozzolanic reactions seem to continue to contribute to the concrete quality up to 450 days of age.

## Water Sorption of Concrete Cores

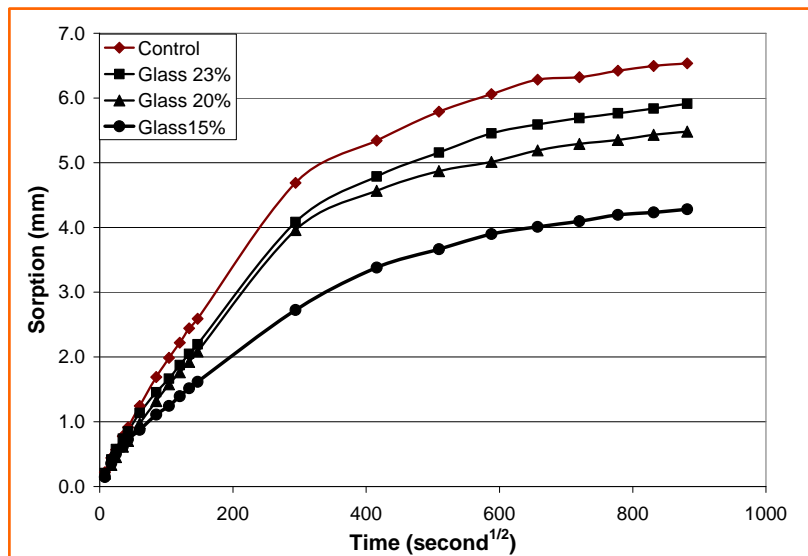
Moisture transport is a fundamental characteristic of concrete that governs its long-term durability [29-31]. Many durability problems in concrete are caused by water transporting dissolved deleterious species into concrete. Moisture itself



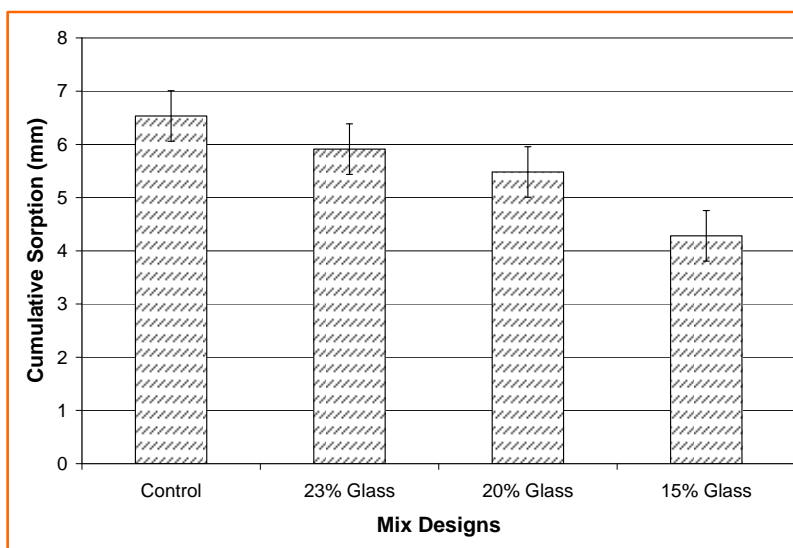
**FIGURE 6**  
Compressive strengths of concrete cores at different ages (means & standard errors)

can play damaging roles under freeze-thaw attack; moisture movements (e.g., drying) of concrete also cause cracking by generating restrained shrinkage stresses. The moisture barrier qualities of concrete can be improved through refinement of the pore size, partial blocking of the continuous capillary pores, and reduction of the pore volume [32]. Milled waste glass, through pozzolanic reactions, brings about these desired changes in the pore structure of hydrated cement paste. Figure 7 shows the results of moisture sorption tests (ASTM C 1585) on 51 mm (2 in.) thick concrete discs prepared from drilled cores at the age of 450 days. The sorbed water versus time plot shows significant improvements in the moisture

sorption attributes of recycled glass concrete materials when compared with control concrete. Figure 8 shows the cumulative water sorption of concrete disc specimens after 9 days of exposure to water. Statistical analysis (of variance) of the 9-day cumulative sorption test results pointed at the statistical significance (at 0.05 significance level) of the contributions of milled waste glass at 15% and 20% cement replacement levels to the resistance of concrete to moisture sorption. At 23% cement replacement level with milled waste glass, however, the cumulative sorption of recycled glass concrete was statistically comparable to that of normal concrete.



**FIGURE 7**  
Water sorption versus time for concrete cores



**FIGURE 8**  
Cumulative water sorption of concrete cores after 9 days of exposure to water (means & standard errors)



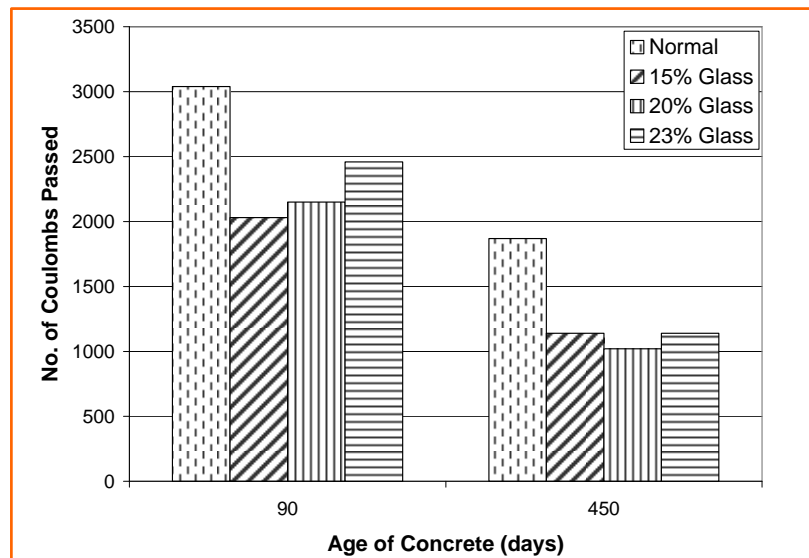
## Chloride permeability of concrete cores

Resistance offered by concrete to chloride ion permeation gives an indication of the barrier qualities of concrete against salt solution, which critically influence its long-term durability. As can be seen in Figure 9, the chloride permeability of the three recycled glass concretes (at 450 days of age) is, on the average, reduced (pointing at improved barrier qualities) by up to 40% when compared with the control concrete. The significant improvements in resistance to chloride permeation are brought about by the partial blocking of pores in hydrated

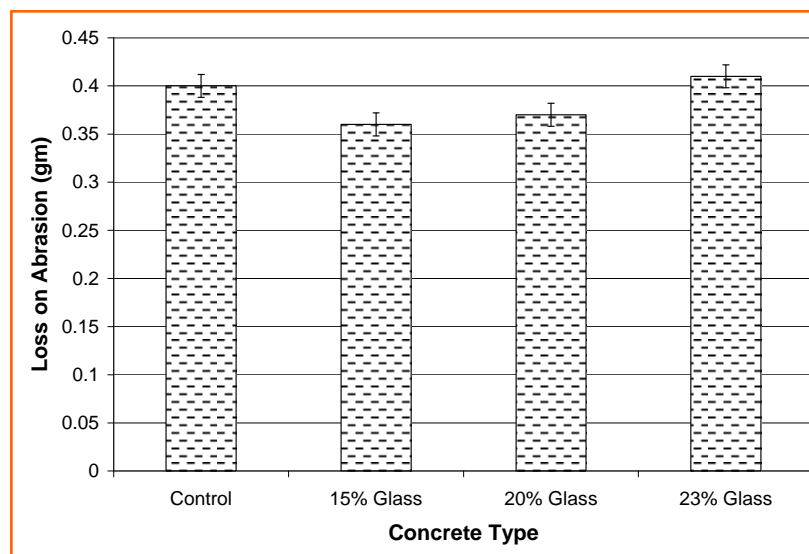
cement paste with the products of pozzolanic reactions involving milled waste glass.

## Abrasion resistance

Abrasion resistance of concrete is an important property influencing the performance of concrete pavements and floors subjected to abrasive action of traffic [33-36]. Figure 10 summarizes the abrasion resistance test results produced using cores obtained from the recycled glass and control concrete pavements at 450 days of age. The abrasive weight



**FIGURE 9**  
Chloride permeability of concrete cores



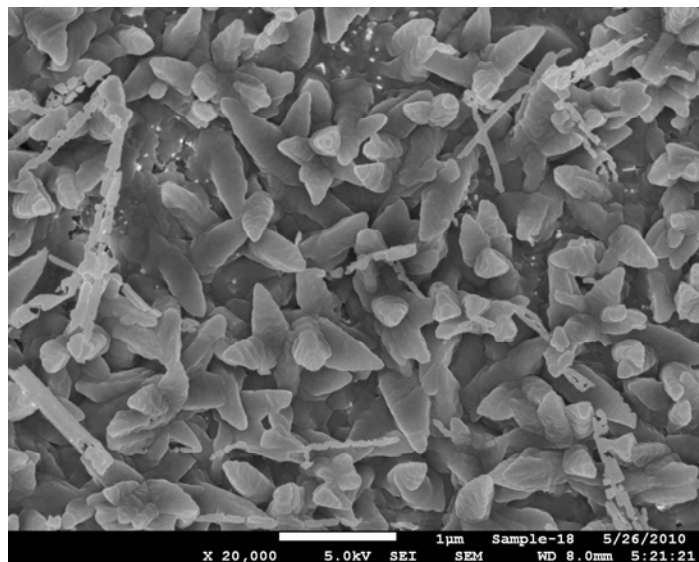
**FIGURE 10**  
Abrasion weight loss of recycled glass and control concretes (means & standard errors)

losses of recycled glass concretes with 15% and 20% cement replacement with milled waste glass were less than that of control, pointing at the positive contributions of the pozzolanic reactions of milled waste glass with cement hydrates to abrasion resistance. The abrasive weight loss of recycled glass concrete with higher (23%) cement replacement level was comparable to that of concrete. Statistical analysis (of variance), followed by pairwise comparison of the abrasion test results indicated that the contributions of milled waste glass to abrasion resistance of concrete was statistically significant (at 0.05 significance) at 15% cement replacement with milled waste glass. Other recycled glass concretes pro-

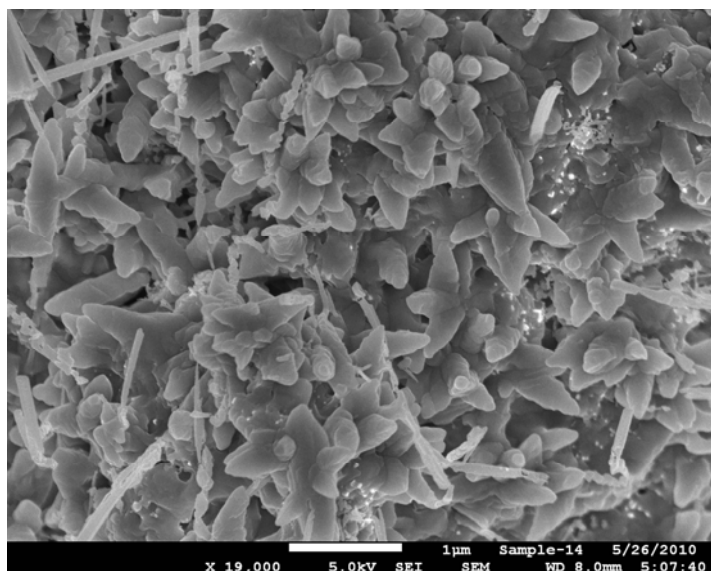
duced abrasion resistances which were statistically comparable to that of control concrete.

### Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS)

SEM and EDS analyses of the specimens prepared from cores were carried out to investigate the effect of milled glass on concrete microstructure and composition. Figures 11 and 12 show scanning electron microscope (SEM) images of concrete materials incorporating milled waste glass as replace-



**FIGURE 11**  
Scanning electron microscope image of a fractured surface of 15% glass concrete



**FIGURE 12**  
Scanning electron microscope image of a fractured surface of 20% glass concrete

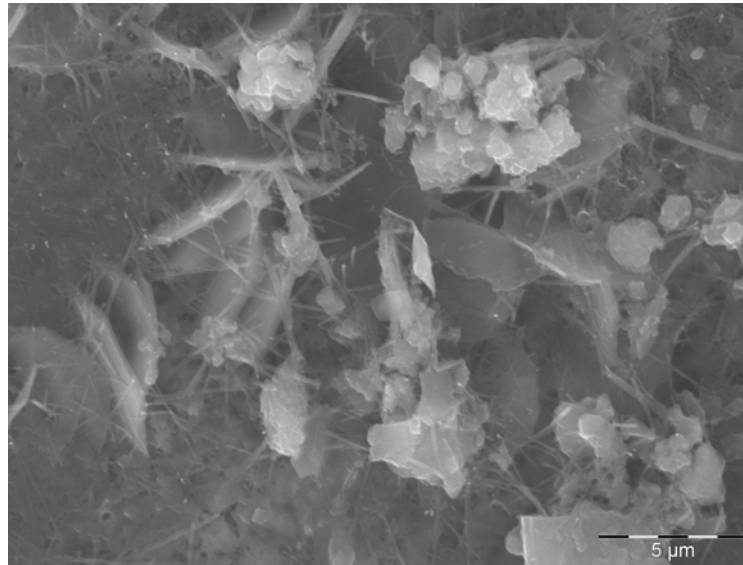
ment for 15% and 20% of cement, respectively; an SEM image of control concrete is shown in Figure 13. The introduction of milled waste glass as partial replacement for cement is observed to produce a relatively dense and uniform microstructure (Figures 11 and 12) when compared with that of control concrete (Figure 13). These effects can be attributed to the pozzolanic reactions of milled waste glass yielding secondary calcium silicate hydrate (C-S-H).

Figure 14 shows the EDS plot of 20% glass concrete taken at the location of Figure 12, and Figure 15 shows the corresponding EDS plot of control concrete at the location of Figure 13. The incorporation of milled waste glass as partial replacement for cement is observed to cause a rise in the peak

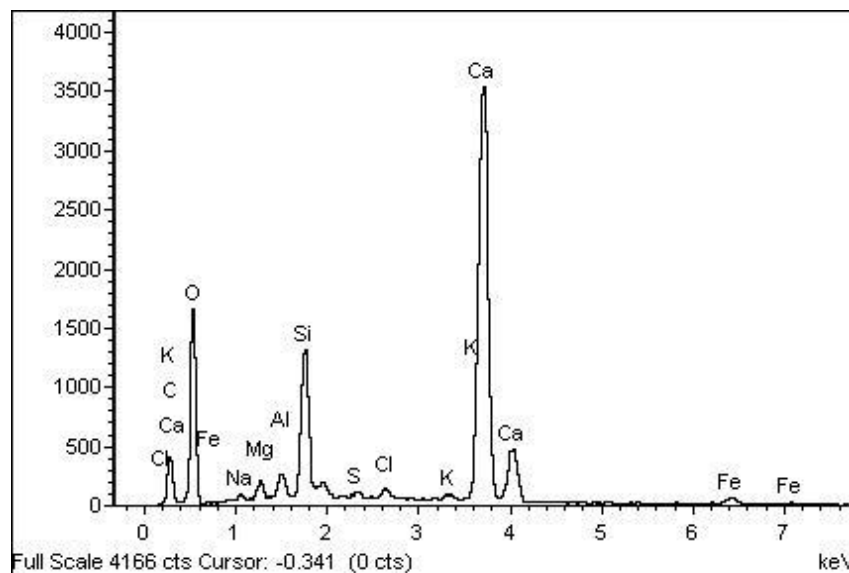
of Si, which points at the silica-rich structure produced by pozzolanic reactions involving glass.

## CONCLUSIONS

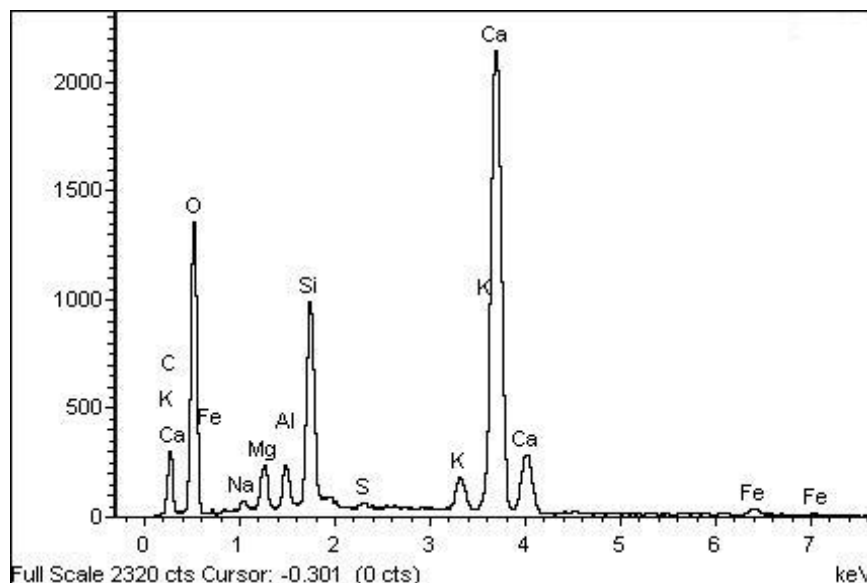
Recycled glass concrete produced by partially replacing cement with milled waste glass of micro-scale particle size is compatible with conventional concrete production and construction techniques. Use of milled waste glass as partial replacement for cement in concrete enhances the resistance of concrete to moisture sorption and transport of deleterious



**FIGURE 13**  
Scanning electron microscope image of a fractured surface of control concrete



**FIGURE 14**  
EDS plot of 20% glass concrete taken at the location of Figure 12



**FIGURE 15**  
EDS plot of control concrete taken at the location of Figure 13

ions, resulting in improved durability characteristics. The abrasion resistance and long-term strength of concrete also benefit from partial replacement of cement with milled waste glass (as far as optimum replacement levels of about 20- wt. % are not exceeded). Recycled glass concrete with about 20% replacement level of cement with milled waste glass has performed satisfactorily in field (pavement and curb) applications over two years of exposure to mid-Michigan weathering effects (and traffic loads). The use of milled waste glass in concrete is a viable practice which would result in important energy, environmental and cost benefits, and would make important contributions towards reducing the carbon footprint of the construction industry.

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## REFERENCES

1. Wastes - Resource Conservation - Common Wastes & Materials. 2009, U.S. EPA.
2. Global Waste Management - Market Assessment. 2007; Available from: [www.bharatbook.com](http://www.bharatbook.com).
3. Egosi, N.G. Utilization of Waste Materials in Civil Engineering Construction. in Mixed Broken Glass Processing Solutions. 1992: ASCE.
4. Meyer, C. Recycled Glass - from waste Material to Valuable Resource. in Recycling and Reuse of Glass Cullet 2001. Dundee, Scotland.
5. Naik, T.R., "Sustainability of concrete construction. Practice Periodical on Structural Design and Construction," 2008. Volume 13, No. 2, p. 98-103.
6. Bremner, T.W., Environmental aspects of concrete: Problems and solutions, in All-Russian Conference on Concrete and Reinforced Concrete 2001.
7. Oss, A.C.P.a.H.G.v., "Cement manufacture and the environment, Part 1: chemistry and technology." *Industrial Ecology*, 2002. Volume 6, No. 1.
8. Van Oss, H.G. and A.C. Padovani, "Cement manufacture and the environment, Part II: Environmental challenges and opportunities." *Journal of Industrial Ecology*, 2003. Volume 7, No. 1: pp. 93-126.
9. Gartner, E., "Industrially interesting approaches to 'low-CO<sub>2</sub>' cements." *Cement and Concrete Research*, 2004. Volume 34, No. 9: pp. 1489-1498.
10. Mehta, P.K., "Reducing the environmental impact of concrete." *Concrete International*, 2001.
11. Scrivener, K.L. and R.J. Kirkpatrick, "Innovation in use and research on cementitious material." *Cement and Concrete Research*, 2008. Volume 38, No. 2: pp. 128-136.
12. Worrell, E., et al., "Carbon dioxide emissions from the global cement industry." *Annual Review of Energy and the Environment*, 2001. Volume 26: pp. 303-329.
13. Uchikawa, H., Approaches to ecologically benign system in cement and concrete industry. 2000, Reston, VA, ETATS-UNIS: American Society of Civil Engineers. 57.
14. Hendriks C. A., E.W., D. de. Jager, K. Blok, and P. Riemer Emission reduction of greenhouse gases from the cement industry Greenhouse gas control technologies conference paper - cement 2004 [cited 2010 January 21];

- Available from: <http://www.wbcsd.org/web/projects/cement/tf1/prghgt42.pdf>.
15. Malhotra, V.M., "Sustainable development and concrete technology." *Concrete International*, 2002.
  16. Malhotra, V.M., "Making concrete 'greener' with flyash." *Indian Concrete Journal*, 1999. Volume 73, No. 10: pp. 609-614.
  17. Mineral commodity summaries, USGS, Editor. 2008.
  18. Malhotra, V.M., Role of Supplementary Cementing Materials in Reducing Greenhouse Gas Emissions in Concrete Technology for a Sustainable Development in 21st Century O.E.G.a.K. Sakai, Editor. 2000, E&FN Spon: London.
  19. PCA, Economics of the U.S. Cement Industry. 2009.
  20. CEMBUREAU, Activity Report 2008, The European Cement Association: Brussels.
  21. Naik, R.N.K.T.R., The role of flowable slurry in sustainable developments in civil engineering, in *Materials and Construction: Exploring the Connection*. 1999, American Society of Civil Engineers: Reston, Va. p. 826-834.
  22. Efficient use of energy utilizing high technology: An assessment of energy use in industry and building 1995, World Energy Council: London.
  23. Cement and concrete: Environmental Considerations. 2004 [cited 2010 Jan 30th ]; Available from: <http://www.wbcsdcement.org/pdf/tf2/cementconc.pdf>.
  24. Meyer, C., "The greening of the concrete industry." *Cement and Concrete Composites*, 2009. Volume 31, No. 8: pp. 601-605.
  25. Meyer, C., Baxter, S., and Jin, W. Alkali-silica reaction in concrete with waste glass as aggregate. in *Materials for a New Millennium, Proceedings of the Fourth Materials Engineering Conference 1996*. Washington, D.C.
  26. Johnston, C.D., "Waste Glass as Coarse Aggregate for Concrete." *Journal of Testing and Evaluation* 1974. Volume 2, No. 5: pp. 344-350.
  27. Dhir, R.K.a.D., T. D. , Maximising Opportunities for Recycling Glass, in *Sustainable Waste Management and Recycling: Glass Waste*, M.C.L.a.J.J. Roberts, Editor. 2004, Thomas Telford: London.
  28. Cattaneo, J. U.S Glass Recycling: Market Outlook. in *Resource Conservation Challenge (RCC) 2008 Workshop*. 2008. Arlington, VA.
  29. Mehta, P.K., Concrete Technology at the Crossroads— Problems and Opportunities, in *Concrete technology - past, present and future*. 1994, ACI, SP 144.
  30. Basheer, P.A.M., S.E. Chidiac, and A.E. Long, "Predictive models for deterioration of concrete structures." *Construction and Building Materials*, 1996. Volume 10 (Compendex): pp. 27-37.
  31. Basheer, L., J. Kropp, and D.J. Cleland, "Assessment of the durability of concrete from its permeation properties: a review." *Construction and Building Materials*, 2001. Volume 15, Nos. 2-3: pp. 93-103.
  32. Mehta P. K., M.P.J.M., Concrete: Microstructure, Properties and Materials. 2006: McGraw-Hill New York.
  33. Fwa, T.F. and P. Paramasivam. Surface-deterioration resistance of concrete pavement materials. in *First International Symposium on Surface Characteristics*, June 8, 1988 - June 9, 1988. 1990. State College, PA, USA: Publ by ASTM.
  34. Kumar, B., G.K. Tike, and P.K. Nanda, "Evaluation of properties of high-volume fly-ash concrete for pavements." *Journal of Materials in Civil Engineering*, 2007. Volume 19 (Compendex): pp. 906-911.
  35. Li, H., M.-h. Zhang, and J.-p. Ou, "Abrasion resistance of concrete containing nano-particles for pavement." *Wear*, 2006. Volume 260 (Compendex): pp. 1262-1266.
  36. Nanni, A., "Abrasion resistance of roller compacted concrete." *ACI Materials Journal*, 1989. Volume 86 (Compendex): pp. 559-565.