Ground-Glass Pozzolan for Use in Concrete

Members of ASTM Subcommittee C09.24 summarize industry context behind new ASTM standard specification

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The construction sector is continually seeking new sources of supplementary cementitious materials (SCMs) to augment the portland cement, fly ash, slag cement, and silica fume used in modern concrete mixtures. Extensive research and testing have shown that several types of ground glass will perform well as a pozzolan in concrete. Supported by those results, ASTM Subcommittee C09.24, Supplementary Cementitious Materials, has drafted ASTM C1866/C1866M-20, "Standard Specification for Ground-Glass Pozzolan for Use in Concrete." The new specification was published earlier this year, after 3-1/2 years of balloting by the committee. This article provides much of the background information and industry context that accompanied the balloting.

Motivation

Glass production is a major source of greenhouse gases. While recycling can reduce the environmental impact,[1] 8.4 million tons (7.6 million tonnes) of container glass is landfilled annually in the United States (almost triple the amount that is recycled).[2] A significant resource is therefore being discarded. A preliminary, third-party life-cycle assessment of one ground-glass pozzolan (GGP) producer's output[3] indicates that the global warming potential (GWP) impact for 1 ton (0.9 tonne) of GGP is 56 kg (123 lb) CO_2e. For comparison, the U.S. industry average GWP for portland cement is 1040 kg (2293 lb) CO_2e. Thus, the GWP calculated for a recent New York City project concrete mixture with 50% cement replacement with GGP would be about 40% less than the GWP for a concrete mixture with cement only.

Glass Sources and Chemistry

Much of the glass produced in the world is one of the following types:

- Container glass (used in packaging)—This material is generally soda-lime glass produced in flint (clear), green, blue, or amber colors and formed by air pressure in molds;
- Plate glass (used as glazing in buildings and automobiles)—This material is also generally soda-lime glass produced in clear or tinted colors and formed by floating on molten tin; or
- E-glass (used as reinforcement in fiber-reinforced polymers)—This material is low-alkali glass formed by extrusion through a bushing to form filaments that are rapidly drawn to a fine diameter before solidifying.

Table 1 summarizes the chemistry of these glass types and other pozzolanic or cementitious materials used in concrete, and Fig. 1 contextualizes GGP versus ordinary portland cement (OPC) and other SCMs. Although the chemistry of E-glass is quite different from the chemistry of container or plate glass, all three glass types have been shown to be suitable for use as a pozzolan in portland cement concrete. Also, because of the controlled processes used to manufacture these glass types, each has a very uniform chemistry worldwide, as demonstrated by the standard deviation reported in Table 2 for container glass chemistry.

The subcommittee members agreed that the three glass sources listed in ASTM C1866/C1866M are produced in sufficient quantities to provide viable resources for concrete production. The subcommittee also agreed that ground glass could be used safely. Glass production is regulated to limit toxic materials content, and the glasses listed in the standard are not included on the U.S. Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) lists of hazardous wastes.[9] Further, the glass pozzolan sources are composed of amorphous silica. Unlike crystalline silica, amorphous silica has not been found to produce cancer in lung tissue.[10,11] However, as with all nonhazardous dusts, the U.S. Occupational Safety and Health Administration (OSHA) provides permissible exposure levels (PEL) for amorphous

Table 1:
Typical composition of three principal glass types and common SCMs used in concrete[4-6]

Compound	Composition, wt.%							
	Soda-lime glass		E-glass	Commonly specified materials				
				Fly ash		Metakaolin	Slag cement	Silica fume
	Container glass	Plate glass		Class F	Class C			
SiO_2	71.0	71.2	59.9	50 to 60	30 to 50	51 to 53	39.4	94.7
Al_2O_3	1.82	0.36	12.5	25 to 35	10 to 25	42 to 44	9.1	0.9
Fe_2O_3	0.61	0.44	0.37	5 to 10	4 to 10	0.52	0.32	1.2
CaO	10.9	9.33	21.4	1 to 12	15 to 30	<0.5	38.7	0.3
MgO	0.94	3.86	2.91	1 to 3	1 to 6	<0.5	11.9	1.8
Na_2O	13.0	13.2	0.77	0.2 to 1.0	0 to 2	<0.1	0.29	—
K_2O	0.52	0.04	0.06	1 to 3	0 to 4	<0.5	0.63	—
SO_3	<0.1	<0.1	<0.1	0.1 to 1.0	1 to 4	<0.5	2	0.5
LOI	<0.5	<0.1	<0.1	0.5 to 5	0 to 3	0.7	<0.01	0.57
Amorphous silica*	~100	~100	~100	50 to 80	80 to 90	~100	>95	~100

*Amorphous silica values are percentages of total silica content in the material

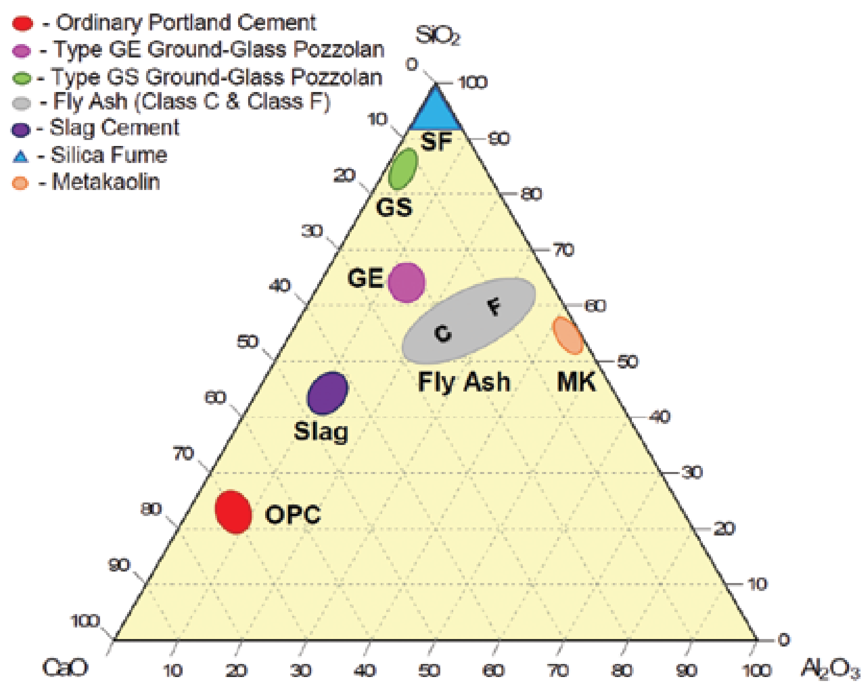

Fig. 1: Ternary plot contextualizing GGPs versus OPC and other SCMs (Note: For ternary plots, values are in wt.%, and they are normalized to the sum of SiO_2, Al_2O_3, and CaO)[4-8]
(figure courtesy of Marija Krstic)

silica dust. The PEL (8-hour time-weighted average) for amorphous silica is 20 million particles/ft^3 of air (mppcf). For comparison, the PEL for mica or soapstone dust is also 20 mppcf, and the PEL for portland cement is 50 mppcf.[12]

Glass Reserves and Supply

Container glass

Per the EPA, the U.S. municipal solid waste (MSW) stream contained 11.4 million tons (10.3 million tonnes) of glass in 2017.[2] About 26%, or 3 million tons (2.7 million tonnes), was recovered for recycling, with the remaining 8.4 million tons (7.6 million tonnes) sent to landfills.[2] Most waste glass is collected in curbside pickup containers in which it is commingled with other recyclables such as paper, cardboard, plastics, and metals.[1] These materials go to single- and dual-stream material recovery facilities where the composite waste is crushed and the glass is separated via screens. Waste glass is also collected at bottle redemption centers in the 11 U.S. states that require bottle deposits on

Table 2:
Chemical analyses of multiple samples of GGP produced from container glass (courtesy of Urban Mining Northeast)

Constituent	Constituent amounts for GGP produced at various times, %						Mean	Std. deviation
	July 2018	Sept. 2018	Nov. 2018	Jan. 2019	Mar. 2019	May 2019		
SiO_2	72.19	70.44	71.16	71.72	70.90	71.24	71.28	0.61
Al_2O_3	1.72	1.64	1.62	1.64	1.61	1.55	1.63	0.06
Fe_2O_3	0.63	0.65	0.43	0.45	0.58	0.50	0.54	0.09
$SiO_2 + Al_2O_3 + Fe_2O_3$	74.54	72.73	73.21	73.81	73.09	73.29	73.45	0.64
CaO	10.72	11.48	11.27	10.99	11.34	11.22	11.17	0.27
MgO	1.44	1.45	1.46	1.46	1.45	1.46	1.45	0.01
Na_2O	12.49	13.52	13.27	12.96	13.31	13.25	13.13	0.36
K_2O	0.45	0.47	0.46	0.46	0.47	0.48	0.47	0.01
SO_3	0.18	0.18	0.16	0.16	0.15	0.13	0.16	0.02

some beverage purchases.[13] This glass is relatively clean and is suitable for color separation into cullet.

Much of the container glass processed at material recovery facilities is optically sorted, based on color, for sale to bottle manufacturers. However, about one-third of the glass is finer than 3/8 in. (9.51 mm), which is not economic to optically color separate.[1] Some of this glass may be suitable for re-melt into fiberglass insulation. Because it is not necessary to color-separate glass for use as a pozzolan, an additional 1 to 2 million tons (0.9 to 1.8 million tonnes) of glass can be sourced for that purpose. The total amount depends on future glass recycling rates in larger urban communities. The production of value-added pozzolans from waste glass will undoubtedly alter the negative perception of glass recycling, and recycling rates should increase significantly. Ultimately, far more than 2 million tons of container glass could be available for pozzolan production annually.

Plate glass

From 1.5 to 2 million tons (1.4 to 1.8 million tonnes) of plate glass in the form of window trim, defective factory windshields, and post-consumer windshields and building window glass can be recycled. Many existing buildings are undergoing energy retrofits that include removal and replacement of envelope glass. Current major markets for recycled plate glass are glass spheres used for traffic paint and for rheology improvement, as well as for aggregate for road subgrades and structural fill. However, it is estimated that at least 400,000 to 500,000 tons (360,000 to 450,000 tonnes) would be available for the glass pozzolan market if the logistics can be streamlined. When processed, this glass will be as white as white cement, and it can be processed to 99.9% purity.

E-glass

E-glass is typically recovered from the manufacture of fiberglass reinforcements at glass factories. It can be processed from undrawn fiber waste, and it can be ground into a white powder without any fiber remnants. About 200,000 tons (180,000 tonnes) of this material are available per year.[5] Per Vitro Minerals, Inc. (**www.vitrominerals.com**), E-glass pozzolans have been widely used for the past 10 years as pozzolans for white cement in decorative concrete applications.

GGP Production

Glass cleaning

The primary sources of recycled glass are material recovery facilities and bottle redemption programs. Much lesser quantities come from bottle manufacturer rejects, municipal glass collection sites, and communities that require restaurants and bars to recycle their glass. Depending on the source of the glass, thermal, wet, and mechanical processes are employed to clean recycled glass for its next use. In thermal processes, the organic fraction is burned and metals are removed using magnets and eddy currents. While thermal processes are effective, state and local permitting authorities may require expensive air pollution control equipment. Wet processes are also effective but must include water treatment facilities. Mechanical cleaning processes use agitation and/or particle-on-particle collisions to abrade the organics off the glass. A series of screens and air jets (the air may be heated) are used to separate glass from nonglass components, and magnets are used to remove ferrous metals. Mechanical cleaning is commonly used for recycling container glass.

The average beverage bottle has a mass of about 225 g (8 oz) and an interior surface area of about 0.08 m^2 (0.86 ft^2). When ground into a powder that passes a 325-mesh wet sieve, the resulting glass particles have a total surface area of about 2 m^2/g. That totals about 550 m^2/container (5920 ft^2/container), so in effect only one glass particle in about 5600 particles will have been exposed to the bottle contents (usually, sugar). Further, the highly abrasive grinding environment abrades off most of any label or food residue material, and these materials are vacuumed into a dust collector for disposal. However, because it is important to limit the amount of organic materials in any concrete mixture, the ASTM subcommittee investigated the effects of loss on ignition (LOI) values in glass powder.

In practice, most of the LOI in recycled glass results from paper residues. To test the impact on concrete air content of organics associated with LOI, the University of Sherbrooke prepared and tested a total of 37 normalweight concrete mixtures with water-cementitious materials ratios (*w/cm*) of 0.55, total cementitious materials content of 375 kg/m^3 (632 lb/yd^3), and target slump of around 175 ± 25 mm (7 ± 1 in.). GGP samples with LOI values from 0.20 to 2.04 wt.% were used to replace 20% (by weight) of ASTM C1157/C1157M Type GU cement. Two reference mixtures were produced with 100% Type GU cement. A plot of fresh air content (measured per ASTM C231/C231M, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method") versus LOI value in GGP (Fig. 2), shows that an LOI value of 0.5 wt.% or less can result in a 2% air content, which is acceptable for non-air-entrained concrete normally specified for interior applications. The committee chose to require the GGP manufacturer to clean glass powder to an LOI value of less than 0.5 wt.%.

Glass grinding

Grinding glass on a commercial scale requires a closed-loop circuit in which the grinding device feeds an air classifier that separates material into two fractions: product having the desired particle size and oversize material (Fig. 3). The oversize material is conveyed back to the mill feed hopper. Product ground to spec is then conveyed pneumatically or via a closed screw auger to a silo for bulk truck loadout or bagging. Precrushing is often employed to reduce particle size prior to the grinding device to increase throughput.

The fineness limit in ASTM C1866/C1866M is set as 5 wt.% retained on a 325-mesh sieve. The fineness uniformity requirement in ASTM C1778, "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete," states that the previous 10 tests cannot vary by more than 5%, so all material meeting the fineness requirement of C1866/C1866M will meet the uniformity requirement of C1778.

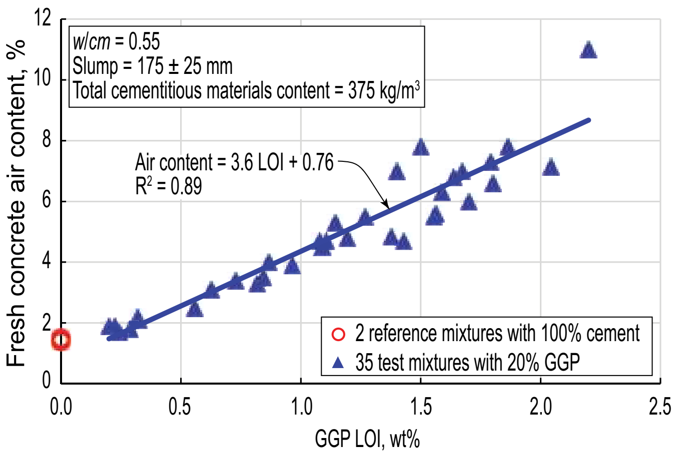

Fig. 2: Fresh air content versus LOI of GGP. The pozzolan comprised 20% of the total cementitious material in the 35 test mixtures *(figure courtesy of Arezki Tagnit-Hamou)* **(Note: 1 mm = 0.04 in.; 1 kg/m^3 = 1.7 lb/yd^3)**

ASR Mitigation Using Ground Glass

ASTM C1866/C1866M requires that a minimum of 95% of the glass powder passes a 325-mesh wet sieve (particles are smaller than 45 microns). Research suggests that particles smaller than 300 microns pose no risk for alkali-silica reaction (ASR).[14,15] When milling to 95% passing a 45-micron sieve, there is negligible risk of any remaining particles large enough to be of concern for ASR, particularly because the closed-loop grinding circuits should ensure that the 95% minimum is always exceeded. However, GGPs should be evaluated in accordance with ASTM C1778 to determine suitability for mitigating ASR. In the following sections, test data are provided for concrete mixtures with highly reactive aggregates. There are no data for glass pozzolans used with aggregates having low or moderate reactivity. As data become available, changes to ASTM C1778 may be proposed.

Glass pozzolans versus other industry pozzolans

In comparison with other industry pozzolans, glass pozzolans have the following characteristics:

- Lower quantities available—Currently, 2 million tons of glass are available domestically per year, the majority of which can be used to make Type GS GGP. As glass-processing technology improves and the cost of competing SCMs increases, the economic viability of GGP processing plants will reach smaller markets that have recyclable glass available. This will increase the 2-million-ton potential;
- Greater purity—Glass pozzolans, sourced from the three identified categories, will have extremely uniform chemistry and be free of any hazardous elements[5];
- Widespread sourcing—Sourcing of glass pozzolans will

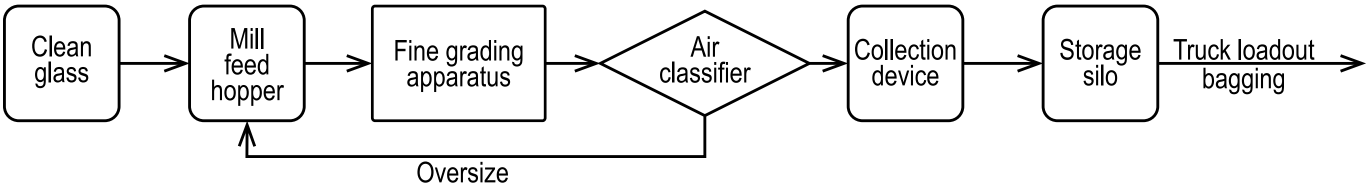

Fig. 3: Process overview for grinding clean glass pieces into pozzolan

Table 3:
Reactivity and water demand for various pozzolans

Pozzolan	Potential cement replacement, %*	Reactivity	Water demand
Container glass	10 to 40	Moderate to high	Reduction
E-glass	10 to 30		
Plate glass	10 to 40		
Class F fly ash	10 to 30	Low†	Reduction
Class C fly ash	10 to 40	Moderate to high	Reduction
Natural pozzolan‡	10 to 20	Low to moderate	Moderate to large increase
Slag cement	25 to 50	Moderate	Neutral
Silica fume	5 to 8	High	Large increase
Metakaolin	5 to 15	High	Large increase

*These values are intended to aid in contextualizing use of GGP among various materials. These materials have been/are used outside these ranges

†Low at early ages

‡Natural pozzolans include a wide range of materials with a spectrum of properties

likely be from smaller, more regional plants as compared with large power plants (fly ash) and steel mills (slag);

- Similar reactivity—Glass pozzolans have moderate to high reactivity, depending on their specific surface area (fineness) after processing (Table 3). Glass pozzolan performance permits cement replacement levels comparable with fly ash and slag[5,14,16-33];
- Lower water demand—Glass pozzolans have low water demand, like fly ash (Table 3). This helps to reduce admixture demand and cement factors in concrete[5,16-20]; and
- Similar environmental impacts—As glass pozzolans are recycled from postconsumer (Type GS) or postindustrial (Type GE) waste streams, their use in the concrete industry will have positive environmental benefits.[29]

Alkali content

It is important to use a cement with a low alkali content (low Na_2O_{eq}) when reactive aggregates will be present in mixtures with no pozzolan additions. E-glass has less than 1% Na_2O_{eq} content,[5] so it follows that its pozzolanic properties will dominate its behavior in concrete. This expectation is confirmed from studies conducted at Clemson University, through ASTM C1567, "Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)," and ASTM C1293, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction," tests (Fig. 4 and 5), which show the expansions over time for mortar and concrete mixtures containing reactive Las Placitas gravel aggregate and ground-glass fiber, a Type GE GGP, at various cement replacement levels.[34,35]

Soda-lime glass has a very high Na_2O_{eq} content of about 13.5%. However, data obtained per ASTM C1293 tests using Spratt aggregate, a known highly reactive aggregate, show that soda glass as ground pozzolan also provides mitigating effects (Fig. 6 and 7). Tests conducted at University of Sherbrooke (Fig. 6) show that Type GS GGP reduced

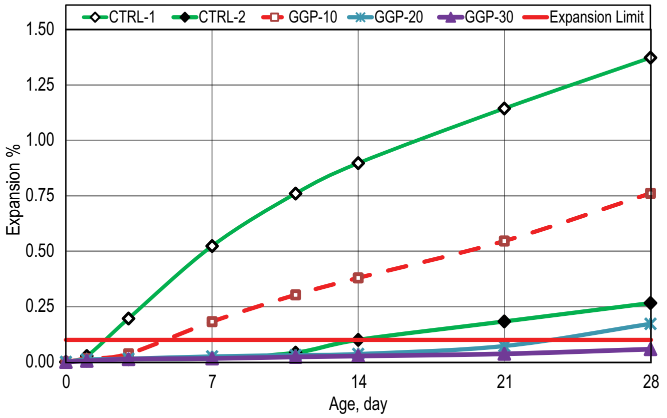

Fig. 4: Accelerated mortar bar expansion per ASTM C1567 for mixtures with 10, 20, and 30% of ground-glass fiber (Type GE GGP) as cement replacement.[34] Mixtures CTRL-1 and CTRL-2 comprised OPC and OPC with 25% replacement with fly ash, respectively (GGP properties: LOI = 1 wt.%; avg. diameter = 4 microns; SG = 2.60; Blaine fineness = 1020 m²/kg)

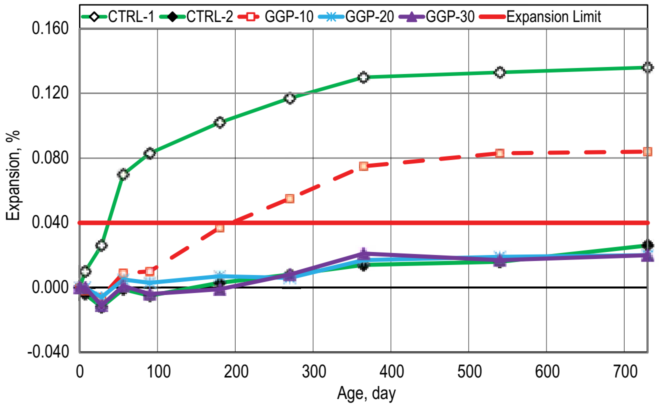

Fig. 5: Concrete prism expansion per ASTM C1293 for mixtures with 10, 20, and 30% of Type GE GGP cement replacement.[35] Mixtures CTRL-1 and CTRL-2 comprised OPC and OPC with 25% replacement with fly ash, respectively (GGP properties: LOI = 1 wt.%; avg. diameter = 4 microns; SG = 2.60; Blaine fineness = 1020 m²/kg)

expansion to about 50% of the control mixture expansion but did not keep the expansion below the ASTM C1293 threshold of 0.04%. However, the threshold was met using a ternary blend with 8% metakaolin. Tests conducted at the University of New Brunswick (Fig. 7) show that at 20% cement replacement, E-glass (Type GE GGP) was effective in keeping prism expansion below the 0.04% limit at 2 years, while Type GS GGP sourced from plate glass reduced expansion compared to the high-alkali cement control (0.91% $Na_2O_{eq.}$) but exceeded 0.1% and was greater than a control mixture with low-alkali cement (0.46% Na_2O_{eq}).

Sulfate Resistance

The results from two studies to evaluate sulfate resistance per ASTM C1012/C1012M, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," are shown in Fig. 8 and 9. The first of these studies (Fig. 8) evaluated the use of Type GE and GS pozzolan. As shown in Fig. 8(a), E-glass (Type GE) at 10 and 20% cement replacement levels reduced the expansion of a high-C3A portland cement concrete (control mixture expansion 0.459% at 6 months) to below the expansion limits specified for ASTM C1157/C1157M Type HS cement (0.05% at 6 months and 0.10% at 1 year), when blended with a high-C3A portland cement. The data also show in Fig. 8(b) that the expansion of mortar bars with either 25% cement replacement with Type GS or Type GE pozzolan was reduced to acceptable levels (again, meeting limits for Type HS cement) when blended with a high-C3A cement (control mixture expansion of 0.99% at 6 months).

The second study was part of a wider study on the use of pozzolans in concrete (Fig. 9). Concrete mixtures containing 20 and 30% of Type GS ground glass cement replacements were studied in comparison with a control concrete mixture. The expansion due to sulfate attack shows that the control concrete exceeds the expansion limit of 0.10% recommended by ASTM C1157/C1157M from 130 days to reach 0.15% after 6 months. The mixtures incorporating 20 or 30% of Type GS GGP have very low expansions well below the limit prescribed by the standard. These expansions are of the same

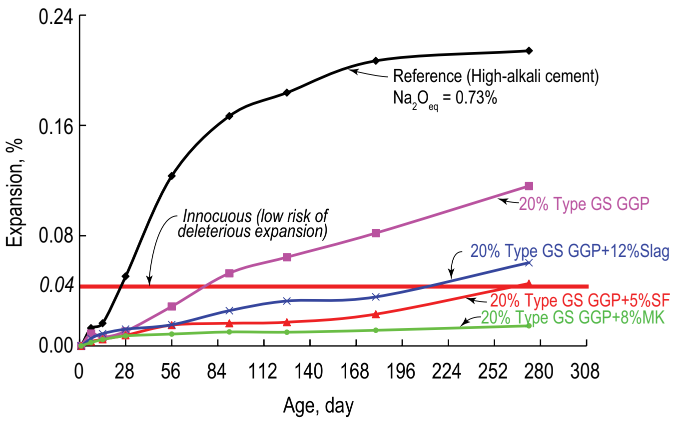

Fig. 6: Concrete prism expansion per ASTM C1293 for mixtures with Spratt aggregate, high-alkali cement, and cement replacement with Type GS GGP, silica fume (SF), and metakaolin (MK) *(figure courtesy of Arezki Tagnit-Hamou)*

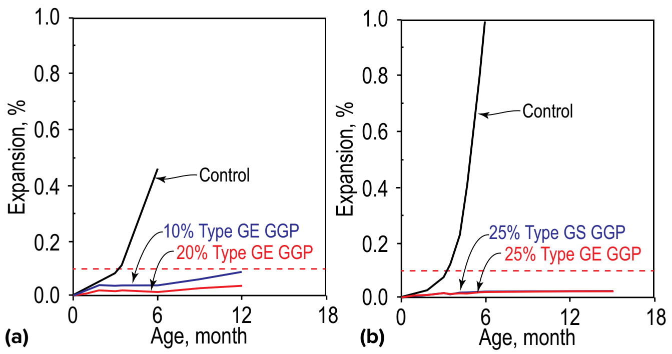

Fig. 8: Expansion per ASTM C1012/C1012M for concrete mixtures with a high-C3A portland cement: (a) 10 and 20% E-glass (Type GE); and (b) 25% Type GS and GE pozzolan *(figure courtesy of Michael D.A. Thomas)*

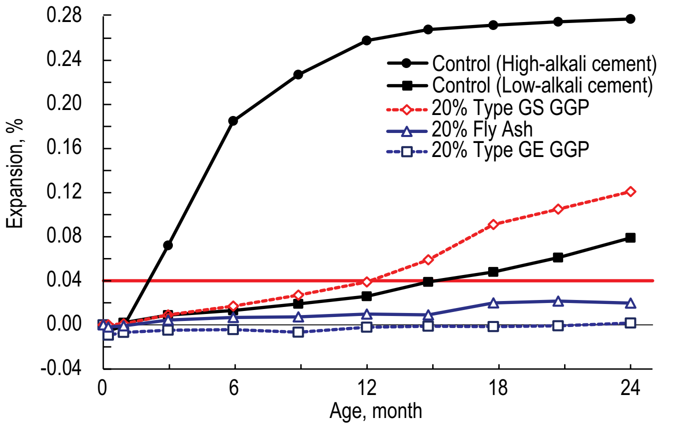

Fig. 7: Concrete prism expansion per ASTM C1293 for mixtures with Spratt aggregate, high- or low-alkali cement, and cement replacement with Type GS GGP, Type GE GGP, or fly ash *(figure courtesy of Michael D.A. Thomas)*

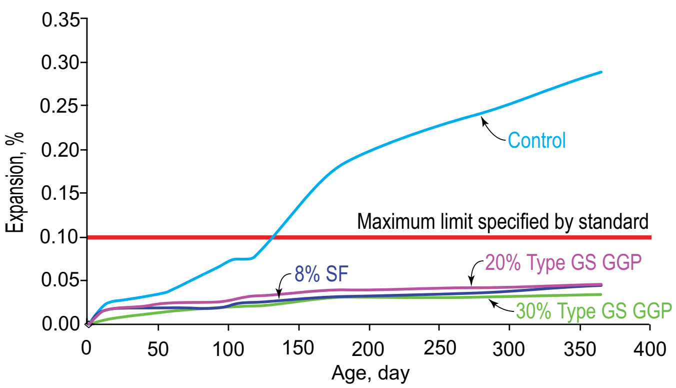

Fig. 9: Expansion per ASTM C1012/C1012M for mixtures with 20 and 30% cement replacements with Type GS ground glass *(figure courtesy of Michael D.A. Thomas)*

order as that of cement type GUSF (general use cement containing around 8% of silica fume), which has strong resistance to sulfate attack.

Chloride Permeability

Concrete mixtures containing GGP were evaluated per ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." In one study, 16 concrete mixtures comprising portland cement and Type GS GGP at cement replacement levels of 20 and 30% were tested for 90 days. Control concrete mixtures included cement only. Mixtures were prepared with a *w/cm* of 0.55 or 0.40, and the GGP had a Blaine surface area of 374 or 436 m^2/kg. As shown in Fig. 10, the total charge passed was low for all mixtures with GGP. The best performance was obtained for mixtures with 30% cement replacement.

In another study,[36] concrete mixtures were prepared using Type I/II portland cement (per ASTM C150/C150M, "Standard Specification for Portland Cement") and Type GS GGP (with d_{50} = 10 μm) at cement replacement levels of 20, 30, and 40% (GS-20, GS-30, and GS-40). All mixtures were prepared with a *w/cm* of 0.40. In addition to a control mixture with 100% portland cement (Control1), one mixture was prepared with 40% portland cement replacement with slag cement (S-40) and a second mixture was prepared with a 30% portland cement replacement with Class F fly ash (FA-30). As shown in Fig. 11, all concrete mixtures with Type GS GGP as a partial cement replacement exhibited very low passed-charge values at 90 days. All mixtures with GGP also performed better than the control mixture or the mixtures with slag cement or fly ash.

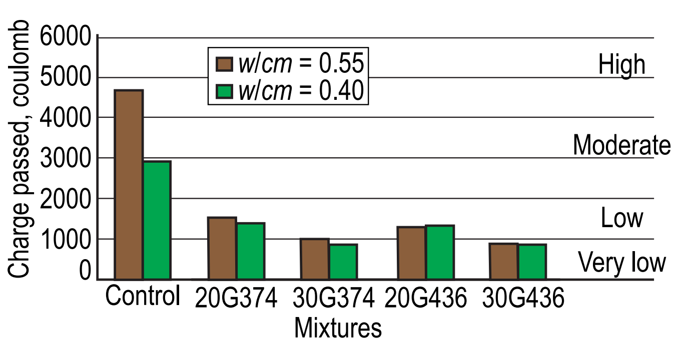

Fig. 10: Total charge passed per ASTM C1202 for concrete mixtures with Type GS GGP at 20 and 30% cement replacement after 90 days of curing[16]

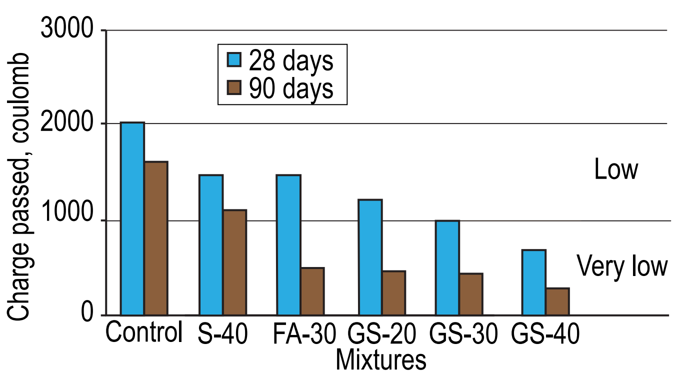

Fig. 11: Total charge passed per ASTM C1202 for concrete mixtures with various Type GS GGP cement replacement levels after 28 and 90 days of curing[36]

Known Field Applications

Industrial-scale use of new alternative cementitious materials in the built environment cannot be expected without field validation through long-term exposure to realistic environmental conditions and loads. Many field installations of concrete mixtures with GGP have taken place over the past 15 years. Type GE GGP has been widely used for the past 15 years as a pozzolan for white cement in decorative concrete applications such as swimming pools, architectural precast concrete, and glass fiber-reinforced concrete (GFRC). Type GS GGP has been used as a partial replacement for cement for the past 10 years in applications such as concrete masonry units, pavers, precast concrete, and sidewalks. The City of Montréal, QC, Canada, began testing Type GS GGP as a cement replacement in sidewalks in 2010, in collaboration with the University of Sherbrooke.

The New York City Department of Design and Construction (NYC DDC), in collaboration with City College of New York, also started evaluating Type GS GGP in sidewalks, starting in 2016.[37] GGP is now included in NYC DDC concrete specifications. In collaboration with US Concrete, many structural concrete mixtures with Type GS GGP content have been tested and placed in New York City high-rise construction projects from 2016 through the present. These mixtures have included 35 to 40% cement replacement with Type GS GGP. Additional high-rise structural placements are being planned for New York City, NY, USA, and Philadelphia, PA, USA, also using Type GS GGP, in mixtures with up to 50% cement replacement. Some of these mixtures will also include slag cement.

Lastly, two bridges are being constructed on the Île-des-Soeurs, Montréal, QC, Canada (Fig. 12). The concrete bridges are being produced with 10% cement replacement with Type GS GGP, saving about 40 tonnes (44 tons) of cement.

Acknowledgments

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Fig. 12: One of two bridges under construction in Montréal comprising concrete with 10% cement replacement with Type GS GGP. The bridges will be instrumented and closely monitored by the University of Sherbrooke and the Ville de Montréal *(photo courtesy of Ville de Montréal)*

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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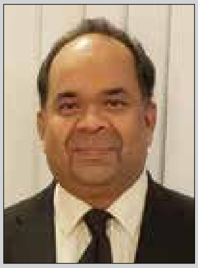

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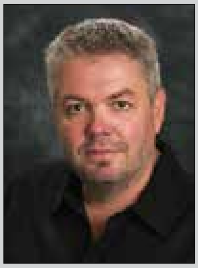

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