

An Investigation of the Benefits of Recycled Glass Powder as a SCM and GUL Cement

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Abstract

A limited number of studies evaluated the suitability of recycled glass powder (GP) as a supplementary cementitious material (SCM) in portland cement concrete (PCC) mixes, and there is a limited use of GP in PCC mixes in Canada. With a motivation to reduce waste, a laboratory testing program was undertaken by Manitoba in 2023-2024 constituting coarse aggregate from four sources, two types of portland cement and five different combinations of GP and fly ash for each cement and aggregate type. The test results indicated that GP has no beneficial impact on the compressive strength, modulus of rupture (MoR) and modulus of elasticity (MoE) of concrete containing General Use (GU) cement. The trends of a durability property of concrete containing GU cement were inconsistent between ages of concrete at the time of testing and among varied glass powder contents in the concrete mixes. For the concrete containing General Use Limestone (GUL) cement, 5% GP (and 15% fly ash) content has shown to provide some beneficial effects as compared to the concrete with no GP and 20% fly ash content (the reference mix). A gradual decrease in concrete quality was noted with further increase in GP (and decrease in fly ash) content in concrete mixes containing GUL cement. The quality of concrete mixes containing GUL cement were shown to be inferior to the concrete having GU cement. This result also confirms the previous findings by MTI that properties of PCC containing GU and GUL cements are not equivalent. Such findings raise question about the environmental benefit of GUL cement and suitability of recycled GP as a SCM. This paper presents the details of the testing, analyses and findings.

Introduction

A large quantity of waste glasses is diverted to landfill every year. According to Statistics Canada¹, over 455,000 tonnes of glass was diverted to landfill in 2022. An economical use of glass waste may contribute to sustainability and circular economy. However, most of the waste glasses generated as part construction-demolition, and commercial and residential disposal of glass containers, bottles, etc. in Manitoba end up in municipal landfills. This happens mainly due to absence of suitable mechanism or avenue for beneficial uses of waste or recycled glasses and lack of recycling facility in Manitoba. Transporting the collected waste glasses out of province for recycling is cost prohibitive because transportation costs often exceed potential recycling revenue. A potential solution to these issues is to properly characterize the glass waste and assess the composition of normally used materials (such as granular aggregate subbase and PCC) and recycled glass for potential local uses. Should the recycled glasses be found to be suitable for any economically feasible application without compromising the performance of the end products, a recycling facility can be established to generate applicable glass based products such as recycled glass powder for use as a SCM in PCC mixes. Few studies have been conducted elsewhere to evaluate the suitability of recycled glass powder as a SCM in PCC mixes. However, an environmental scan by Manitoba Transportation and Infrastructure (MTI) noted a limited use (only by the City of Montreal) of recycled glass powder in concrete mixes in Canada. As such, additional assessment was required before accepting recycled GP as a SCM to ensure that the resulting PCC mixes meet the local performance requirements.

Alternatively, GUL cement is being promoted as more sustainable and lower carbon cement, which reduces the CO₂ emissions by up to 10% and still provides an equivalent performance including comparable strength and durability properties as provided by the PCC mixes with GU cement. The GU cements may contain up to 5% ground limestone, whereas the GUL cements contain up to 15% limestone. By reducing the amount of clinker used in the cement manufacturing process, the required energy and thereby emissions per tonne of GUL cement are reduced². Manitoba approved the use of GUL cement in

2020 for use in PCC mixes for roadways and associated road features (curbs, apron, medians, etc.). However, laboratory and field testing in Manitoba and elsewhere have shown that the strength and durability properties of PCC mixes with GUL cement are not equivalent to PCC mixes with GU cement. To further verify the quality of PCC mixes containing GUL cement, additional laboratory testing was warranted. This led to the inclusion of both GU and GUL cements in the study for assessing the feasibility of recycled GP as a SCM in PCC mixes.

Background

Manitoba Liquor and Lotteries Corporation approached the MTI in 2022 to investigate the potential use of recycled glass powder as a SCM in concrete mixes in Manitoba to reduce waste and carbon footprint and promote circular economy. The silicate material in glass is considered to react with calcium hydroxide, which is produced as part of the portland cement hydration process, to create C-S-H gel. The C-S-H gel contributes to enhanced strength and durability of concrete. To ensure that recycled GP is a viable SCM with adequate pozzolanic properties, a laboratory testing program was undertaken in 2023-2024 with some financial support from Manitoba department of Environment and Climate Change.

The GUL cement has been introduced in 2008 in Canada to reduce carbon footprint associated with portland cement production. It contains up to 15% unprocessed (raw) fine grounded limestone and shown to enhance the microstructure of the concrete. Cement manufacturing industry and some research studies have indicated that GUL cement improves the strength and durability properties of the hardened PCC or it provides equivalent performance as of GU cement. However, many others reported lower strength of PCC with GUL cement than the PCC with GU cement. For example, a survey report by National Ready Mixed Concrete Association (NRMCA)³ indicated that i) 50% of the agencies noted a lower 28-day strength, ii) 30% of the agencies noted a lower early strength, iii) most agencies observed higher water demand or 40% increase in water reducing admixture, and iv) some agencies noted unstable air content of PCC mixes with GUL cement as compared to PCC mixes with GU cement.

Prior to the approval of GUL cement in 2020 for use in PCC mixes for highways, MTI's Central Laboratory prepared two sets of PCC mix designs with GU and GUL cements as part of department's standard practice of assessing and monitoring of any new product prior to adding it to the Approved Product List (APL). The PCC mix design for GUL cement was repeated with three separate batches (shipments) of GUL cements. Each repeated mix design of PCC with GUL cement yielded the same strength, which is significantly lower than the PCC with GU cement. At the end, MTI ended up using 25-32 kg more GUL cement per cubic metre of PCC mixes as compared to the GU cement. Manitoba is also encountering low strength issues of PCC mixes supplied to highway projects in the last several years, which often results in increased material costs and project delays. The results of the final mix designs for two projects are presented in Tables 1 and 2.

As shown in Table 1, for equivalent mix properties, significantly higher quantities of both air entraining and water reducing (plasticizer) admixtures were required for concrete with GUL cement. Project #1 required 351 kg of GUL cement, while it required 319 kg of GU cement per cubic metre of concrete. For Project #2, the amount of GUL cement was intentionally reduced to 345 kg/m³ of concrete to limit the total cementitious content, whereas it required 320 kg of GU cement per cubic metre of concrete. Still, the PCC mix with GUL cement required higher amount of admixtures than the PCC mix with GU cement.

Table 1. Fresh concrete mix properties for two projects

PCC Mix Properties	Project #1		Project #2	
	PCC Mix with GU Cement	PCC Mix with GUL Cement	PCC Mix with GU Cement	PCC Mix with GUL Cement
Air Content (%)	8.3	6.2	6.8	7.5
Slump (mm)	30	40	60	65
Wet Density (kg/m ³)	N/A	2336	2333	2282
w/cm ratio	0.41	0.39	0.40	0.40
Total Cementitious Materials (cm) Content (kg/m ³)	319	351	320	345
Fly Ash Content (%)	20.1	20.2	20	20
Concrete Temperature (°C)	19.0	17.6	20.0	21.9
Air Temperature (°C)	17.3	14.2	22.8	22.2
Air Entraining Admixture (ml/m ³)	711 (Master air AE 200)	3555 (Master air AE 200)	875 (Daravair 1400)	900 (Daravair 1400)
Plasticizer (ml/m ³)	1575 (BASF Polyhed 980)	1858 (BASF Polyhed 980)	125 (WRDA 64)	150 (WRDA 64)
Coarse/Fine Aggregate Ratio	57/43	55/45	57/43	57/43

Table 2. Hardened concrete mix properties for two projects

Age at Testing (Days)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Modulus of Rupture (MPa)	RCP (Coulombs)	Surface Electrical Resistivity (kohms.cm)
Project #1: PCC Mix with GU Cement (Total 319 kg/m ³ Cementitious Materials)					
7	28.8				
28	38.2	23911	4.14		19.0
56	42.1	24477	5.62	763	
Project #1: PCC Mix with GUL Cement (Total 351 kg/m ³ Cementitious Materials)					
7	33.2				
28	42.1	26090	4.48		15.7
56	45.4	26616	6.12	812	
Project #2: PCC Mix with GU Cement (Total 320 kg/m ³ Cementitious Materials)					
7	31.6				
28	43.9				
56	45.5				
Project #2: PCC Mix with GUL Cement (Total 345 kg/m ³ Cementitious Materials)					
7	29.7				
28	36.6				
56	39.5				

Table 2 shows the hardened concrete properties. The tests for modulus of elasticity (MoE), modulus of rupture (MoR), rapid chloride permeability (RCP), surface resistivity (SR) and surface scaling for Project #1 were completed at the concrete laboratory of University of Manitoba. As shown in the table, PCC mix with GUL cement provided slightly higher compressive strength (at all ages of testing), MoE and MoR, with an additional 32 kg/m³ of total cementitious materials (cm) content, than the PCC mix with GU cement. The durability properties in terms of RCP and SR were better for concrete with GU cement, despite a lower total amount of cm content, than the PCC mix with GUL cement. There was no noticeable difference between two mixes in terms of surface scaling. For Project #2, the PCC mix containing GUL cement provided lower strength, with an additional 25 kg/m³ of cm content, than the PCC mix containing GU cement at all ages of testing.

The findings as discussed above raised question about the environmental benefit of concrete containing GUL cement. As such, GUL cement was also included in the test matrix while assessing the potential benefits of recycled glass powder as a SCM.

Findings from Literature Review

Tagnit-Hamou et al.⁴ investigated the effect of utilizing ground glass pozzolan as SCM replacement for concrete containing 390 kg/m³ of cementitious materials and found to have negative effect on compressive strength in the short term (at 28 days). However, in the long term (at 90+ days), the mixes using ground glass pozzolan were found to have a higher compressive strength than the control. The chloride permeability was found to decrease as ground glass pozzolan replacement level increased, when compared to the control at both 28 and 91 days. The study also investigated scaling resistance and drying shrinkage, and found that mixes using ground glass pozzolan have a negative effect in scaling resistance, and no noticeable effect on drying shrinkage. Kaminsky et al.⁵ suggested that ground glass pozzolan when carefully processed, can have positive effects in alkali-silica reaction, sulfate resistance and chloride permeability.

Ferraro et al.^{6,7} evaluated silica-based materials including ground glass and Type F fly ash as SCM, both at 20% replacement for mixes using Type I/II and Type IL (limestone) cements. Properties such as initial and final set times, concrete compressive strengths, flexural strengths, modulus of elasticity (MoE), surface and bulk resistivity were investigated. It was found that the concrete mix with ground glass replacement has an accelerated initial set time but slower final set time, when compared to the mix with Type F fly ash, in both Type I/II and Type IL concrete mixes. The compressive strengths were comparable between mixes using ground glass and Type F fly ash, but there was a reduction of compressive strengths for Type IL as compared to Type I/II concrete mixes at the same ground glass and fly ash replacement level. The flexural strength for the mix using ground glass was found to be slightly higher than the mix using Type F fly ash. Like the compressive strength, there was a reduction of flexural strengths for Type IL when compared to Type I/II concrete mixes. The MoE for the mixes with ground glass and Type F fly ash were comparable. The MoE between Type I/II and Type IL mixes at the same ground glass and fly ash replacement were also comparable. The surface and bulk resistivities increases with time for all mixes. The Type I/II mix with Type F fly ash have comparable resistivities when compared to the Type IL counterpart, while the Type I/II mix with ground glass have lower resistivities when compared to the Type IL mix. However, this study used 40 kg additional cementitious material (total cm of 437 kg/m³) in concrete with GG as compared to the control mix and mix with fly ash (total cm of 397 kg/m³).

Yasien et al.⁸ found that mixes with limestone cement (PLC) showed an accelerated final set time as compared to the general use cement (GU), which coincides with the higher initial temperature during the dormant/transport period. The PLC mix was also found to have a positive effect in compressive strengths and chloride permeability in the short term (up to 28 days). The chloride permeability was revisited after three years and found that both PLC and GU mixes have further improvements in penetrability with the PLC mix having a slightly lower value.

A study by Ramezaniapour⁹ with varied limestone contents from 0 to 21.8% in portland cement showed that the sulphate resistance of PCC mixes gradually decreased with increased proportion of limestone content. The compressive strengths of mortar cubes made with 100% cement at 28 and 56 days were shown to be increasing up to 2.4% limestone content, but gradually decreased with further increase in limestone contents (up to 21.8%). The study also investigated slag up to 50% and metakaolin at 10% replacement. The 30% slag replacement level was the most effective in improving the compressive strength of both PLC and GU mixes, while the compressive strengths decreased at 50% replacement. With slag replacement of up to 30% and metakaolin at 10%, the optimum level of limestone content shifted from 2.4% to 10.6%, but the compressive strengths decreased with further increase in limestone contents. Holland et al.¹⁰ investigated the replacement of cement with lime ranging from 14 to 43%. The study showed that the compressive strength decreases with increase in lime replacement. It was also found that more water is required to maintain workability as lime replacement increases.

Scope, Objectives and Significance

The literature review shows conflicting results for the impact of ground limestone and glass on mechanical and durability properties. This laboratory testing program (Phase II study) was aimed to assess the potential benefits of incorporating glass powder as a SCM into concrete mixes for Manitoba highways. Building upon the review of environmental scan conducted in Phase I, this study focused on laboratory tests to evaluate the physical, mechanical, and durability properties of concrete mixes containing GP as compared to a typical PCC mix (control mix) containing fly ash as a SCM. The study also compared the test results of concrete containing two different (GU and GUL) cement types. The testing and analysis program included coarse aggregate from four sources, two types of portland cements and five different combinations of glass powder (0 to 20%) and fly ash (20 to 0%) for each cement and aggregate type. This resulted in specimen preparation and testing of forty (40) concrete mixes.

The objectives of the Phase II study were as follows:

- Prepare concrete mixes with four different aggregate types, five different combinations of fly ash and glass powder contents, and two different cement types;
- Test fresh concrete mixes for physical properties (consistency, workability and entrained air in terms of fresh concrete density, slump and air voids), and the hardened concrete for mechanical properties (compressive strength, flexural strength, modulus of elasticity and coefficient of

thermal expansion), and durability properties (rapid chloride permeability, bulk resistivity and surface resistivity);

- Compare the concrete properties containing different proportion of glass powder with the control (reference or standard) mix containing 20% fly ash (no glass powder) and assess the potential benefits of glass powder as a SCM;
- Compare the hardened concrete properties containing GU cement with concrete containing GUL cement and assess the suitability GUL cement; and
- Provide recommendations based on the test results and analysis.

The objective of this paper is to present the details of the above specified testing, analyses and findings. The presented information may help agencies and interested individuals in assessing the suitability of the recycled glass powder as a SCM and benefit of GUL cement.

Methodology

Materials and Trial Matrix

Aggregates, fly ash, and two types of cement (namely, GU and GUL) were collected from local sources. The recycled glass powder was obtained from a certified supplier. Materials were stored in a dry and clean environment until incorporation into the concrete mixes. Table 3 shows the trial mix combinations with various proportions of fly ash and glass powder contents, which separately apply to each cement type as well as each aggregate type.

Table 3. Trial mix combinations with different proportions of fly ash and glass powder

Trial Mix #	Fly Ash (%)	Glass Powder (%)
1 (Reference/Control Mix)	20	0
2	15	5
3	10	10
4	5	15
5	0	20

All concrete mixes were prepared using a mechanical mixer and with a pre-set design proportions of mix constituents. Four different types of coarse aggregates: gravels from southern-east and south-west Manitoba and limestones from two different areas of a quarry, five different combinations of SCMs (refer to Table 3), and two types of cement (GU and GUL) were used. Fine aggregate (sand) from a single source was used in all mixes. Table 4 presents the typical physical properties of aggregates used in these trials. The total amount of cementitious materials including SCMs (fly ash and/or GP) remained the same at 340 kg per cubic metre of concrete. The percentages of GP and fly ash reflect the percentages of these materials by total weight of the cementitious materials (portland cement, fly ash and GP).

Testing Fresh Concrete Mixes

All fresh concrete mixes were tested for density, slump and air voids. Concrete mixes with GUL cement, 0% glass powder (20% fly ash) and 20% glass powder (0% fly ash) were also tested for initial and final setting time.

Table 4. Physical properties of aggregates

Aggregate Source	Aggregate Type	Specific Gravity (Oven Dry)	Absorption (%)	Los Angeles Abrasion (%)	Fineness Modulus
Source A (BP)	Gravel	2.651	0.80	24.3	-
Source B (ML)	Gravel	2.678	1.73	23.5	-
Source C (LAF)	Limestone	2.683	1.53	22.5	-
Source D (Stonewall)	Limestone	2.641	2.00	23.3	-
Grunthal, NW33-5-5E	Sand	2.640	1.20	-	2.584

Testing Concrete Specimens

Concrete specimens were cast and cured in a controlled environment for 28 to 56 days. They were then tested for hardened concrete physical, mechanical, and durability properties using appropriate equipment and test procedures. Three specimens were used for each type of test.

Results, Analysis and Discussion

This section presents the comparison of average test results from all types of aggregates and analysis for different combination of SCMs (fly ash and glass powder) and cement types. Since the coefficient of thermal expansion (CTE) values are mostly dependent on aggregate quality, no additional analysis is done for this paper in this respect. The surface electrical resistivity and bulk electrical resistivity are two new tests for concrete durability properties for use as routine quality assurance tool. However, based on the past studies conducted in Manitoba and elsewhere, the correlations of these two tests with the well-established RCP test were found to be poor or inconsistent. MTI conducted these two resistivity tests again as part of ongoing effort to develop new correlations with the RCP, but the outcomes were still unsatisfactory. As such, the results of these two resistivity tests are excluded from analysis of the effect of GP and GUL cement.

Fresh Concrete Properties

Table 5 shows the average test results of fresh concrete properties for different combinations of SCMs. No significant difference in average fresh concrete mix physical properties, such as consistency, workability and entrained air in terms of density, slump and air voids, among the mixes was noted.

Table 5. Fresh concrete mix properties

Cement Type	Fly Ash (%)	Glass Powder (%)	Density (kg/m ³)	Slump (mm)	Air Content (%)
GU/GUL	20	0	2348	49	6.9
GU/GUL	15	5	2347	44	6.8
GU/GUL	10	10	2332	46	7.1
GU/GUL	5	15	2330	46	6.9
GU/GUL	0	20	2323	43	7.2

Table 6 shows a comparison of average initial and final setting time of two concrete mixes. As shown in the table, the GP slightly reduced the setting time of the concrete as compared to that for the concrete with no GP (20% fly ash) content.

Table 6. Initial setting time of concrete mixtures by penetration resistance test (ASTM C403)

Mix Combination	Initial Set Time (hr:min)	Final Set Time (hr:min)
Concrete with GUL cement and 0% glass powder (20% fly ash)	6:55	8:35
Concrete with GUL cement and 20% glass powder (0% fly ash)	6:25	8:15

Effect of Glass Powder on Hardened Concrete Properties Containing GU Cement

Table 7 shows the average values of hardened concrete mechanical and durability properties from all four aggregate types and GU cement for five trial combinations of glass powder and fly ash contents. Figures 1 through 5 graphically show the trend of different properties for the variation of glass powder and fly ash contents in PCC mixes.

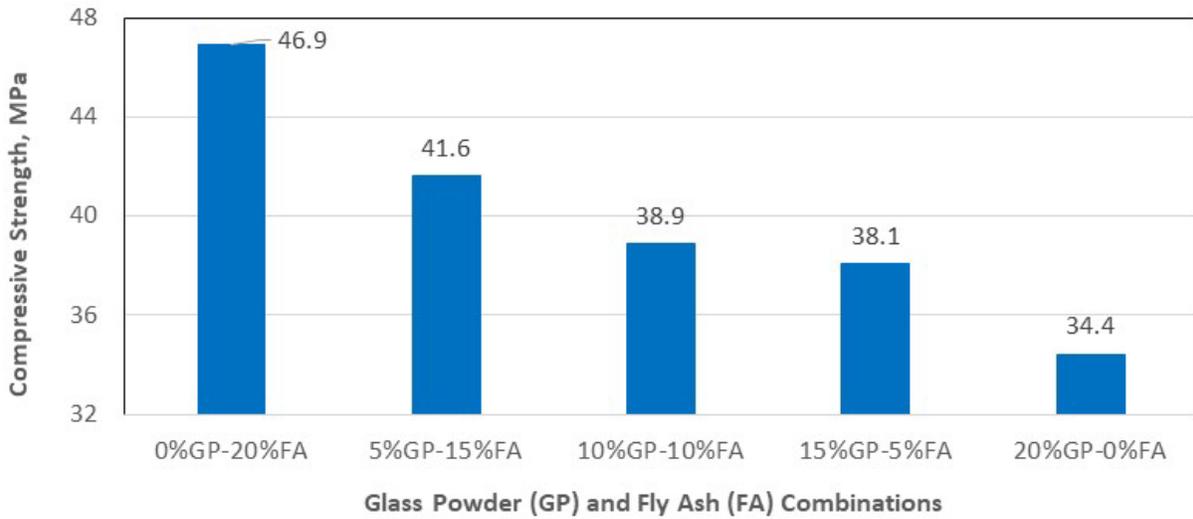
Table 7. Summary of hardened concrete properties for different combination of fly ash and glass powder in concrete mixes containing GU cement

Properties	0% Glass Powder (20% Fly Ash)	5% Glass Powder (15% Fly Ash)	10% Glass Powder (10% Fly Ash)	15% Glass Powder (5% Fly Ash)	20% Glass Powder (0% Fly Ash)
Compressive Strength at 28 Days (MPa)	46.9	41.6	38.9	38.1	34.4
Flexural Strength or Modulus of Rupture (MoR) at 28 Days (MPa)	6.4	6.1	5.9	6.1	5.5
Modulus of Elasticity (MoE) at 28 Days (GPa)	35.9	34.1	33.0	32.6	31.2
Rapid Chloride Permeability (RCP) at 28 Days (Coulombs)	2097	2276	2301	2476	2810
Rapid Chloride Permeability (RCP) at 56 Days (Coulombs)	1224	1157	1227	1150	1299

GP and GU Cement: Trend of Compressive Strength

Figure 1 shows that the compressive strength of concrete gradually reduces with an increase in glass powder (GP) content from 0% to 20% and the corresponding reduction in fly ash (FA) content from 20% to 0%. Such a decrease in compressive strength with the incorporation of glass powder and increase of glass powder contents in concrete mixes do not support the usefulness of glass powder as a pozzolanic material alone or in combination with fly ash when GU cement is used in concrete mixes.

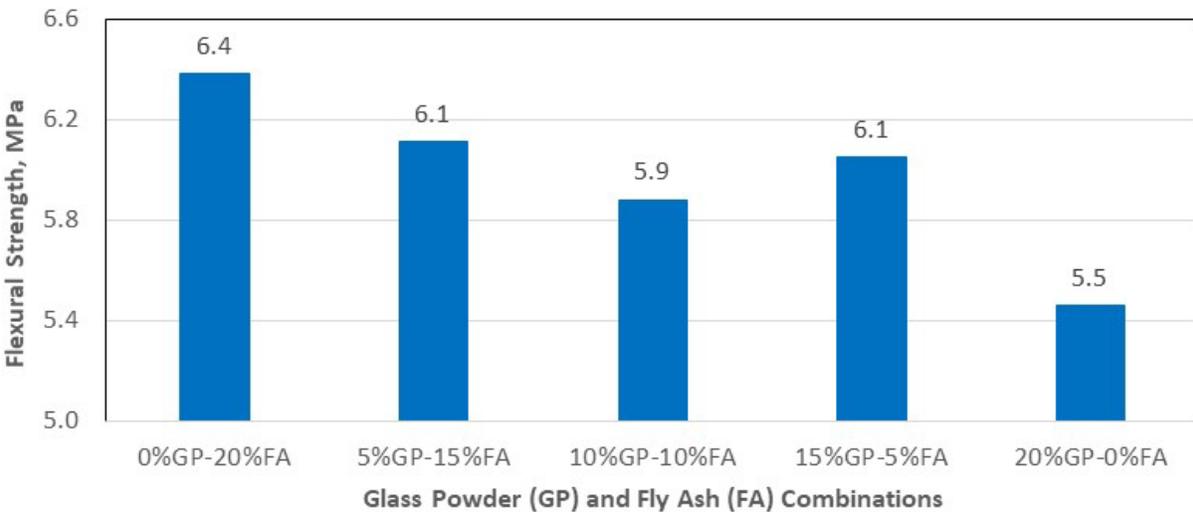
Figure 1. Variation of 28-day compressive strength for different combinations of SCMs (for GU cement)



GP and GU Cement: Trend of Flexural Strength

Figure 2 shows a general trend of decreasing flexural strength (modulus of rupture) of concrete with an increase in glass powder content from 0% to 20% and the corresponding reduction in fly ash content from 20% to 0%. An increase in flexural strength of concrete in the case of 15% glass powder and 5% fly ash contents as compared to 10% glass powder and 10% fly ash contents seems to be an outlier, which is most likely due to variability in sampling, specimen preparation and/or set up for testing. The general decrease in flexural strength with increased amount of glass powder in concrete mixes does not contemplate the beneficial effect of using glass powder as a pozzolanic material alone or in combination with fly ash when GU cement is used in concrete mixes.

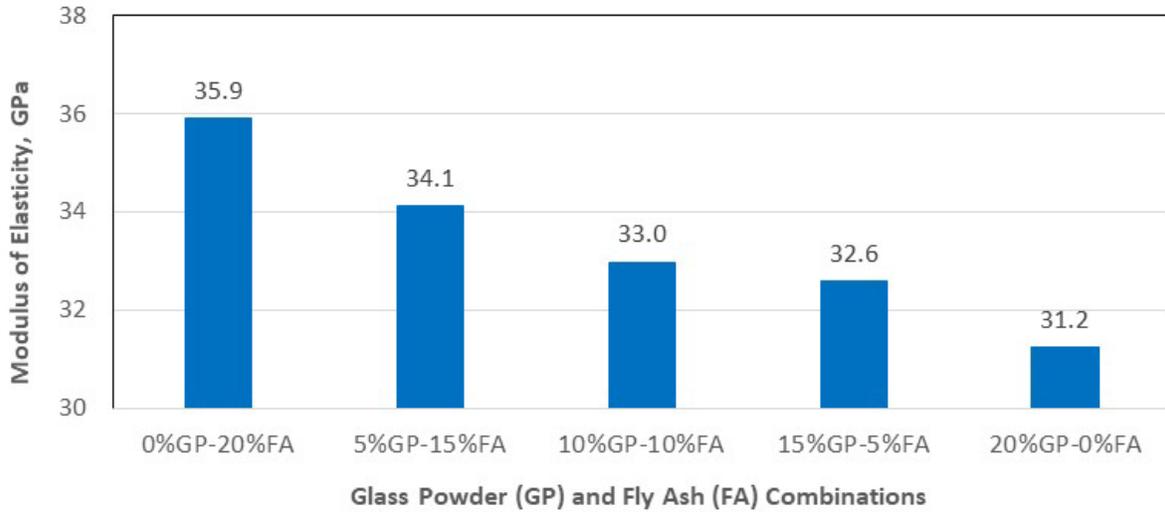
Figure 2: Variation of 28-day flexural strength for different combination of SCMs (for GU cement)



GP and GU Cement: Trend of Modulus of Elasticity

Figure 3 also shows that modulus of elasticity of concrete at the age of 28 days gradually decreases with an increase in glass powder content from 0% to 20% and the corresponding reduction in fly ash content from 20% to 0%. Such a decrease in concrete elastic modulus after the incorporation of glass powder once again does not support usefulness of glass powder as a pozzolanic material alone or in combination with fly ash when GU cement is used in concrete mixes.

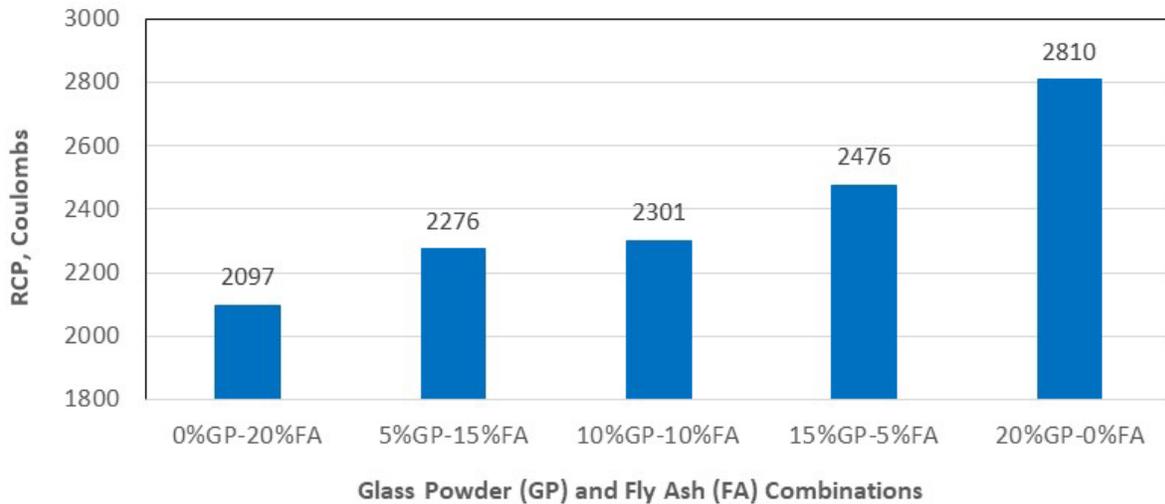
Figure 3. Variation of 28-day elastic modulus for different combinations of SCMs (for GU cement)



GP and GU Cement: Trend of Chloride Permeability at 28 Days

Figure 4 shows that the rapid chloride permeability (RCP) of concrete at the age of 28 days gradually increases with an increase in glass powder content from 0% to 20% (decrease in fly ash content from 20% to 0%). Such an increase in the RCP with the incorporation and increase of glass powder in concrete mixes is not encouraging.

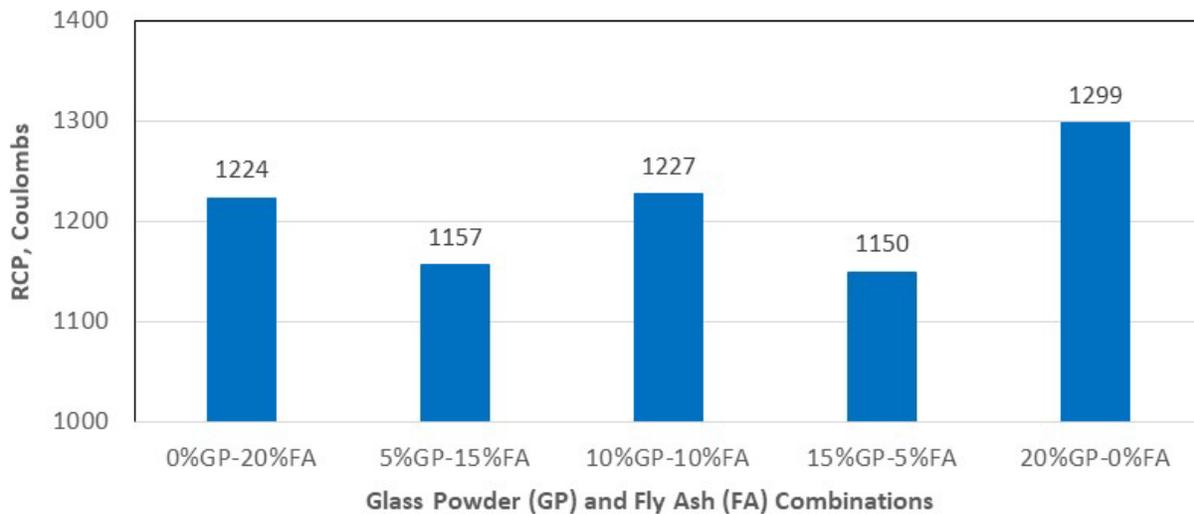
Figure 4. Variation of RCP at 28 days for different combinations of SCMs (for GU cement)



GP and GU Cement: Trend of Chloride Permeability at 56 Days

Figure 5 shows that RCP value of concrete slightly decreases at 56 days after incorporating 5% glass powder (with 15% fly ash) in concrete mix as compared to concrete mix with no glass powder (reference mix with 20% fly ash content). However, the RCP of concrete increased when 10% glass powder was incorporated as compared to concrete with no glass powder as well as concrete with 5% glass powder contents. The RCP then decreased again with the incorporation of 15% glass powder (with 5% fly ash). Such variation of RCP of concrete at the age of 56 days with the variation of glass powder content has appeared to be inconsistent. However, the differences in RCP values among different combinations of fly ash and glass powder contents in concrete mixes seem to be small. Such small differences in RCP values could be due to the level of accuracy of equipment and test method, variation in aggregate compositions and variation in specimen preparation. These results seem to indicate that no combination of glass powder, fly ash and GU cement is beneficial for concrete mixes, whether it is assessed from an economical or sustainability perspective.

Figure 5. Variation of RCP at 56 days for different combinations of SCMs (for GU cement)



Effect of Glass Powder on Hardened Concrete Containing GUL Cement

Table 8 shows the average values of hardened concrete mechanical and durability properties from all four aggregate types and GUL cement for five trial combinations of glass powder and fly ash contents. Figures 6 through 15 graphically show the trend of different properties of concrete containing GUL cement for the variation of glass powder and fly ash contents, and comparison of properties between concrete containing GU and GUL cements.

Table 8. Summary of hardened concrete properties for different combinations of fly ash and glass powder in concrete mixes containing GUL cement

Properties	0% Glass Powder (20% Fly Ash)	5% Glass Powder (15% Fly Ash)	10% Glass Powder (10% Fly Ash)	15% Glass Powder (5% Fly Ash)	20% Glass Powder (0% Fly Ash)
Compressive Strength at 28 Days (MPa)	35.8	39.5	36.3	35.4	32.7
Flexural Strength or Modulus of Rupture (MoR) at 28 Days (MPa)	5.6	5.8	5.8	5.8	5.7
Modulus of Elasticity (MoE) at 28 Days (GPa)	31.8	33.7	32.8	32.6	32.0
Rapid Chloride Permeability (RCP) at 28 Days (Coulombs)	2322	2190	2028	2046	2118
Rapid Chloride Permeability (RCP) at 56 Days (Coulombs)	1560	1281	1245	1139	1177

GP and GUL Cement: Trend of Compressive Strength

The trend of average compressive strength (from all aggregate types) in Figure 6 seems to indicate that concrete with 5% glass powder and 15% fly ash will provide an increase in compressive strength as compared to concrete with 20% fly ash (i.e., the reference mix with no glass powder) when GUL cement is used. However, increased strength was not realized for all aggregate types e.g., for limestone Source D, there was a 2.5 MPa decrease in compressive strength with 5% GP as compared to the concrete with no GP. Compressive strength reduces with further increase in glass powder content. However, the average compressive strength of concrete having 10% glass powder is still higher than the average strength of concrete having no glass powder. Further testing is required to confirm the test results for concrete containing no glass powder and 5% glass powder contents for all aggregate types.

Figure 6. Variation of 28-day compressive strength for different combinations of SCMs (for GUL cement)

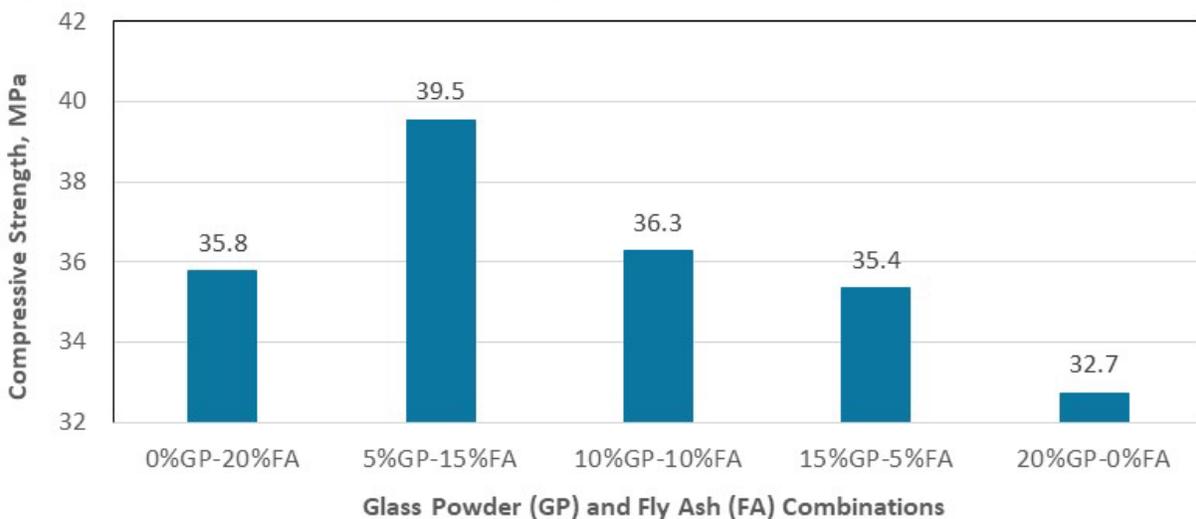
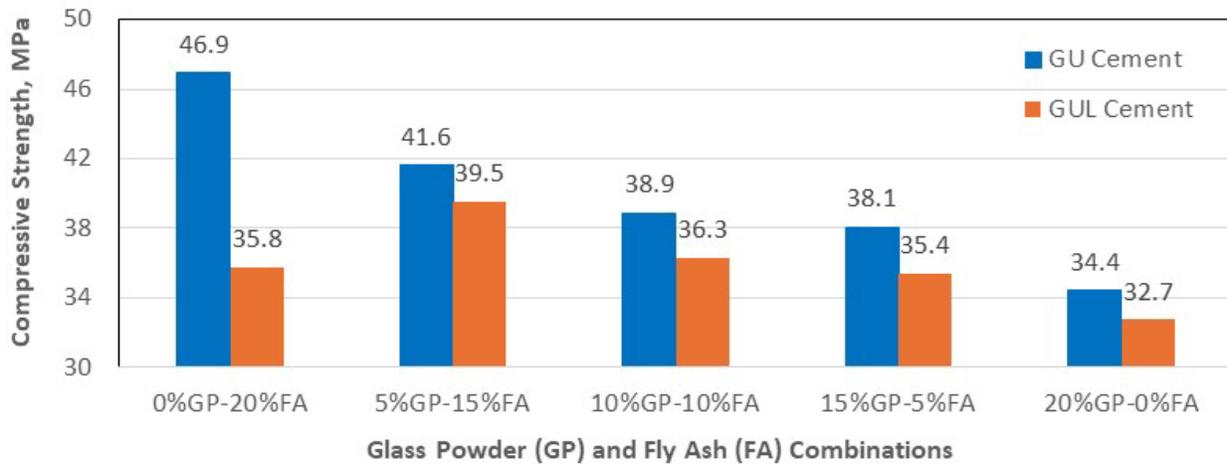


Figure 7 shows that the compressive strength of concrete containing GUL cement is consistently lower than the compressive strength of concrete containing GU cement. A significantly lower strength (35.8 MPa) of concrete having GUL cement, 20% fly ash and no glass powder, as compared to the strength (46.9 MPa) of concrete having GU cement, 20% fly ash and no glass powder indicate that GUL and GU cements are not equivalent. As mentioned earlier, previous studies and testing by MTI also indicated that an additional 25 to 32 kg GUL cement is required to achieve an equivalent strength of concrete containing GU cement. Figure 7 also shows that the concrete containing GUL cement exhibits lower compressive strength than the concrete containing GU cement for all combinations of glass powder and fly ash contents. These results raise questions about the environmental benefit of concrete with GUL cement.

Figure 3. Comparison of 28-day compressive strength: GU cement versus GUL cement



GP and GUL Cement: Trend of Flexural Strength

Figure 8 shows a minor increase in average flexural strength (from all aggregate types) of concrete containing 5% glass powder and 15% fly ash as compared to the average flexural strength of concrete having 20% fly ash and no glass powder when GUL cement is used. However, such increased flexural strength was not observed for all aggregate types (e.g., for gravel Source A, there was no increase in flexural strength). A further increase in glass powder content has resulted in no change or decrease of flexural strength of concrete containing GUL cement. These results may indicate that 5% glass powder and 15% fly ash is a good combination when GUL cement is used in concrete mixes. However, further testing is required to confirm the test results for concrete containing 5% glass powder and no glass powder for all aggregate types.

Figure 8. Variation of 28-day flexural strength for different combinations of SCMs (for GUL cement)

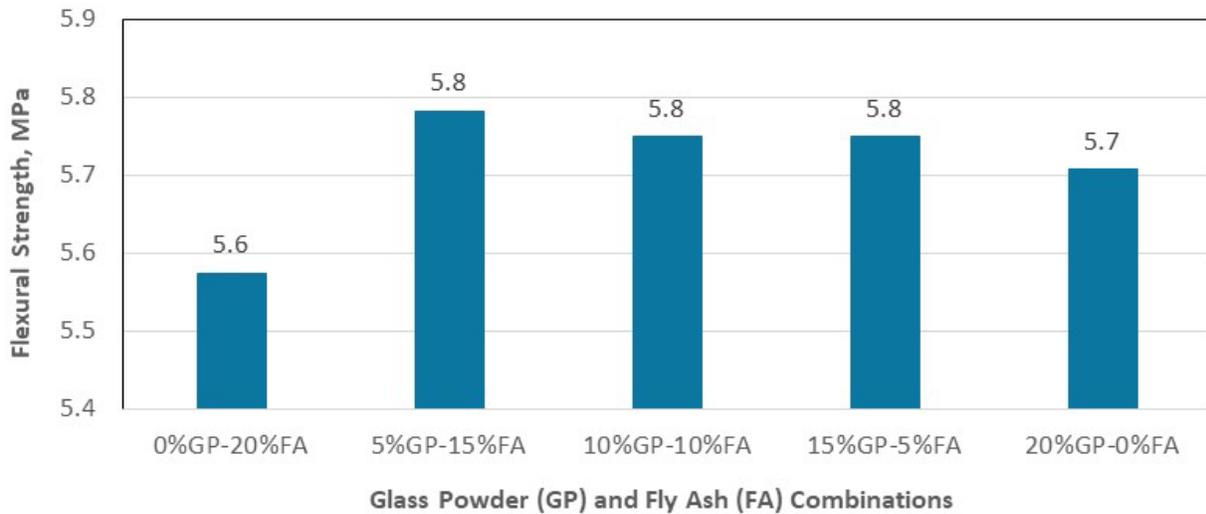
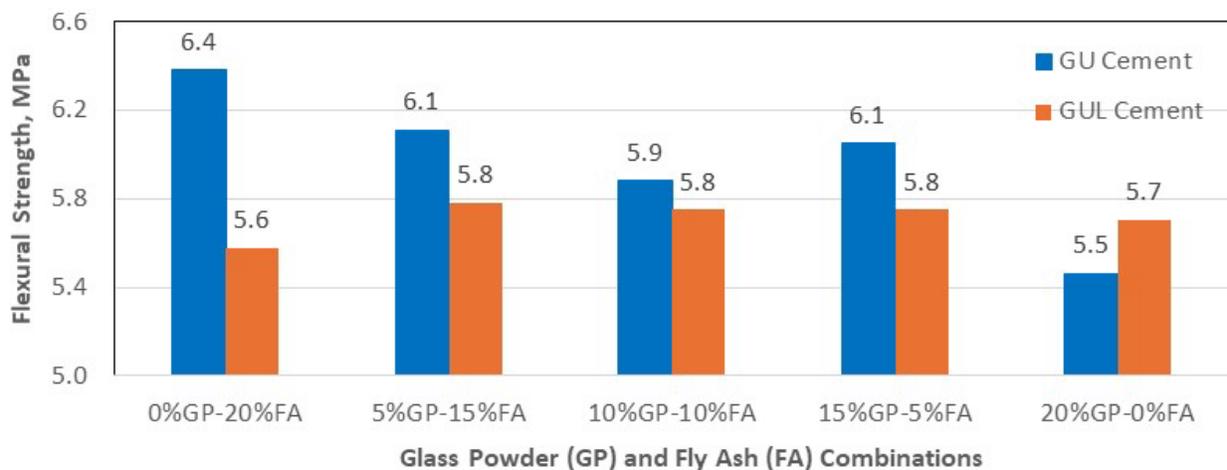


Figure 9 shows a comparison of flexural strength of concrete containing GU and GUL cements. A noticeably lower flexural strength (5.6 MPa) of concrete having GUL cement, 20% fly ash and no glass powder, as compared to the flexural strength (6.4 MPa) of concrete having GU cement, 20% fly ash and no glass powder further indicates that GUL and GU cements are not equivalent. A lower flexural strength was observed for concrete containing GUL cement as compared to the concrete containing GU cement for each combination of fly ash and glass powder, except for the concrete having no fly ash. These results again raise questions about the environmental benefit of concrete with GUL cement.

Figure 9. Comparison of 28-day flexural strength: GU cement versus GUL cement



GP and GUL Cement: Trend of Modulus of Elasticity

Figure 10 shows that the average modulus of elasticity (MoE) of concrete (average from all aggregate types) containing GUL cement increases after the incorporation of 5% glass powder, although there was a reduction of MoE for aggregate Source D. The MoE starts to decrease with a further increase in glass powder content. Further testing is required to confirm the test results for concrete with 0% and 5% glass powder contents for all aggregate types.

Figure 10. Variation of elastic modulus for different combinations of SCMs (for GUL cement)

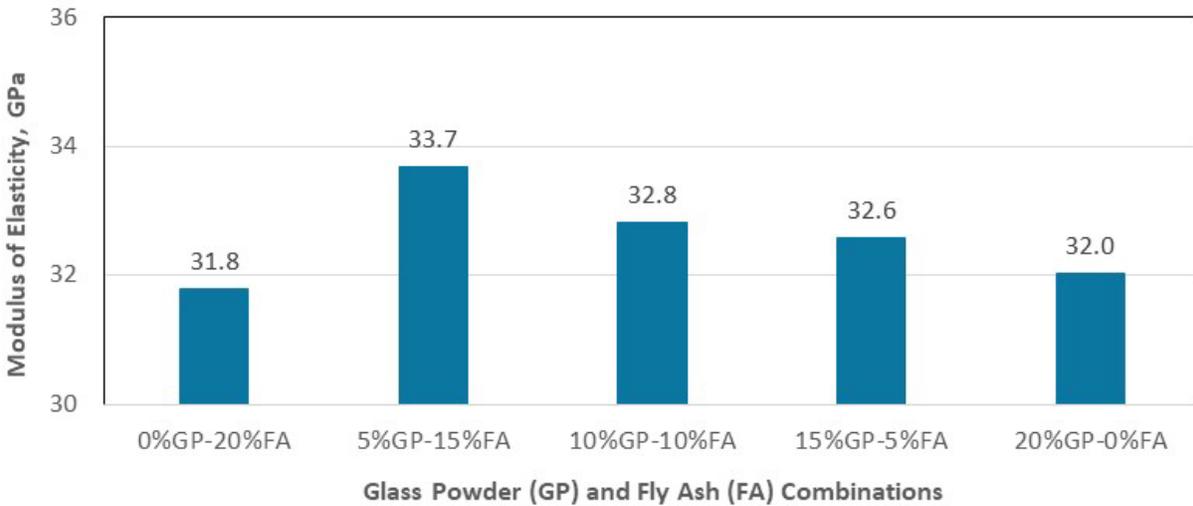
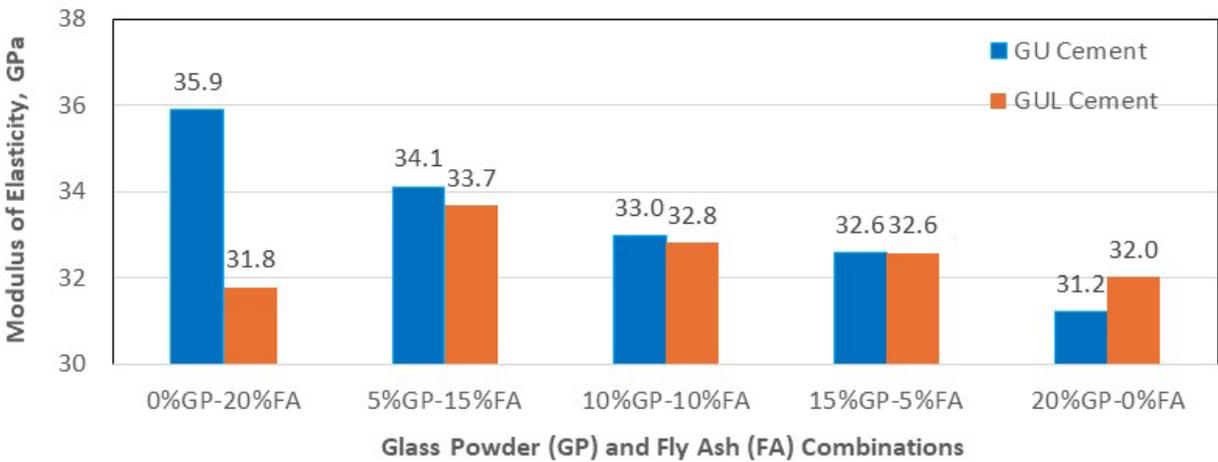


Figure 11 shows that the MoE (31.8 GPa) of concrete containing GUL is significantly lower than the MoE (35.9 GPa) of concrete having GU cement (both having 20% fly ash and no glass powder). Concrete containing GUL cement and 5% as well 10% glass powders also exhibited lower MoE than the concrete containing GU cement. This further raises the question about the environmental benefit of concrete containing GUL cement.

Figure 11. Comparison of 28-day elastic modulus: GU cement versus GUL cement



GP and GUL Cement: Trend of Chloride Permeability at 28 Days

Figure 12 shows that the average RCP value of concrete (containing GUL cement) at 28 days decreases (durability improves) with an increase in glass powder content up to 10%. The RCP value of concrete increases with further increase in glass powder content. There were some inconsistencies of the RCP values among aggregate types for different amounts of glass powder contents. Further investigation is required to confirm the test results.

Figure 12. Variation of RCP at 28 days for different combinations of SCMs (for GUL cement)

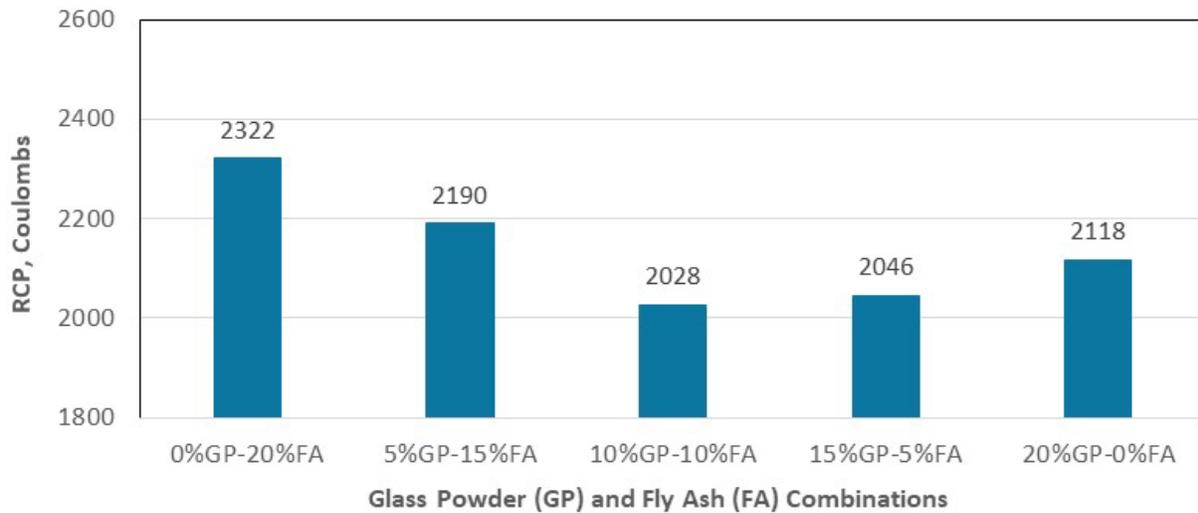
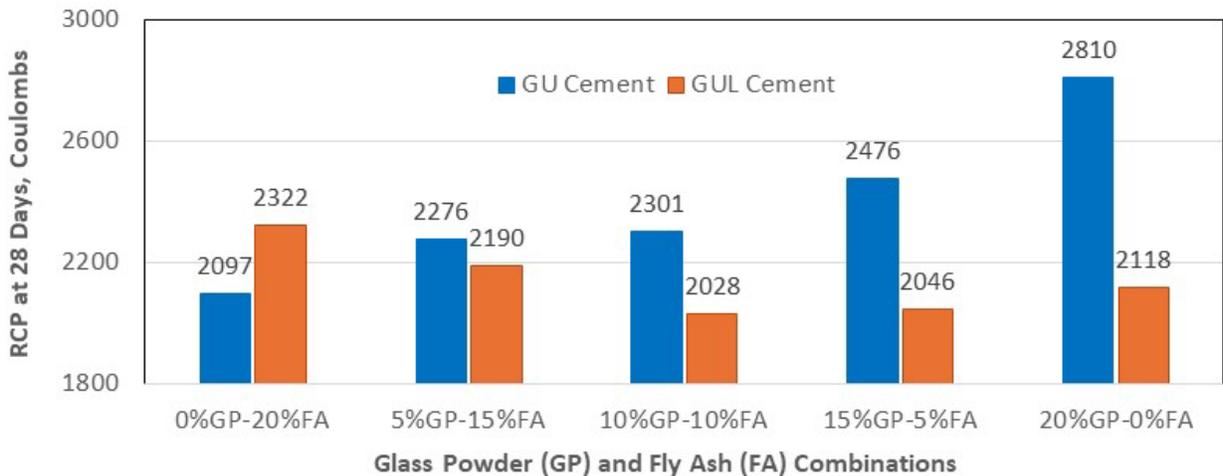


Figure 13 shows that the RCP (2,322 coulombs) of concrete containing GUL is noticeably higher than the RCP (2,097 coulombs) of concrete having GU cement (both having 20% fly ash and no glass powder). These results indicate that concrete with GUL cement exhibits lesser durability properties than concrete with GU cement. However, the concrete containing GUL cement seems to perform better in combination with fly ash and glass powder contents as compared to the concrete having fly ash alone as a SCM.

Figure 13. Comparison of RCP at 28 days: GU cement versus GUL cement



GP and GUL Cement: Trend of chloride permeability at 56 Days

Figure 14 shows that the average RCP value of concrete (containing GUL cement) at 56 days decreases with an increase in glass powder content up to 15%. The decrease in RCP values was for up to 10% glass powder contents for aggregate Source B and 5% glass powder content for aggregate Source D. Such inconsistencies in RCP values require further investigation.

Figure 14. Variation of RCP at 56 days for different combinations of SCMs (for GUL cement)

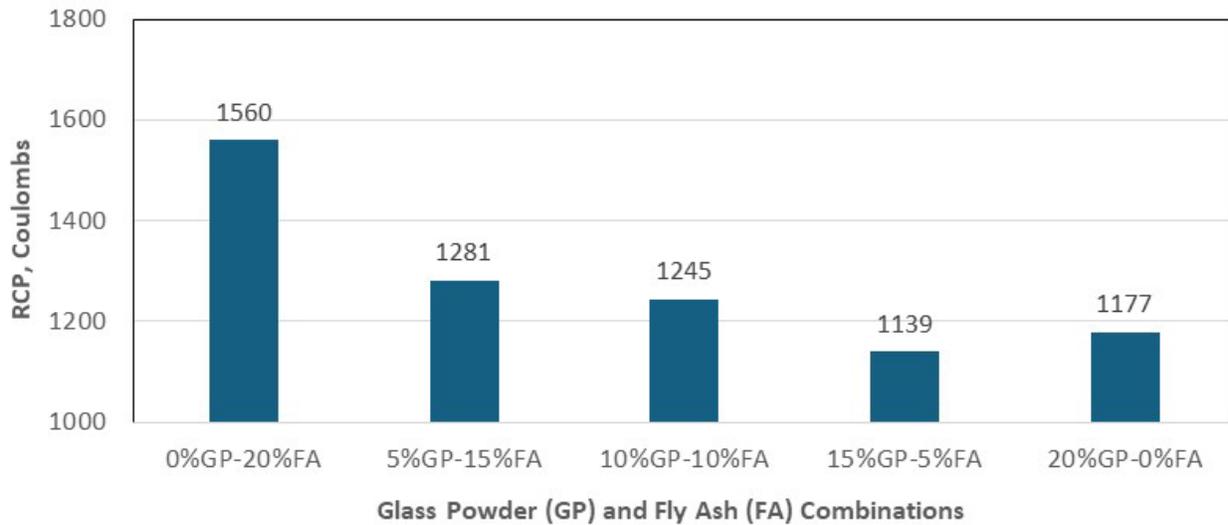
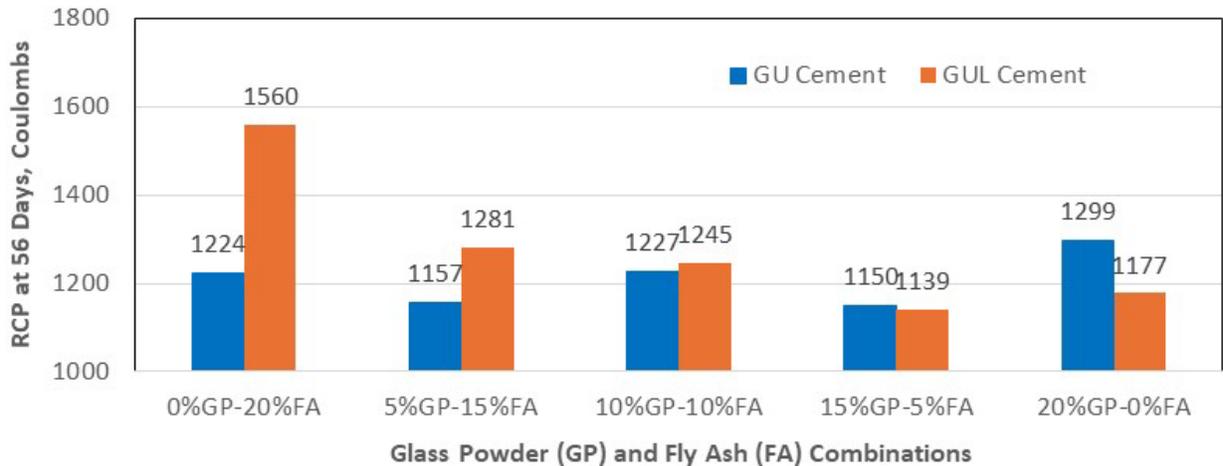


Figure 15 also shows that the RCP (1,560 coulombs) at 56 days of concrete containing GUL cement is noticeably higher than the RCP (1,224 coulombs) of concrete having GU cement (both having 20% fly ash and no glass powder). These results further indicate that concrete containing GUL cement exhibits inferior durability properties than the concrete containing GU cement. Figure 15 shows that, at the age of 56 days, the durability property, with higher RCP values, of concrete with GUL cement dropped behind the concrete containing GU cement for 5% and 10% GP contents. Such a trend does not seem to be consistent with the trend that was observed for concrete at the age of 28 days (see Figure 13). At the age of 56 days, the difference in RCP values between concrete with GU cement and GUL cement also reduced for concrete with 15% and 20% GP contents as compared to the difference in RCP values at 28 days. These trends seem to indicate that there is no long-term benefit of GP in concrete mixes.

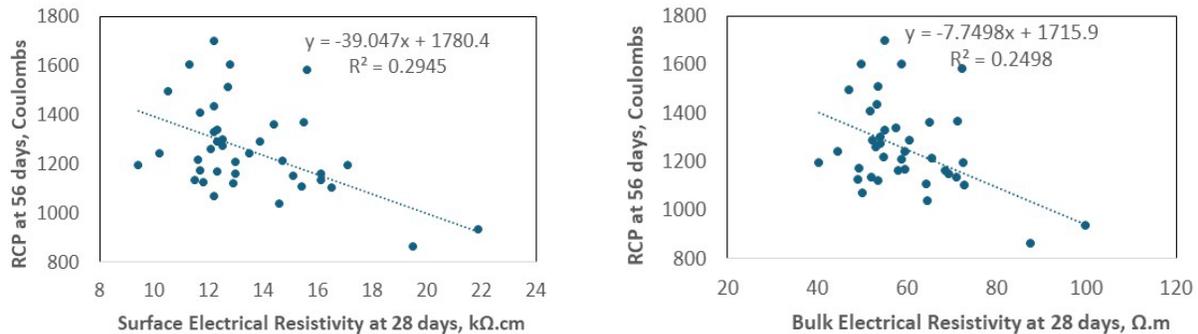
Figure 15. Comparison of RCP at 56 days: GU cement versus GUL cement



Correlations Between Electrical Resistivity Values and RCP

Figure 16 shows the correlation between surface electrical resistivity and RCP as well as between bulk electrical resistivity and RCP of concrete. As shown in the graphs, the correlations of 28-day electrical resistivity values of concrete with the 56-day RCP values are poor with R^2 values of less than 0.3.

Figure 16. Correlations between surface resistivity, bulk resistivity, and RCP values



Summary, Conclusions and Recommendations

Based on the testing completed in this Phase II study, glass powder has not shown to provide any positive benefit in terms of strength (compressive and flexural) and stiffness (modulus of elasticity) properties of concrete containing GU cement. The trends of the durability property (in terms of RCP) of concrete containing GU cement were inconsistent between ages of concrete at the time of testing and among varied glass powder contents in the concrete.

For the concrete containing GUL cement, 5% glass powder (and 15% fly ash) has shown to provide beneficial effects as compared to the concrete with no glass powder (20% fly ash and 0% GP). However, the quality of concrete containing GUL cement was still inferior to the concrete with GU cement.

Based on the test results and analysis presented in this paper, the following recommendations are made for moving forward:

- 1) Retest concrete incorporating 20% fly ash (no glass powder) and GU cement to confirm its superior qualities and that the glass powder has no beneficial effect to concrete containing GU cement;
- 2) Retest concrete incorporating 20% fly ash (no glass powder) and GUL cement to confirm its low strength and durability properties, and that the glass powder has beneficial effect to concrete containing GUL cement;
- 3) Retest concrete with 5% glass powder, 15% fly ash and GUL cement to confirm that this composition is the most beneficial one when GUL cement is used;
- 4) Do not incorporate glass powder into concrete mixes for Manitoba highways, unless further detailed studies in Manitoba context confirm its potential beneficial effects as a SCM;
- 5) Reinvestigate the potential environmental benefits of typical concrete mixes containing GUL cement as compared to concrete mixes with GU cement, not GUL cement alone; and

- 6) Do not use Surface Electrical Resistivity (SER) or Bulk Electrical Resistivity (BER) as acceptance tests for concrete mixes in Manitoba until further development in these aspects.

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