Case Studies in Construction Materials 15 (2021) e00745

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Long-term field performance of concrete produced with powder waste glass as partial replacement of cement

Roz-Ud-Din Nassar [a,*], Parviz Soroushian [b], Muhammad Sufyan-Ud-Din [c]

[a] Department of Civil and Infrastructure Engineering at American University of Ras Al Khaimah (AURAK), Ras Al Khaimah, United Arab Emirates
[b] Metna Co., 1926 Turner Street, Lansing, MI 48906, USA
[c] Department of Civil Engineering at American University of Sharjah, United Arab Emirates

ARTICLE INFO

Keywords:
Waste glass powder
Concrete
Strength
Durability
Field investigation

ABSTRACT

This paper reports the long-term field and laboratory-tested performance of concrete produced with 20 wt% replacement of cement with powder waste glass (WG). Field investigations of WG concrete were carried out in a large-scale field project comprising of various segments subjected to harsh weathering conditions and service load over a period of about three years. While laboratory cured WG concrete and normal concrete specimens were tested in compression and flexure at various concrete ages ranging from 3 days to 300 days. After about three years of field exposure, concrete cores were extracted from various segments of the project and tested for compressive strength, moisture sorption, and abrasion resistance. A detailed survey of the various segments of the project was carried out to physically examine the state of WG concrete after three years of service. Test results of the field WG concrete showed enhanced compressive strength, up to 57% reduction in moisture sorption and up to 61% reduction in abrasion weight loss in comparison to normal concrete at 300 days of concrete age. Similarly, the laboratory tests showed 43% gain in compressive strength and 28% gain in flexural strength of WG concrete in comparison to that of normal concrete at 90 days of concrete age. Detailed physical examination of various project segments showed no signs of deterioration or material failure after three years of service. The field project also demonstrated the constructability of WG concrete similar to that of normal concrete.

1. Introduction

Globally about 130 million tonnes of glass was produced in 2018 out of which only 21% was recycled [1]. In 2018 in the 28 countries of European Union, 20.65 million tonnes of WG was produced [2]. Similarly, in the United States about 8.88 million tonnes of WG was produced in 2018 out of which 55.36% was landfilled [3]. Since glass is a non-biodegradable material, its landfilling is not an environmentally feasible option. Particularly, lead glass which is used in the manufacturing of display monitors has a higher content of lead oxide (PbO), its landfilling can result in contamination of soil and underground water [4]. Similarly, some of the heavy metal ions used as colorants in colored glass may pollute the soil and groundwater by leaching these heavy or toxic metals [5]. Contrary to the common belief, the chances of recycling of WG in the production of new glass are limited owing to its mixed color which also indicate variation in the chemical composition of the glass, its contamination with labels and bottle caps, and the strict quality control

* Corresponding author.
E-mail address: rozuddin.nassar@aurak.ac.ae (R.-U.-D. Nassar).

https://doi.org/10.1016/j.cscm.2021.e00745
Received 31 July 2021; Received in revised form 25 September 2021; Accepted 12 October 2021
Available online 13 October 2021
2214-5095/

Table 1
Physical properties of powder WG.

Specific gravity	Specific surface area	Average particle size	Moisture content	% passing # 325 mesh
2.44 g/cm^3	4450 cm^2/g	20 μ	0.1%	95.5

Table 2
Chemical composition of powder WG and OPC.

Item	Powder WG	OPC
SiO_2	72%	20.25%
Na_2O	11.5%	0.34%
CaO	10.5%	64.5%
Al_2O_3	8%	6.15%
MgO	1%	2.50%
K_2O	< 1%	0.50%
Fe_2O_3	< 1%	2.55%
LOI	0.6%	2.0%

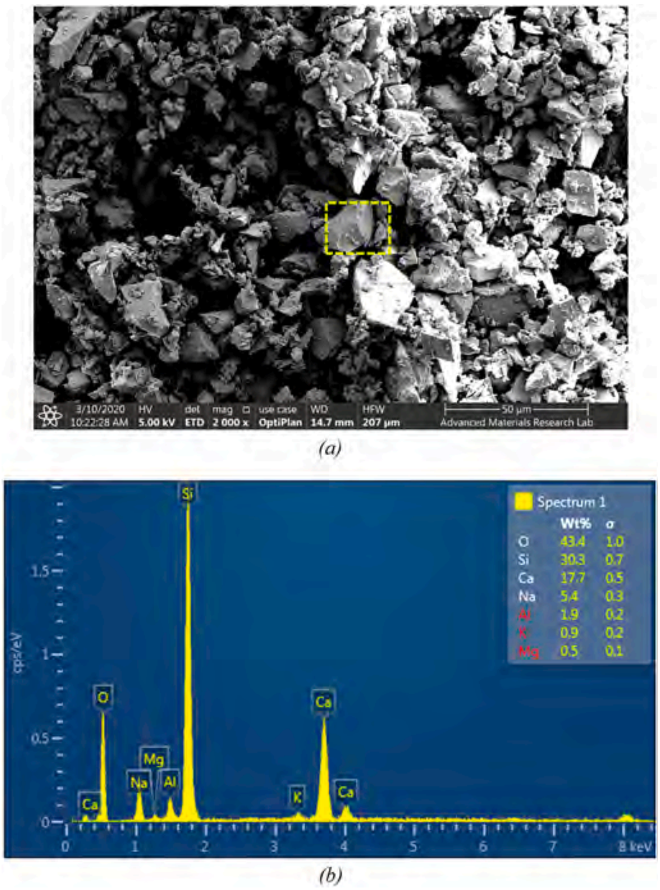

Fig. 1. Powder WG (a) SEM image (b) EDX plot at the marked location in (a).

requirements of the glass manufacturers. The given situation warrants to explore alternate venues to safely consume the huge quantity of WG. Concrete is one possibility which can absorb huge quantity of WG towards its production.

Use of WG in manufacturing of concrete is a favorable practice in many ways. Firstly; glass has the ability to undergo pozzolanic reaction when used as partial replacement of cement for manufacturing of concrete, secondly; recycling of glass in concrete does not require any special treatment (sorting by color and type) other than crushing and reducing it to the desired size, thirdly; the risk of leaching of toxic and heavy metals is minimum to none, fourthly; with an annual global production of about 9 billion tonnes [6,7], concrete can consume substantial part of the WG in its production, fifthly; the use of glass in concrete as partial replacement of cement

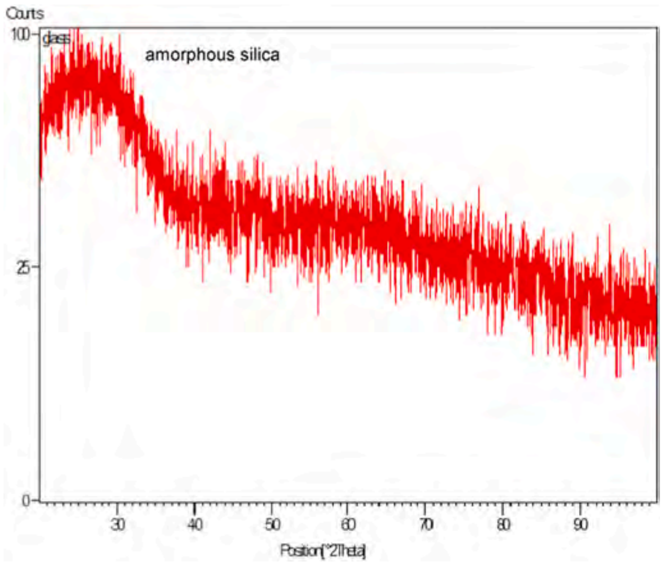

Fig. 2. XRD plot of the powder WG.

Table 3
Concrete mix design used in the experimental program.

Mix Design	Coarse aggregate kg/m^3	Fine aggregate kg/m^3	W / C ratio	Cement content kg/m^3	Water content kg/m^3	Powder WG kg/m^3
MC1	875.25	580.48	0.38	443.5	168.53	–
MC2	875.25	580.48	0.46	443.5	204	–
RG1	875.25	580.48	0.38	354.8	168.53	88.7
RG2	875.25	580.48	0.46	354.8	204	88.7

Table 4
Use of concrete mixtures in various segments of the field project.

Project Location	Component Type	MC1	MC2	RG1	RG2
Recycling Center	Sidewalks, curb, bicycle parking, gutter, curb	✓		✓	
Hubbard Hall	Sidewalks		✓		✓
International center	Sidewalks	✓		✓	
Bessey Hall	Sidewalks, bicycle parking		✓		✓
Breslin Center	Sidewalks, bicycle parking	✓		✓	

is bound to reduce the carbon footprints of cement / concrete production, noting that each tonne of cement production releases about 0.9 tonne of carbon dioxide and concrete production accounts for 8% of the world's carbon dioxide emissions and hence requires immediate attention of the planners [8–16]. Inclusion of glass shall significantly reduce the overall energy consumption of concrete production as manufacturing of cement is also an energy-intensive process, which ranks third after aluminum and steel production in terms of energy consumption. The use of WG in concrete can be made in various forms, such as an additive in the production of concrete, as partial replacement of coarse and / or fine aggregates for manufacturing of concrete and as partial replacement of cement for concrete production [17–19]. Use of glass has been reported to be of significant advantage towards enhancement of the mechanical characteristics of concrete produced with other recycled materials for example recycled aggregate [20–22]. Consensus exists among the researchers that the most beneficial contribution of the glass in concrete can be realized if it is reduced to powder size and used as partial replacement of cement for concrete production [23–28]. Reduction to powder size having average particle size smaller than that of cement results in increasing the surface-to-volume ratio of the unhydrated mixture and hence increases its rate of hydration by providing more hydration sites [29]. Furthermore, reduction to powder size increases the pozzolanic reactivity of glass and suppresses its ability to cause alkali silica reaction (ASR) [23,29].

Wealth of findings have been reported by the researchers with regards to the use of glass in concrete. Shayan and Xu [30] evaluated the use of glass powder up to 30% replacement of cement in their field experimental work on glass concrete slabs. They have reported that powder glass can be used towards production of structural concrete having a target compressive strength of 40 MPa with satisfactory performance of drying shrinkage, alkali reactivity and ability to reduce chloride ion penetrability. Ramdan et al. [31] investigated the pozzolanic activity of WG powder. Authors found that the use of glass powder at 10% and 15% replacement of cement in various concrete mixtures resulted into weak or moderate pozzolanic activity of these mixtures and hence negatively affected their

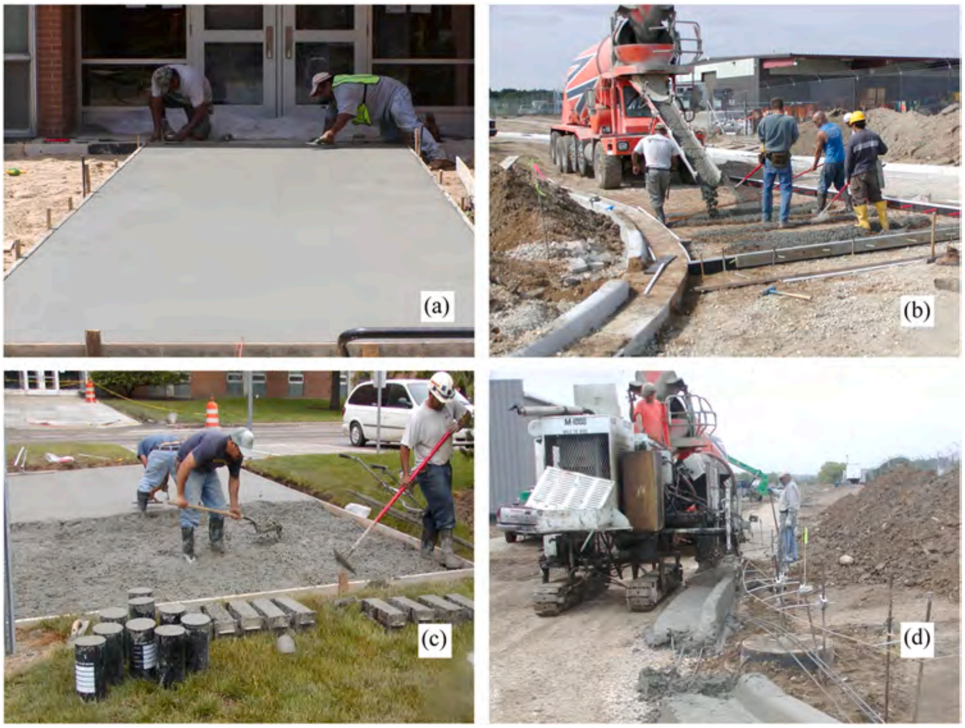

Fig. 3. Pouring / finishing of WG concrete in various segments of field project (a) Sidewalk (Hubbard hall) (b) Reinforced pavement (Recycling center) (c) Bicycle parking (Recycling center) (d) Gutter (Recycling center).

physicomechnical properties. However, the authors found that the use of nano MgO and $MgFe_2O_4$ spinel NPs at 0.5 and 1 mass% in glass powder containing concrete mixtures significantly improved their compressive strength, reduced the total porosity and water absorption and enhanced their microstructures. Authors opined that the improvement in performance of concrete mixtures is brought about by the formation of additional hydration products caused by the addition of nano particles. Mirzahosseini and Riding [32] investigated the effect of curing temperature on the pozzolanic reactivity of glass powder. The authors found that curing of cementitious mixture containing glass powder having particle size < 25 μm at high temperature (50 °C) significantly increases the pozzolanic reactivity of glass powder. Curing of powder class containing mixtures at elevated temperature also showed enhancement in compressive strength and sorptivity. The authors also found green glass to be more reactive than clear glass. In another study [33] authors found considerable reduction in the later age chloride permeability of glass powder modified concrete (compared to control concrete) while replacing cement with glass powder at 10% and 20% levels. Authors attributed this gain to the microstructure refinement of concrete mixtures caused by the glass powder inclusion. Other researchers found that 20 wt% replacement of cement with ground waste glass microparticles is an optimum replacement level which enhances the strength and durability attributes of the resulting concrete mixtures [34]. The researchers observed increase in compressive, flexural, and splitting tensile strengths of the resulting concrete at this level of replacement. They further reported improvement in ASR, drying shrinkage, and workability of concrete mixtures if the cement replacement level is kept up to 20 wt%. Based on the results of their experimental work, Ali-Boucetta et. al [26], concluded that use of glass powder in combination with blast furnace slag improved the compressive strength, reduced the gas permeability, and increased the resistance to the chloride ion penetration of the resulting self-compacting concrete mixtures. They further observed that the inclusion of glass powder didn't improve the carbonation resistance of the concrete. Hwang and Cortef [35] and Nassar and Soroushian [19] produced sustainable green mortar mixtures with enhanced strength and durability characteristics by partially replacing cement with WG in the cementitious mixtures. Based on long-term field experimental work, Yang et al. [36] have reported that the use of up to 50% glass aggregate combined with glass powder as supplementary cementitious material in production of dry-mixed blocks mixture did not show any signs of ASR related damage. Various other researchers [37–40] investigated the use of glass in combination with other industrial wastes such as crumb rubber, recycled plastic, and waste granite. These researchers have not only reported the compatibility of using glass with other industrial wastes but in most cases found increase in key characteristics of the resulting mixtures.

Most of the earlier investigations on the performance powder WG in concrete are based on laboratory-level experimental work. Long-term field performance of such concrete when subjected to heavy service load under harsh weathering conditions has not been fully explored to the best of the authors knowledge. Hence; following the earlier pilot-scale field project by the authors [41], this project was planned for the use of WG concrete for construction of rigid pavement, sidewalks, curbs and parking lots at Michigan State University's (MSU) campus. The project evaluated the field performance of WG concrete under severe mid-Michigan weather over period of about three years while subjected to actual service load in large scale construction work project. For comparison purpose,

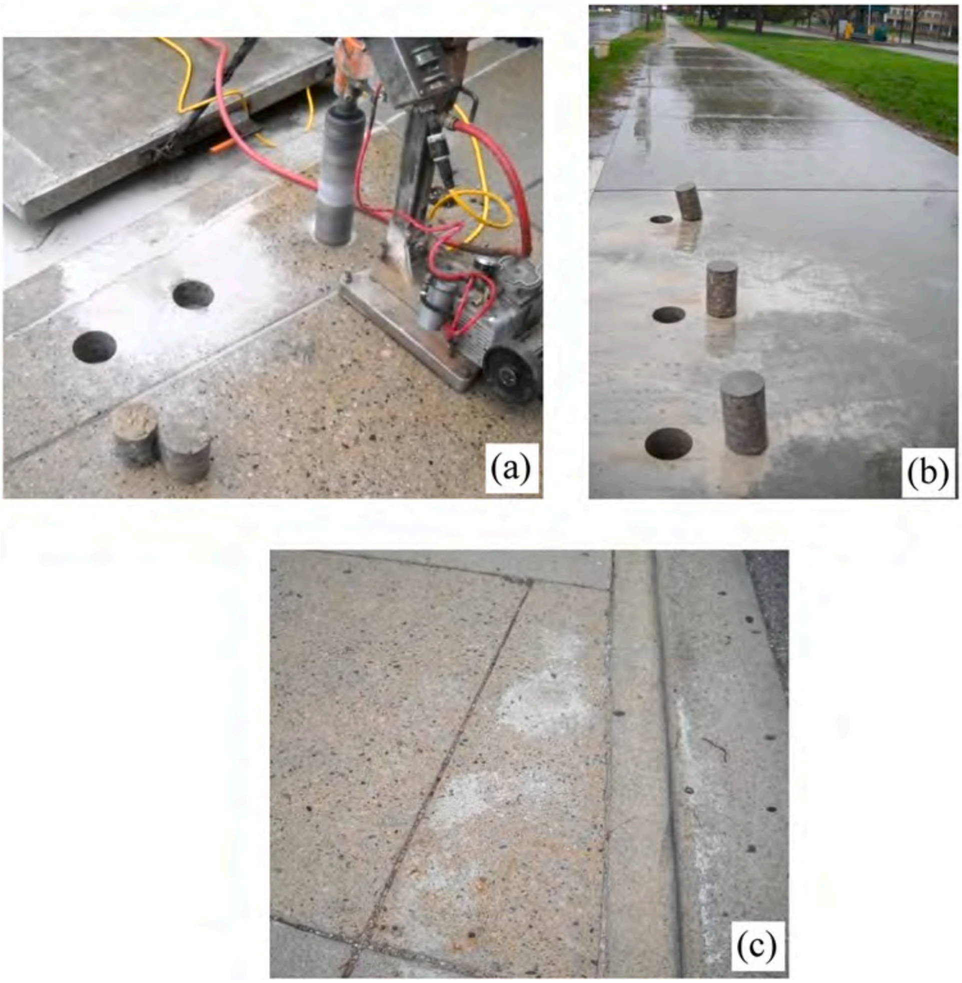

Fig. 4. (a) Extraction of core samples (b) extracted cores (c) repaired core-holes.

Fig. 5. Water sorption test setup.

normal concrete segments were also constructed at the same locations. Field study comprised of various tests on cores extracted from various segments of the WG concrete project and the physical observations of the constructed infrastructure components after long-term loading. Besides; long-term laboratory level investigations of WG and normal concrete mixtures were also carried out to compare the laboratory and field performance of WG concrete.

2. Materials and methods

Mixed color powder WG having physical characteristics shown in Table 1 was used as 20 wt% replacement of ordinary Portland

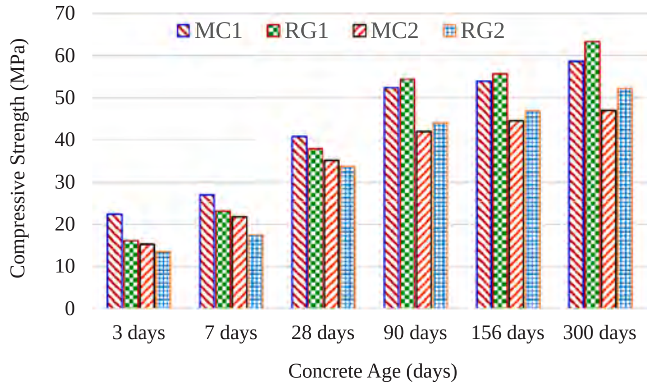

Fig. 6. Compressive strength test results of laboratory-cured specimens.

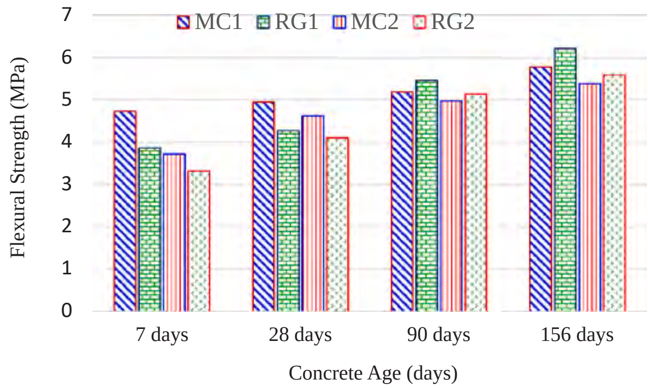

Fig. 7. Flexural strength test results of laboratory-cured specimens at different ages.

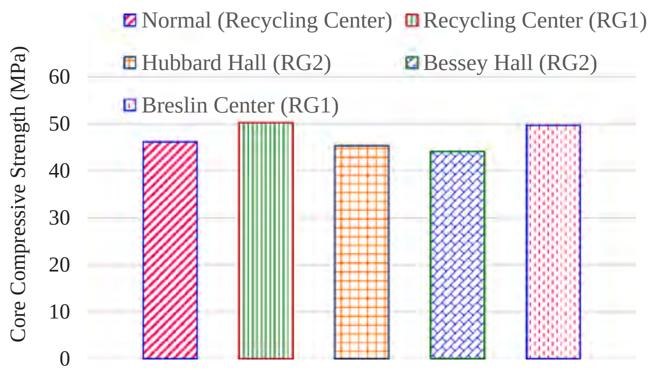

Fig. 8. Compressive strength of concrete cores extracted from various project segments.

cement (OPC) in two of the four concrete mixtures produced in this experimental program. The 20 wt% replacement level of OPC with WG was chosen to be the optimum based on the earlier findings of the authors [41,42]. Table 2 shows the chemical compositions of the WG and OPC, Fig. 1 shows the SEM micrograph and EDX plot, while Fig. 2 shows the XRD plot of the powder WG used in this project. Four concrete mix designs two each with and without partial replacement of OPC with powder WG at two different levels of water to cementitious ratios (w/cm), were produced as per the mixture details provided in Table 3. Two levels of w/cm were chosen to capture the effect of increase in w/cm on the strength and durability attributes of concrete containing WG as partial replacement of cement. The use of these concrete mixtures for construction of various infrastructure components in different segments of the field project is detailed in Table 4.

Concrete casting in various segments of the field project is shown in Fig. 3. For each segment of the field project, concrete cylinder and beam specimens were casted near the poring site for long term laboratory testing for compressive and flexural strengths.

Fig. 9. Views of tested WG concrete cores extracted from recycling center.

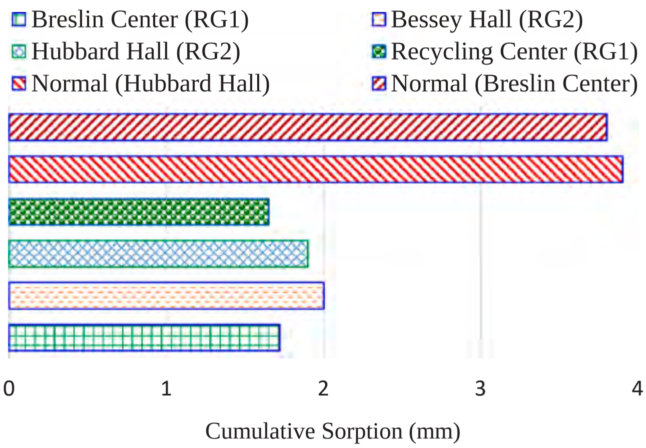

Fig. 10. Cumulative sorption test results of core-discs after 8-day continuous exposure to water.

Cylinder specimens having size of 150 mm (diameter) and 300 mm (height) were produced and cured in lime saturated water according to the provisions of ASTM C192 for each of the mix design sated in Table 3. Two replicates, each comprising of three cylinders were tested at concrete ages of 3, 7, 28, 90, 156, and 300 days in compression according to the guidelines of ASTM C39/ C39M. Similarly, two replicates of beam specimens with each comprising of three beams, having cross section of 100 mm × 100 mm and length of 400 mm were tested in flexure at concrete ages of 7, 28, 90, and 156 days following the procedure outlines in ASTM C78/ C78M.

After about three years of service, cores were drilled from the various segments of the field project and tested in compression. Fig. 4 shows views of cores extraction and the extracted cores from various segments of the project. It is to ne noted that the core holes were eventually filled with fast-setting concrete. This fast-setting concrete mix is designed for repair of cored locations and it reaches final set in 20–40 min (ASTM C191). As shown in Fig. 5, durability test in the form moisture sorption was conducted on circular disc specimens having diameter of 100 mm and thickness of 50 mm cut out from cylinder cores having even diameter according to the procedure outlines in ASTM C1585. Concrete specimens cut from cores were also tested for abrasion resistance according to the method of ASTM C779 / C779M. Finally, a detailed survey of all segments of the field project was conducted in order to evaluate the physical condition of WG concrete after three years of exposure to mid-Michigan weathering and service traffic.

3. Results and discussions

3.1. Test results of laboratory cured specimens

3.1.1. Compressive strength

Fig. 6 shows the compressive strength test results of the laboratory cured test specimens at different ages for all mixtures. In both the low and high w/cm mixture categories, the compressive strengths at earlier ages (3, 7, 28 days) of concrete materials produced with powder WG were lower than those of the corresponding concrete materials without powder WG. This trend was reversed at 90,

Fig. 11. A view of the abrasion testing machine [48].

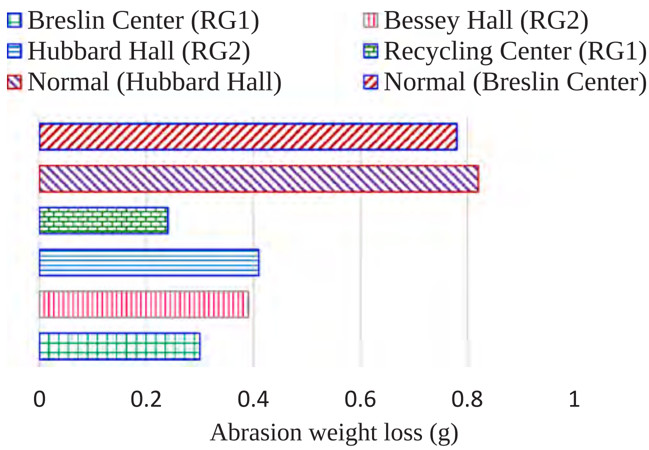

Fig. 12. Abrasion weight loss test results of core samples extracted from various segments.

156 and 300 days of age, when partial replacement of cement with powder WG benefited the compressive strength of concrete. A compressive strength gain of about 43% is noted between 28 and 90 days of concrete ages for RG1 mixture, while for RG2 mixture this increase is about 31%. Statistical analysis (of variance) of test results indicated that the 28-day compressive strengths of concrete materials with and without powder WG were statistically comparable (at 95% level of confidence). At 90, 156 and 300 days of age, however, statistical analyses pointed at the statistically significant benefits (at 95% level of significance) of powder WG to the compressive strength of concrete. As in the case of normal concrete, WG concrete responded to increase in w/cm similarly (comparison of compressive strengths of RG1 and RG2 mixtures).

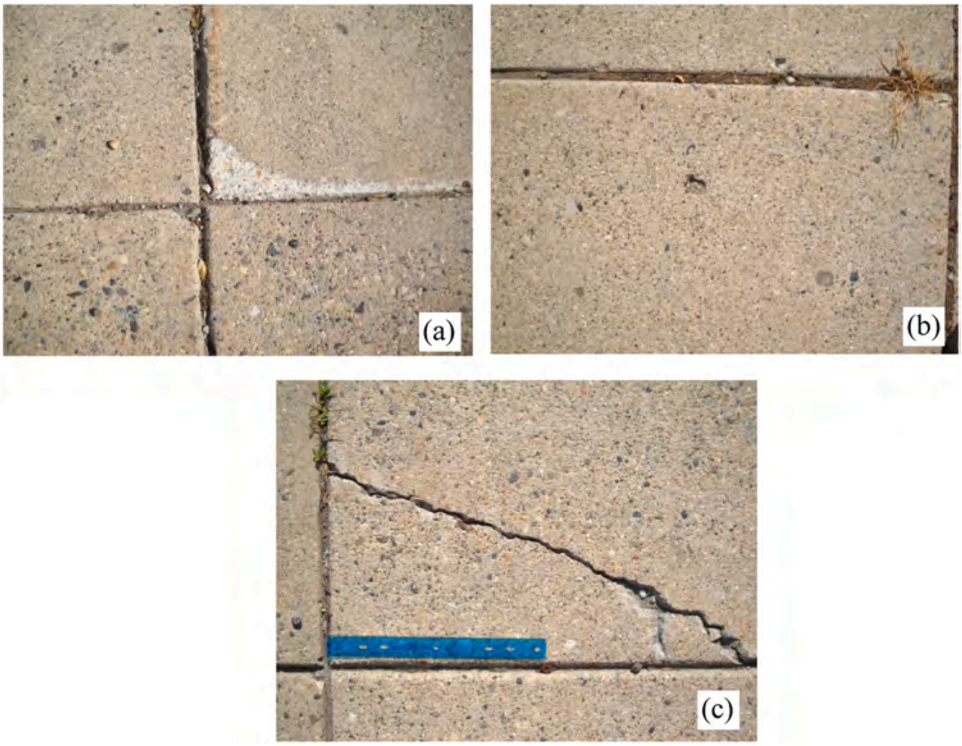

Fig. 13. (a) Chipped edges of the sidewalk panels at Hubbard Hall; (b) pit holes observed in panels; (c) cracking detected at corners of some panels.

Fig. 14. Advanced (a) and initial (b) stages of sidewalk panel cracking caused by differential settlement resulting from inadequate base preparation.

The long-term advantages of glass concrete over normal concrete can be attributed to the enhanced binding qualities of the calcium silicate hydrate which result from pozzolanic reaction of powder WG with calcium hydroxide. The pozzolanic reaction of highly reactive amorphous silica in powder WG with calcium hydroxide results into formation of secondary calcium silicate hydrate which consequently enhances the long-term compressive strength of the WG containing concrete. Furthermore, the lower energy required to dissolve powder glass particles facilitates the pozzolanic reaction of glass with the hydrates of cement which significantly improves mechanical properties including the compressive strength of the concrete [43,44]. These test results also suggest that there is an upper limit on the cement replacement level with powder WG if one desires to produce WG concretes with long-term strengths that are equivalent to or greater than those of normal concrete.

3.1.2. Flexural strength

Fig. 7 presents the flexural strength test results of low and high w/cm ratio mixtures at various concrete ages. In both categories, the flexural strength of WG concrete mixtures followed the trend of compressive strength test, that is past 28 days of concrete age the beneficial effects of partial replacement of cement with powder WG enhances the flexural strength of concrete mixtures in comparison to that of normal concrete mixtures. The RG1 mixture shows an increase of 28% in flexural strength between concrete ages of 28 and 90

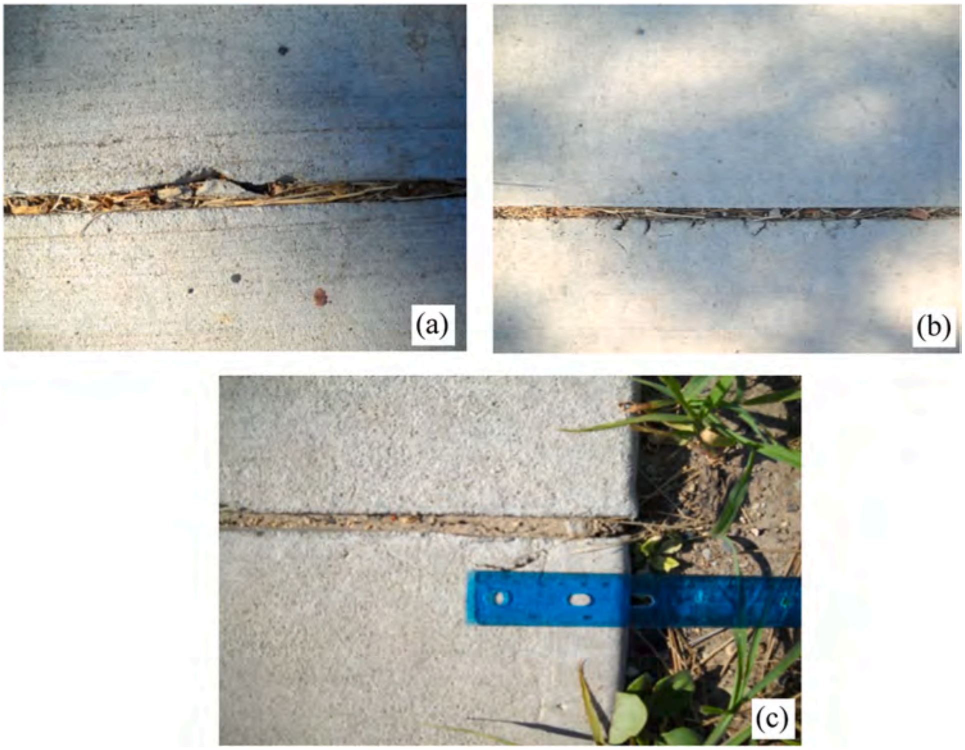

Fig. 15. (a) & (b) Chipping of the Breslin Center sidewalk panel edges; (c) a single crack with length of 3.5 cm observed near edge of one sidewalk panel.

days while corresponding increase for RG2 mixture is noted to be about 25%. In this case too, the effect of incorporation of powder WG as partial replacement of cement was found to be significant at 95% confidence level towards increase in later age flexural strength. The flexural strength of WG concrete mixture produced with higher w/cm ratio was lower as compared to low w/cm ratio WG concrete mixture at the corresponding age, showing a trend similar to that of normal concrete.

3.2. Test results of concrete cores

3.2.1. Compressive strength of cores

Cores with 100 mm diameter and heights varying from 175 to 200 mm drilled from the WG and normal concrete project segments, were tested in compression according to procedure outlined in ASTM C 42. Fig. 8 shows the compressive strength test results of cores drilled from various segments of the project. The low w/cm WG concrete mixture cores showed higher strength as compared to that of corresponding control concrete. As expected, compressive strength of field cured concrete is less than that of corresponding lab cured concrete mixtures (comparison of Figs. 6 and 8). Due to controlled molding of specimens, continuous moist curing under ideal conditions and better geometric shape, lab cured specimens would yield better strength than the field concrete cores. Any damage to field specimens during coring may have also reduced their strength.

After exposure to mid-Michigan weather and service load for about three years, cores of WG concrete extracted from various segments of field project provide compressive strengths which are either greater than or comparable with the corresponding lab cured specimens at 156 days of concrete age. Fig. 9 shows views of failed core specimens of WG concrete in compression. The dense and uniform matrix of the concrete after three years of exposure to aggressive weather and durability of WG concrete, which has retained or increased its strength in service environment service loads can be noted in the figure. These finding point at the weathering resistance and.

3.2.2. Moisture sorption of concrete cores

Moisture sorption is an important durability characteristic of a concrete mixture pointing at the quality of its microstructure. Enhanced resistance to moisture sorption is an indicator of improved barrier characteristics to the ingress of various deleterious agents into concrete matrix, which in turn results into long service life of the structural member, it forms. Sorption is measured as the change in mass divided by the product of the cross-sectional area of the test specimens and the density of water (0.001 g/mm^3). In this experimental program the cumulative secondary sorption was measured as per the guidelines of ASTM C1585-20 which defines it as capillary absorption between 6 h. until 8 days [45]. Fig. 10 shows the cumulative water sorption of concrete disc specimens after continuous eight days of exposure to water. The plots show significant improvements in the moisture sorption attributes of WG

Fig. 16. (a) Sidewalk in front of Recycling Center entrance door; (b) Chipping of the edges of the sidewalk along the road; (c) Control Joint cracks developed in the panels along the road.

concrete materials when compared with control concrete. Huge reductions of 57% and 50% in cumulative sorption are noted for RG1 and RG2 mixtures, respectively when compared with that of normal concrete at same concrete ages. Significant improvement in moisture barrier characteristics of WG containing concrete mixtures is thought to be the pore filling and pore refinement effect of powder WG in concrete [25,46]. Statistical analysis (of variance) of the 8-day cumulative sorption test results pointed at the statistical significance (at 0.05 significance level) of the WG contributions to the moisture resistance of concrete materials. WG concrete mixture produced with low w/cm ratio (RG1) showed better resistance to moisture sorption as compared to high w/cm ratio WG concrete mixture (RG2) pointing at improved microstructure of WG concrete with decrease in w/cm ratio. The differences between sorption qualities of different WG concrete materials can also be attributed to the difference in the mode of construction of individual project segments and variation in the quality of workmanship from one segment to the other. It is to be noted that such difference in performance becomes significant in case of large scale pouring of concrete, especially when handled by different crews of workers.

3.2.3. Abrasion resistance of concrete cores

Abrasion resistance of concrete is another important property influencing the durability of concrete pavements and floors subjected to abrasive action of traffic. Concrete with enhanced abrasion resistance results in longevity of service life of the infrastructure it forms. Abrasion resistance test was carried out according to the guidelines of ASTM C-779 [47]. Fig. 11 shows view of the abrasion test machine used in the experimental program. The abrasion test results of field WG (and control) concrete, presented in Fig. 12, point at major (and statistically significant) improvements in abrasion resistance of concrete upon partial replacement of cement with powder WG. It is postulated that the pore filling effect of powder WG results in reduction in the porosity of the resulting concrete which enhances its abrasion resistance in comparison to that of normal concrete. About 61% reduction in abrasion weight loss is recorded for RG1 mixture in comparison to normal concrete while in the case of RG2 mixture this reduction stands at 50%. The increase in w/cm ratio of WG concrete mixture on its abrasion resistance showed similar effect as in the case of water sorption. That is RG1 mixture had better abrasion resistance when compared with that of RG2 mixture, pointing at its improved durability performance brought about by

Fig. 17. (a) Cracking caused probably by differential settlement of the flatwork panel; (b) Shrinkage cracking around a rigid insert in concrete; and (c) WG concrete curb at Recycling Center.

the reduction in w/cm ratio.

3.3. *Field surveys*

3.3.1. *Hubbard hall*

Field survey of the WG concrete in this segment of the project showed it to be in good condition, with no visual distinctions between normal and WG concrete. Some corners and edges were chipped off in flatwork panels (Fig. 13a), and two panels appeared to have pits of 5 cm × 5 cm and 3.9 cm × 3 cm dimensions (Fig. 13b). Apart from these, no continuous pitting was observed elsewhere in the WG concrete work in this segment of the project. Few panels had developed cracks at corners (Fig. 13c) due to settlement of base layer. One sidewalk panel experienced differential settlement cracking (Fig. 14a), which resulted from inadequate base preparation (unrelated to concrete quality). Another panel exhibited initial signs of such cracking (Fig. 14b).

3.3.2. *Breslin center*

The WG concrete in this part of the field project was found to be in good condition as well, with a visual appearance comparable to that of normal concrete in the vicinity. The normal joint width (spacing between sidewalk panels) was found to be about 1 cm (Fig. 15a & b). Edges of few panels exhibited minor damage or chipping. Apart from these minor damages, only one small crack was found, which was 3.5 cm long and 0.3 cm wide (Fig. 15c). As the crack was observed at the edge of a panel, it could be inferred that in future it might lead to chipping of concrete from that part of the panel. Except for these minor damages, all WG concrete sidewalk panels appeared to be in good condition, exhibiting no cracking, spalling or pitting. WG concrete has thus performed desirably after few years of exposure to weathering (and service load) effects.

3.3.3. *Recycling Center*

Generally, the WG concrete exterior flatwork and curbs at the Recycling Center appeared to be in a very good condition (Fig. 16a). There were no pits. The minor chipping (Fig. 16b) is thought to have been caused during the snow removing operation. Concrete was also observed to have developed control joint cracks (Fig. 16c), as planned (by introduction of partial-depth joints). These joints are essentially "weakened planes" which define a desired location and orientation of shrinkage cracks.

Some rare cracking could also be detected, which was probably caused by differential settlement of inadequately prepared base (Fig. 17a) or shrinkage restrained by an internal rigid component placed in concrete (Fig. 17b). The WG concrete curb at the Recycling Center appeared to be in perfect shape, with no damage whatsoever (Fig. 17c).

4. Conclusions

The long-term field and laboratory investigations of WG concrete produced with 20 wt% replacement of cement with powder WG showed enhanced strength and durability characteristics specially after exposure to harsh weathering conditions and service load for a period of about three years. Following conclusions are drawn.

- The use of powder WG in the field concrete subjected to harsh weathering and service load conditions, resulted into increase in its compressive strength, up to 57% reduction in moisture sorption and up to 61% reduction in abrasion weight loss when compared with that of normal concrete at 300 days of concrete age.
- The laboratory test results showed up to 43% gain in compressive strength and 28% gain in flexural strength of WG concrete in comparison to that of normal concrete at 90 days of concrete age.
- After three years of service in harsh weather conditions, the detailed physical examinations of various project segments showed no signs of deterioration or material failure.
- The field project demonstrated the constructability of WG concrete similar to that of normal concrete. The use of powder WG in concrete is a viable practice which would result in important energy, environmental, cost and performance benefits.
- If adopted on large scale for the construction of built-infrastructure, the use of powder WG concrete would make important contributions towards reducing the carbon footprint of the construction industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This project was sponsored by MSU Physical Plant Division. Their financial support is thankfully acknowledged.

References

[1] I. Tiseo, Key figures on glass recycling worldwide as of 2018, in Energy and Environment, 2020.
[2] E. Union, Generation of Waste by Waste Category, Hazardousness and NACE Rev. 2 Activity, Eurostat, 2021.
[3] Agency, U.S.E.P., Facts and Figures about Materials, Waste and Recycling, 2018: Washington, DC.
[4] Q. Song, X. Zeng, J. Li, H. Duan, W. Yuan, Environmental risk assessment of CRT and PCB workshops in a mobile e-waste recycling plant, Environ. Sci. Pollut. Res. Int. 22 (16) (2015) 12366–12373.
[5] D. Chen, H. Masui, H. Miyoshi, T. Akai, T. Yazawa, Extraction of heavy metal ions from waste colored glass through phase separation, Waste Manag. 26 (9) (2006) 1017–1023.
[6] C. Meyer, Concrete materials and sustainable development in the USA, Struct. Eng. Int. 14 (3) (2004) 203–207.
[7] C.A.o. Canada, Annual global production of concrete, 2018.
[8] L. Rodgers, Climate change: The massive CO2 emitter you may not know about, 2018.
[9] D.L. Chandler, Researchers have created emissions-free cement, in MIT News, 2019, World Economic Forum.
[10] S.A. Miller, V.M. John, S.A. Pacca, A. Horvath, Carbon dioxide reduction potential in the global cement industry by 2050, Cem. Concr. Res. 114 (2018) 115–124.
[11] A. Schmitz, J. Kamiński, B. Maria Scalet, A. Soria, Energy consumption and CO_2 emissions of the European glass industry, Energy Policy 39 (1) (2011) 142–155.
[12] V. Sousa, J.A. Bogas, Comparison of energy consumption and carbon emissions from clinker and recycled cement production, J. Clean. Prod. 306 (2021), 127277.
[13] A. Adesina, Recent advances in the concrete industry to reduce its carbon dioxide emissions, Environ. Chall. 1 (2020), 100004.
[14] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, Annu. Rev. Energy Environ. 26 (1) (2001) 303–329.
[15] E. Gartner, Industrially interesting approaches to "low-CO_2" cements, Cem. Concr. Res. 34 (9) (2004) 1489–1498.
[16] J. Hilburg, Concrete production produces eight percent of the world's carbon dioxide emissions, in Cementing Climate Change, 2019.
[17] Y. Jani, W. Hogland, Waste glass in the production of cement and concrete – A review, J. Environ. Chem. Eng. 2 (3) (2014) 1767–1775.
[18] C. Shi, K. Zheng, A review on the use of waste glasses in the production of cement and concrete, Resour. Conserv. Recycl. 52 (2) (2007) 234–247.
[19] R.-U.-D. Nassar, P. Soroushian, Green and durable mortar produced with milled waste glass, Mag. Concr. Res. 64 (7) (2012) 605–615.
[20] R.-U.-D. Nassar, P. Soroushian, Use of milled waste glass in recycled aggregate concrete, Proc. Inst. Civ. Eng. - Constr. Mater. 166 (5) (2013) 304–315.
[21] A.T. Gebremariam, A. Vahidi, F. Di Maio, J. Moreno-Juez, I. Vegas-Ramiro, A. Łagosz, R. Mróz, P. Rem, Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes, Constr. Build. Mater. 273 (2021), 121697.
[22] J.-X. Lu, X. Yan, P. He, C.S. Poon, Sustainable design of pervious concrete using waste glass and recycled concrete aggregate, J. Clean. Prod. 234 (2019) 1102–1112.
[23] A. Shayan, A. Xu, Value-added utilisation of waste glass in concrete, Cem. Concr. Res. 34 (1) (2004) 81–89.
[24] W. Dong, W. Li, Z. Tao, A comprehensive review on performance of cementitious and geopolymeric concretes with recycled waste glass as powder, sand or cullet, Resour. Conserv. Recycl. 172 (2021), 105664.
[25] R.-U.-D. Nassar, P. Soroushian, Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement, Constr. Build. Mater. 29 (2012) 368–377.

[26] T. Ali-Boucetta, M. Behim, F. Cassagnabere, M. Mouret, A. Ayat, W. Laifa, Durability of self-compacting concrete containing waste bottle glass and granulated slag, Constr. Build. Mater. 270 (2021), 121133.
[27] M.N.N. Khan, A.K. Saha, P.K. Sarker, Reuse of waste glass as a supplementary binder and aggregate for sustainable cement-based construction materials: a review, J. Build. Eng. 28 (2020), 101052.
[28] B. Hilton, K. Bawden, K. Winnebeck, C. Chandrasiri, E. Ariyachandra, S. Peethamparan, The functional and environmental performance of mixed cathode ray tubes and recycled glass as partial replacement for cement in concrete, Resour. Conserv. Recycl. 151 (2019), 104451.
[29] P. Guo, W. Meng, H. Nassif, H. Gou, Y. Bao, New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure, Constr. Build. Mater. 257 (2020), 119579.
[30] A. Shayan, A. Xu, Performance of glass powder as a pozzolanic material in concrete: a field trial on concrete slabs, Cem. Concr. Res. 36 (3) (2006) 457–468.
[31] M. Ramadan, S.M.A. El-Gamal, F.A. Selim, Mechanical properties, radiation mitigation and fire resistance of OPC-recycled glass powder composites containing nanoparticles, Constr. Build. Mater. 251 (2020), 118703.
[32] M. Mirzahosseini, K.A. Riding, Effect of curing temperature and glass type on the pozzolanic reactivity of glass powder, Cem. Concr. Res. 58 (2014) 103–111.
[33] J.A. Jain, N. Neithalath, Chloride transport in fly ash and glass powder modified concretes – Influence of test methods on microstructure, Cem. Concr. Compos. 32 (2) (2010) 148–156.
[34] Y. Sharifi, I. Afshoon, Z. Firoozjaei, A. Momeni, Utilization of waste glass micro-particles in producing self-consolidating concrete mixtures, Int. J. Concr. Struct. Mater. 10 (3) (2016) 337–353.
[35] S.S. Hwang, C.M. Moreno Cortés, Properties of mortar and pervious concrete with co-utilization of coal fly ash and waste glass powder as partial cement replacements, Constr. Build. Mater. 270 (2021), 121415.
[36] S. Yang, J.-X. Lu, C.S. Poon, Recycling of waste glass in dry-mixed concrete blocks: evaluation of alkali-silica reaction (ASR) by accelerated laboratory tests and long-term field monitoring, Constr. Build. Mater. 262 (2020), 120865.
[37] K.L. Jain, G. Sancheti, L.K. Gupta, Durability performance of waste granite and glass powder added concrete, Constr. Build. Mater. 252 (2020), 119075.
[38] M. Saberian, J. Li, M. Boroujeni, D. Law, C.Q. Li, Application of demolition wastes mixed with crushed glass and crumb rubber in pavement base/subbase, Resour. Conserv. Recycl. 156 (2020), 104722.
[39] Z.C. Steyn, A.J. Babafemi, H. Fataar, R. Combrinck, Concrete containing waste recycled glass, plastic and rubber as sand replacement, Constr. Build. Mater. 269 (2021), 121242.
[40] M. Saberian, J. Li, D. Cameron, Effect of crushed glass on behavior of crushed recycled pavement materials together with crumb rubber for making a clean green base and subbase, J. Mater. Civ. Eng. 31 (7) (2019), 04019108.
[41] Ra.S. Nassar P., Field investigation of concrete incorporating milled waste glass, J. Solid Waste Technol. Manag. 37 (4) (2011) 307–319.
[42] P.S. Amirpasha Peyvandi, N. Roz-Ud-Din, Recycled Glass Concrete. Concrete International. 35(1).
[43] B. Taha, G. Nounu, Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors, Cem. Concr. Compos. 30 (6) (2008) 497–505.
[44] R. Idir, M. Cyr, A. Tagnit-Hamou, Pozzolanic properties of fine and coarse color-mixed glass cullet, Cem. Concr. Compos. 33 (1) (2011) 19–29.
[45] C1585-20, A, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, ASTM International, West Conshohocken, PA, 2020.
[46] S. Nunes, A.M. Matos, T. Duarte, H. Figueiras, J. Sousa-Coutinho, Mixture design of self-compacting glass mortar, Cem. Concr. Compos. 43 (2013) 1–11.
[47] (ASTM), A.S.f.T.a.M, ASTM C779 - Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces, ASTM, 2019.
[48] R.-U.-D. Nassar, Characteristics of recycled aggregate concrete produced with crushed stone sand as fine aggregate, Civ. Eng. Archit. 8 (4) (2020) 632–640.