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Waste glass powder as partial replacement of cement for sustainable concrete practice

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Abstract

Million tons of waste glass is being generated annually all over the world. Once the glass becomes a waste it is disposed as landfills, which is unsustainable as this does not decompose in the environment. Glass is principally composed of silica. Use of milled (ground) waste glass in concrete as partial replacement of cement could be an important step toward development of sustainable (environmentally friendly, energy-efficient and economical) infrastructure systems. When waste glass is milled down to micro size particles, it is expected to undergo pozzolanic reactions with cement hydrates, forming secondary Calcium Silicate Hydrate (C–S–H). In this research chemical properties of both clear and colored glass were evaluated. Chemical analysis of glass and cement samples was determined using X-ray fluorescence (XRF) technique and found minor differences in composition between clear and colored glasses. Flow and compressive strength tests on mortar and concrete were carried out by adding 0–25% ground glass in which water to binder (cement + glass) ratio is kept the same for all replacement levels. With increase in glass addition mortar flow was slightly increased while a minor effect on concrete workability was noted. To evaluate the packing and pozzolanic effects, further tests were also conducted with same mix details and 1% super plasticizing admixture dose (by weight of cement) and generally found an increase in compressive strength of mortars with admixture. As with mortar, concrete cube samples were prepared and tested for strength (until 1 year curing). The compressive strength test results indicated that recycled glass mortar and concrete gave better strength compared to control samples. A 20% replacement of cement with waste glass was found convincing considering cost and the environment.

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Keywords: Waste glass; Recycling; Supplementary cementitious material; Environment; Sustainability

1. Introduction

As of 2005, the total global waste glass production estimate was 130 Mt, in which the European Union, China

and USA produced approximately 33 Mt, 32 Mt and 20 Mt, respectively (IEA, 2007; Rashed, 2014). Being non-biodegradable in nature, glass disposal as landfill has environmental impacts and also could be expensive.

Sustainable construction practice means creation and responsible management of a healthy built environment considering resource efficiency and ecology (Plessis, 2007). Being versatile and economical, concrete became prime construction material over the world, however, it has impacts on the environment (Naik, 2008). Manufacturing

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of cement (key ingredient used for the production of concrete) is a major source of greenhouse gas emissions (Imbabi et al., 2012). The use of supplementary cementitious materials (SCMs) to offset a portion of the cement in concrete is a promising method for reducing the environmental impact from the industry. Several industrial by-products have been used successfully as SCMs, including silica fume (SF), ground granulated blast furnace slag (GGBS) and fly ash (Islam et al., 2011; Imbabi et al., 2012). These materials are used to create blended cements which can improve concrete durability, early and long term strength, workability and economy (Detwiler et al., 1996). Another material which has potential as a SCM, however, has not yet achieved the same commercial success is waste glass (Rashed, 2014). Researches indicated that glass has a chemical composition and phase comparable to traditional SCMs (Ryou et al., 2006; Binici et al., 2007; Nassar and Soroushian, 2012). It is abundant, can be of low economic value and is often land filled (Byars et al., 2003). Milling of glass to micro-meter scale particle size, for enhancing the reactions between glass and cement hydrates, can bring major energy, environmental and economic benefits when cement is partially replaced with milled waste glass for production of concrete (Rashed, 2014). Studies also focused on used of waste glass as aggregate in concrete production (Rashed, 2014; Taha and Nounu, 2009). Study on durability of concrete with waste glass pointed better performance against chloride permeability in long term but there is concern about alkali-silica reaction. Deleterious chemical constituents include sulfides, sulfates, and alkalis (which add more alkali to concrete) creates higher risk of ASR over the life of the concrete. A good pozzolan functions both to mitigate ASR and to consume the lime to greatly reduce efflorescence (Matos and Sousa-Coutinho, 2012; Rashed, 2014). Utilization of waste glass in ceramic and brick manufacturing process is discussed in a recent study (Andreola et al., 2016).

The properties influence the pozzolanic behavior of waste glass and most pozzolans in concrete, are fineness, chemical composition, and the pore solution present for reaction (Imbabi et al., 2012; Rashad, 2015). The pozzolanic properties of glass were first notable at particle sizes below approximately 300 μm , and below 100 μm , glass can have a pozzolanic reactivity at low cement replacement levels after 90 days of curing (Shi et al., 2005). This size can be achieved by using a grinding operation with the help of “Ball Mill” which is generally used in cement industry to grind cement clinker. Several researches show that, at the higher age recycled glass concrete (15% to 20% of cement replaced) with milled waste glass powder provides compressive strengths exceeding those of control concrete (Nassar and Soroushian, 2011). However, review study by Rashed (2014) showed that previous studies with glass addition were not conclusive considering workability and strength while the chloride resistance of glass added concrete was found to be similar with control condition. This research examined the potential of waste glass powder to produce

sustainable concrete. Experimental work was carried out on the performance of glass in mortar and concrete. Mortar samples were prepared to evaluate the flow and strength properties. Furthermore, compressive strength of concrete cube samples were also determined by crushing it. In addition, the study discussed the packing and pozzolanic effect of glass by using superplasticizer in selected mortar samples.

2. Materials and methods

2.1. Materials

CEM I of strength class 42.5N was used in this research. The percentage of clinker and gypsum in the cement was 95–100% and 0–5% respectively, while the specific gravity and fineness of OPC was found to be 3.15 and 99.3% (#200 sieve) according to ASTM C187 (ASTM, 2011) and ASTM C786 (ASTM, 2016d), respectively.

Specific gravity and fineness of clear and colored waste glass powders (prepared by ball mill) were 3.01 & 0.9% (#200 sieve) and 3.02 & 0.9% respectively as per ASTM standard mentioned above. Chemical composition of both glass powders were examined using a XRF-1800 Sequential X-ray fluorescence spectrometer. 20% binder was added to 80% glass powder to keep the material in position during test. Then the whole mixture was pressed using 140 kN pressing force. The chemical composition of glass powder is compared with other pozzolanic materials in the discussion. As the results of fineness, specific gravity and chemical composition test of color and clear glass powder were found similar, further experimental work with mortar and concrete was conducted with clear glass powder.

The fine aggregate used for the study was prepared according to graded sand requirements ASTM C778 (ASTM, 2013). Properties of fine aggregate are shown in Tables 1 and 2. For the flow test sand grading was prepared as per EN 196-1 (EN, 2005).

To evaluate the pozzolanic effect more clearly, mortar strength tests were carried out using superplasticizers. The water reducing admixture used in mortar work is based on polycarboxylate ether chemistry. Properties of admixture are given in Table 3. For concrete work the coarse aggregate size and amount was selected as per ASTM C33 (ASTM, 2016a). Physical properties of aggregates used in concrete work are shown in Table 4.

2.2. Flow test on mortar

The standard test method for flow of hydraulic cement mortar, determines how much a mortar sample flows when

Table 1
Physical properties of fine aggregate.

Bulk specific gravity (SSD)	2.55
Absorption capacity (%)	1.66
Fineness modulus (FM)	2.65
Field moisture content	0.68

Table 2
Grading of sand used for mortar compressive strength test (ASTM, 2013).

Sieve No.	Sieve opening (mm)	% Cumulative pass
16	1.19	100
30	0.60	75
50	0.3	25
100	0.15	0

Table 3
Properties of admixture.

Aspect	Light brown liquid
Relative density	1.08 ± 0.01 at 25 °C
pH	≥6
Chloride ion content	<0.2%
Expected water reduction	>20%
Conforming standards	ASTM C-494, EN 934-2

it is unconfined and consolidated. Mortar is placed inside 2-inch high conical brass mold. The top and bottom diameter of the mold was 2.75 inch and 4 inch respectively. After filling, compacting and removing the mold, the mortar is vibrated at 1.67 Hz as the flow table rises and drops ½ inch, 25 times in 15 seconds. The mortar changes from a 4-inch conical shape to a “pancake”. The change in diameter of the mortar was measured and expressed in mm as per ASTM C1437 (ASTM, 2015b). Experimental set up for flow test is shown in Fig. 1. A constant water to binder ratio (0.5) was used with different glass contents in mortars.

2.3. Strength evaluation

2.3.1. Mix details and preparation of mortar

As with flow, test on mortar is also carried out for compressive strength. The mass ratio of sand to (cement + glass powder) was fixed at 2.75 according to ASTM C109 (ASTM, 2016c) for all batches. A water binder ratio of 0.485 was used and kept constant for every mixes. The mix proportion for the mortar is given in Table 5. The same mix details was used for the preparation of mortar with superplasticizing admixture (1% by weight of cement). As the flow test results with different levels of glass addition did not give any significant difference, the water to binder ratio for mortar with admixture remained unchanged. The mortar was prepared and placed in the 50 × 50 × 50 mm steel mold as per ASTM C109 (ASTM, 2016c). Material within the mold is kept in a moist condition for 24 h and then after demolding the specimens were placed in curing tank. After a specified period of curing, strength test of the specimens was conducted shortly after taking those out from storage water as per ASTM C109.

Table 4
Physical properties of coarse aggregate.

Bulk specific gravity (SSD)	2.67
Absorption capacity (%)	1.21
Dry rodded unit weight (kg/m ³)	1560
Moisture content (%)	0.92

2.3.2. Concrete mix proportion and preparation

Trial mix design were conducted to obtain the target strength of 35 MPa at 28 days with a workability of 100–125 mm as per American Concrete Institute ACI 211.1 (ACI, 2009). The glass powder replacement in cement was varied (0–25%). Mix proportion of concrete is shown in Table 6. Firstly, stone chips and sand were dry mixed for a minute. Appropriate quantity of glass powder was blended with cement in a separate container and then incorporated into the aggregate matrix (mixed earlier). Measured quantity of water was added to the matrix and thoroughly mixed for 5 more minutes. After mixing, workability of the concrete was determined using slump test. It was confirmed that the slump values of concrete at different glass replacement level remained within the target slump range of 100–125 mm without changing the water content. The concrete was placed, compacted and surface finished with a smooth steel trowel in cube mold. The material was kept within the mold for 24-h in moist condition before demolding. After demolding the concrete was placed under fresh curing water in tank for specified period before testing. No admixtures was used in concrete compressive strength tests.

2.3.3. Compressive strength test

The compressive strength of a material is the uni-axial compressive stress reached when the material fails completely. A set of three cubes were tested in each case and the average value of these three was reported. Compressive strength test of mortar and concrete were done as per ASTM C109 (ASTM, 2016c) and ASTM C39 (ASTM, 2016b). Experimental set up for compression tests in mortar and concrete are shown in Fig. 2. Ultimate load is noted for each specimen. Compressive loading for mortar and concrete was maintained as 900–1800 N/s and 20–50 psi/s. Both mortar and concrete samples were tested for compressive strength at 7, 14, 28, 56, 90, 180 and 365 days.

3. Result and discussion

3.1. Chemical composition of glass powder and cement

The chemical composition of glass powder samples (clear and colored) are determined using a XRF technique. The results obtained are compared with other pozzolanic materials in Table 7. According to ASTM C618 (ASTM, 2015a), (SiO₂ + Al₂O₃ + Fe₂O₃)’s minimum requirement for a standard pozzolana is 70% which is comparable with the results obtained for the waste glass samples. The standard also sets maximum limit of SO₃, Loss on Ignition (LoI) and Moisture content as 4%, 10% and 3% respectively. As shown in Table 7, the SO₃ contents of the glass samples were found well below the acceptable limit and LoI and moisture content was negligible. Therefore, the glass powder samples are expected to show pozzolanic behavior in cementitious system.



Figure 1. (a) Mortar sample in brass mold, and (b) mortar sample turned to pancake shape.

Table 5
Mix details of mortars used for compressive strength test.

Specimen details	Cement	Glass powder	Sand	Water
Control sample (0% Glass powder)	300 g	0 g	#30	206 g
			#50	413 g
			#100	206 g
10% Glass powder	270 g	30 g	Do	Do
15% Glass powder	255 g	45 g	Do	Do
20% Glass powder	240 g	60 g	Do	Do
25% Glass powder	225 g	75 g	Do	Do

Table 6
Mix proportions of concrete used in experimental work.

Materials	Quantity
Water	215 kg
Cement or (cement + glass powder)	445 kg
Fine aggregate (SSD)	625 kg
Coarse aggregate (SSD)	1005 kg

Minor compounds such as BaO, PbO, As₂O₃, TiO₂, ZrO₂, Cr₂O₃, MnO, CuO, NiO are also found in glass samples under consideration, however, the amount of individual component was not more than 0.5%. As given in Table 7, difference in quantities of individual compounds between clear and colored glass powder is minor. Therefore, further experimental work with mortar and concrete were conducted with clear glass power only.

3.2. Mortar work

3.2.1. Flow test

As per EN 196-1 (EN, 2005), a constant water to binder ratio (0.5) was maintained for preparing mortar samples for the flow tests. Minor increase in mortar flow was achieved with amount of cement replaced with glass powder as shown in Fig. 3. The increase in mortar flow with the addition of glass powder might be the effect of glass material which is cleaner in nature. Review by Rashed (2014) showed that previous studies indicated increase in workability with glass addition. As there was minor difference between the flow results at different glass replacement levels, it is expected that the flow with admixture will give similar trend. However, there should be a vertical shift between flow with and without admixture.

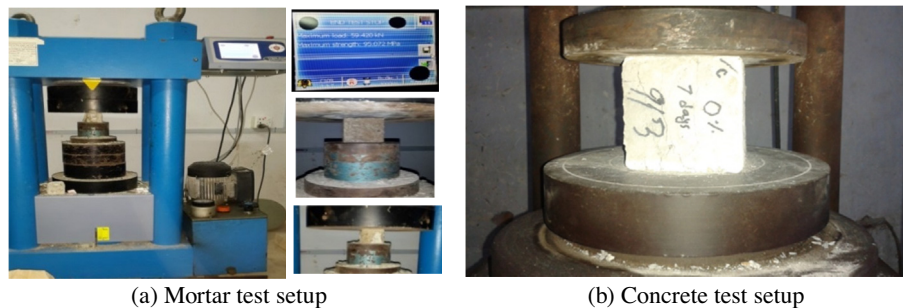


Figure 2. Compressive strength test.

Table 7

Chemical composition of waste glass samples, OPC and other reference pozzolanas.

Compound	Clear glass powder	Color glass powder	OPC	Waste glass ^a	Slag ^b	Silica fume ^c	Fly ash ^d
SiO ₂	68.1	68.7	22.8	68	35	90.9	59.2
Al ₂ O ₃	0.9	1.0	5.9	7	12	1.1	25.6
Fe ₂ O ₃	0.6	0.9	3.5	<1	1	1.5	2.9
CaO	14.5	12.0	63.0	11	40	0.7	1.1
MgO	1.8	1.8	1.5	<1	–	0.8	0.3
K ₂ O	0.8	1.0	1.0	<1	–	–	0.9
Na ₂ O	12.2	13.3	0.1	12	0.3	–	0.2
SO ₃	0.4	0.1	2.0	–	9.0	0.4	0.3
LOI	–	–	1.5	–	1.0	3.0	1.4
Moisture	–	–	–	–	–	–	–

^a Nassar and Soroushian (2012).^b Warren and Reardon (1994).^c Binici et al. (2007).^d Islam et al. (2011).

3.2.2. Compressive strength with age

Compressive strengths with the addition of recycled glass in mortars at different ages are given in Fig. 4. Lower mean compressive strengths, compared to the control mortar (0% glass replacement) were obtained at 7, 14, 28 and 56 days age. Except 25% glass addition, all other cement replaced mortars' mean compressive strength exceeded that of control mortar at 90 days. The results agree with the earlier field investigation by Nassar and Soroushian (2011). Review by Rashed (2014) indicated that overall there is a contradiction; some reported strength increment while other reported decrease in strength. The current study at 90 days, 10% cement replacement level gave the greatest compressive strength in mortar.

Similar trend was observed at the age of 180 days, however, 15% cement replacement gave the greatest compressive strength among the glass added mortars. However, the increase in compressive strength of recycled glass mortars compared to the control mortars both at 90 and 180 days were found statistically insignificant. As with 90 days test 365 days mortar specimen gave maximum compressive strength with 20% waste glass addition which is 8% higher than the control mortar without glass.

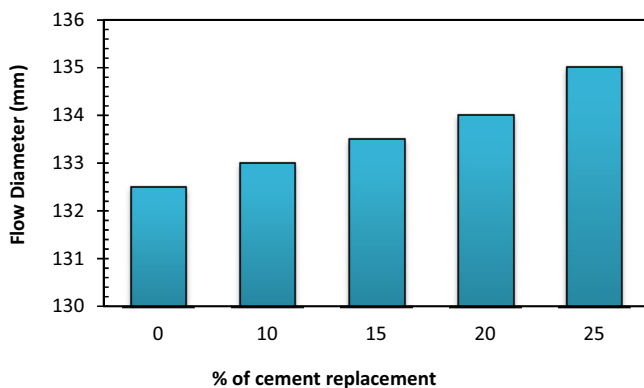


Figure 3. Glass quantity vs flow in cement mortar.

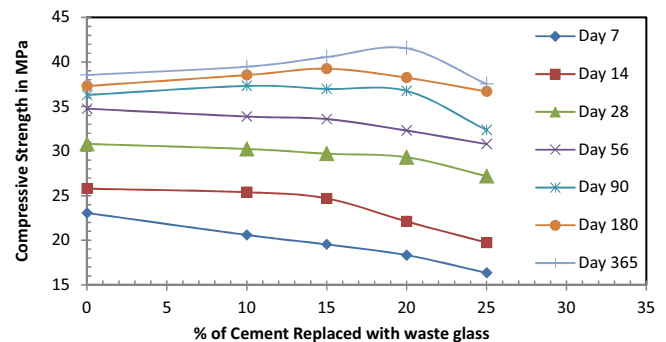


Figure 4. Compressive strength of mortar specimen without admixture.

3.2.3. Effect of admixture on compressive strength

Fig. 5 shows effect of admixture on compressive strengths of glass added mortars (0–25% addition) at various ages. Early age i.e. in 7 and 14 days compressive strength of mortar specimens are shown in figures (a) and (b) which clearly depicts the positive effect of admixture on compressive strength of mortar. Though the trend of compressive strength was decreasing with addition of glass powder, use of admixture always gave higher compressive strength at early ages. For control mortars adding 1% admixture dose gave compressive strength as high as 43% and 35% at 7 and 14 days, respectively. With the addition of glass the difference in compressive strength became lower at these ages. This indicates that the super-plasticizing effect on ground glass is lower compared to the Portland cement as cement starts diluting and reacting as soon as water is added to the mix but glass requires longer period to start pozzolanic reaction (Islam et al., 2011).

Similar trends were obtained among the compressive strengths at 28, 56 and 90 days (Figures c, d and e). The effect of admixture became less significant than previous ages. However, a different behavior was noted for control concrete compared to the glass added concrete. With the increase in glass content the difference between compressive strengths decreased and the difference was

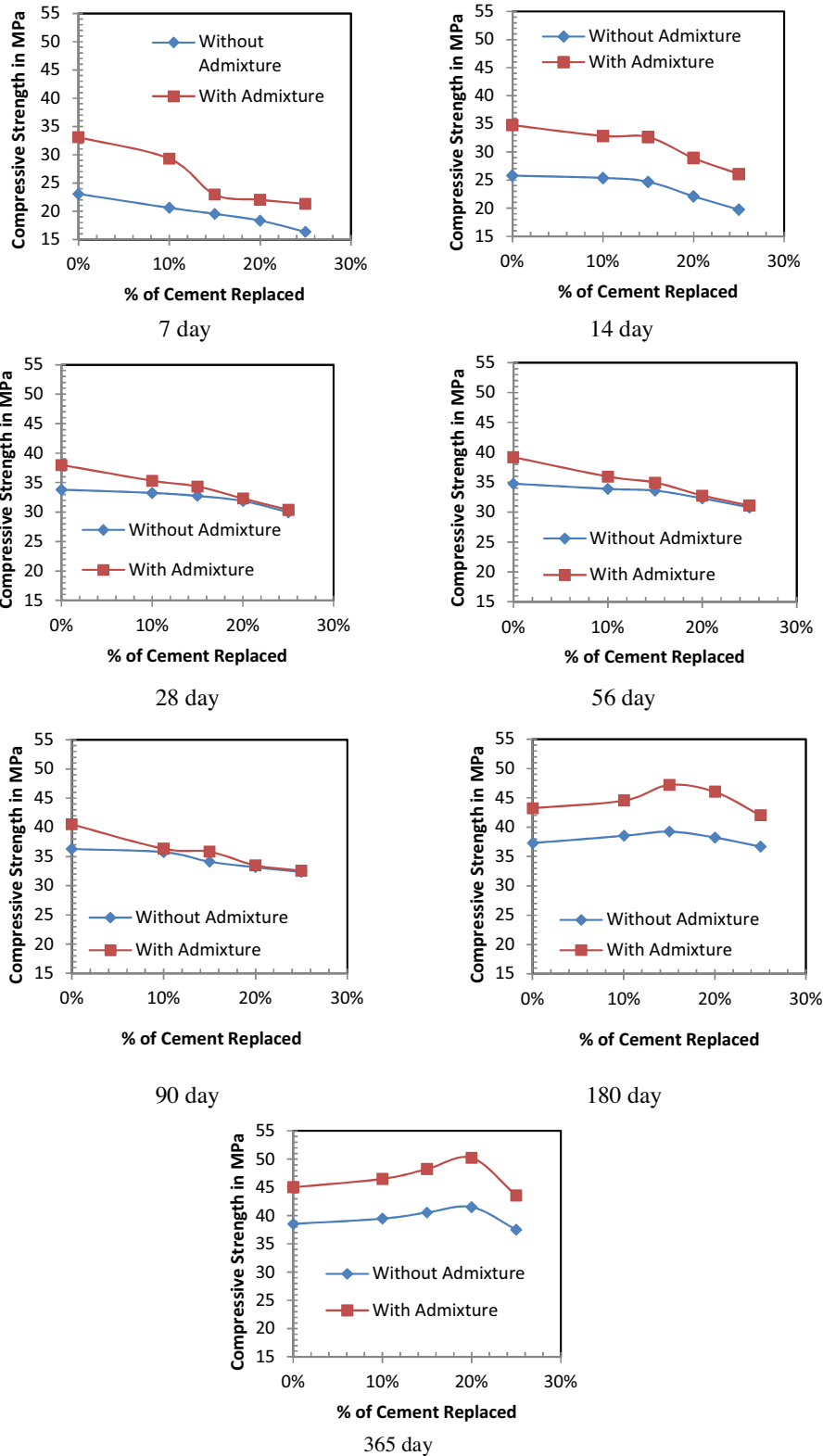


Figure 5. Effect of admixture on compressive strength of glass added mortar specimens.

almost eliminated at 25% replacement level. This indicates progression of pozzolanic reaction at this ages as the compressive strength is combined effect of packing (compaction), cement hydration and pozzolanic reaction

(Tangpagasit et al., 2005). At earlier ages very little/no pozzolanic reaction occurs and thus only effect of superplasticizer are visible and the packing effect gave higher compressive strength of mortar.

The effects of admixtures at 180 and 365 days shown in Fig. 5(f) and (g) are similar to those of early age effects shown in figures (a) and (b). The effect of admixture and therefore, difference in compressive strength was within a narrow band of 14–20% at 180 days and that was 16–21% at 365 days. It is expected that pozzolanic reaction would mostly occur in between 28 and 91 days (Omran and Tagnit-Hamou, 2016). Therefore, only the effect of admixture, i.e. packing is visible again at latter ages (180 and 365 days).

3.3. Concrete compressive strength

For compressive strength test concrete samples was prepared without any admixture. Compressive strengths of recycled glass concrete (0–25% glass addition) at different ages are shown in Fig. 6. Target compressive strength of 35 MPa at 28 days was achieved for all samples up to 0–20% glass addition while that for 25% addition was slightly lower. With the addition of glass, lower mean compressive strengths compared to the control concrete (0% glass) are obtained at 7, 14, 28 and 56 days age. With further progression of reaction at the age of 90 days, recycled glass concretes with 10, 15 and 20% glass addition provided mean compressive strengths exceeding the control concrete and 10% cement replacement gave the highest value among them. 25% glass addition gave slightly lower (approximately 2%) compressive strength than control concrete.

Except 10% glass addition, 90 day test results indicated that the differences in compressive strengths between recycled glass and control concretes were not significant. This indicate the optimum reaction period of glass replaced concrete (Nassar and Soroushian, 2011; Omran and Tagnit-Hamou, 2016).

The difference in compressive strength between the control and 25% glass replaced concrete at 180 and 365 days were further reduced and provided similar mean compressive strengths. At these stage 10, 15 and 25% cement replacement gave higher compressive strength than the control concrete while compressive strength with 20% cement replacement was found to be greatest. At 180 and 365 days the 20% glass added concrete gave 10% and 14% higher strengths respectively than control concrete.

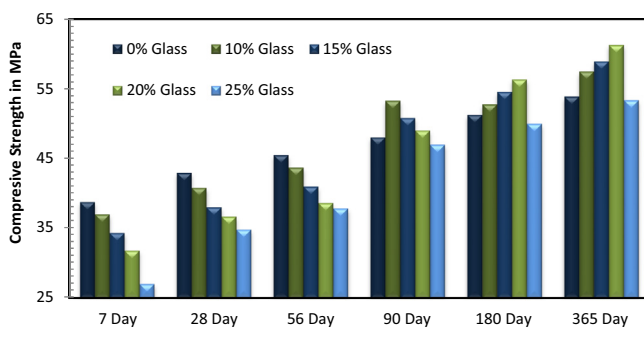


Figure 6. Compressive strength of concrete specimens at different age and glass replacement level.

The results show that compressive strength gain in glass added concrete occurs at a lower rate than that in controlled concrete, but in long-term recycled glass concrete has the potential to exceed control concrete strength (Nassar and Soroushian, 2011).

3.4. Environmental and financial considerations

There is an impetus to use industrial by-products/waste material in construction industry to achieve sustainability in this sector. One ton cement manufacturing results in emission of 0.9 ton of carbon dioxide (CO₂) to the atmosphere. Cement production also involves emission of moderate quantities of NO_x, SO_x, and particulates (Cattaneo, 2008). Recycling of each ton of glass saves over one ton of natural resources. Waste glass is not bio-degradable and therefore, rational consideration for alternative utilization dictates a diversion of the material away from landfill disposal sites. Utilization of waste glass in concrete production not only provides significant environmental benefits but also enhances performance of the concrete (both mechanical and durability performance) when used at optimum quantity (Joshi and Lohtia, 1997). From the test results and decision it was concluded that up to 20% glass powder addition could be beneficial considering compressive strength (EN 450 suggests to evaluate pozzolanic activity up to 90 day; EN, 2005). In local market of Bangladesh the price of waste glass is approximately 2 BDT/kg. In addition, after processing and grinding the total cost of glass powder might be increased up to 2.5 BDT/kg. Therefore, considering price of a 50-kg cement bag as 450 BDT, replacing 10 and 20% cement by glass powder can reduce its price by 7% and 14% respectively. Fig. 7 gives cost and compressive strength comparison.

From the compressive strength test results in mortar and concrete at 90 days, the optimum glass content was found to be 20% for which compressive strength was 2% higher than the control concrete. Therefore, as shown in Fig. 7, with addition of 20% glass in cement will save 14% cost of construction from cement itself. At the same time replacing 20% cement will reduce production and release of 18% CO₂ in the environment. Considerable amount of

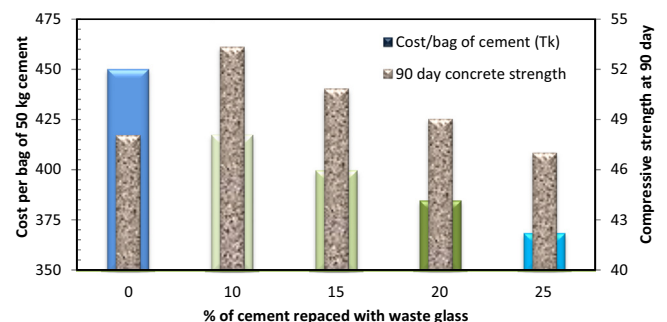


Figure 7. Cost of glass blended cement and compressive strength.

NO_x, SO_x, and particulates will also be reduced with this CO₂ emission reduction.

4. Conclusion

The chemical composition of clear and colored glass powders are very similar and the materials could be declared as pozzolanic material as per ASTM standard. Being cleaner in nature, the flow of glass replaced mortar was found to be increased slightly with glass powder content. The optimum glass content is 20% considering mortar and concrete compressive strength at 90 days. In this age the compressive strength was found slightly higher (2%) than the control concrete specimen. In general, considering the similar performance with replaced material, glass addition can reduce cost of cement production up to 14%. In addition, production of every six ton glass powder concrete results in the reduction of each ton CO₂ emission from cement production and save the environment significantly by reducing green-house gas and particulate production. Generally, the high surface area of milled waste glass changes the kinetics of chemical reaction toward beneficial pozzolanic reaction utilizing the available alkalis before production of a potential ASR gel. However, further research on durability and ASR aspects of glass replaced concrete is required to suggest this material for sustainable concrete practice.

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