

## Development of Environment-Friendly Concrete through Partial Addition of Waste Glass Powder (WGP) as Cement Replacement

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### Abstract

This paper presents the study carried out on the utilization of Waste Glass Powder (WGP) as supplementary cementitious material in concrete. The evaluation of the influence of WGP on the mechanical properties of concrete was carried out by casting and testing of concrete samples as per ASTM standards (cylinders and beam elements). The control samples were designed to represent field conditions with a target compressive strength of 20,000 kPa. The Portland cement in concrete was substituted with WGP in proportions of 0%-35% by weight, in increments of 5%. Two curing domains were adopted in the preparation of the test samples to evaluate the effect of pozzolanic material wherein the tested samples were cured for 28, 56, and 84 days. The study results indicated a reduction in compressive strength of concrete up to 10% with partial replacement of cement with 25% of WGP when standard curing of 28 days was adopted. Furthermore, with the same replacement proportion and prolonged curing for 84 days, the gap in strength reduction was reduced by 5%. However, a significant decrease in workability was noted between the control concrete samples and glass powder infused concrete. Furthermore, the Waste Glass Powder Concrete (WGPC) exhibited an improved flexural strength with the modulus of rupture for WGPC being 2% higher than control concrete at the age of 84 days. Based on the results of this study it was concluded that 25% replacement of cement with WGP provides an optimum replacement ratio.

*Keywords:* Supplementary Cementitious Materials; Waste Glass Powder; Pozzolanic; Prolong Curing; Recycling; Green Concrete.

### 1. Introduction

The construction industry has experienced a boom in wake of the development of concrete as a construction material. One of the major advantages of concrete as a construction material is the versatility with which it can be adapted to different construction scenarios. However, the manufacture of the conventional binding agent in concrete (cement) has a negative impact on the environment. It is estimated that cement production contributes approximately 7% of the overall carbon footprint [1, 2]. This has consequently led researchers to explore waste materials which can be used as partial replacement of cement. However, it is imperative that the waste material used as replacement of cement does not affect the mechanical properties of concrete beyond an acceptable level. Several studies have been carried out to this effect, where a number of materials such as bagasse ash, marble powder, silica fume, and fly ash, etc. have been used to replace a portion of cement in concrete [2-5]. These materials, in general, have demonstrated

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pozzolanic properties and exhibited acceptable mechanical behavior, hence a significant amount of attention has been given to these materials by researchers in recent times. Waste glass (WG) is one such material that has shown promise as a non-conventional cementitious material for use in concrete [5-11].

The ability of a material to be recycled is dependent upon its potential to preserve its chemical composition and crystalline structure. Typical replacement materials that have been studied such as rice husk, silica fume and fly ash, etc. are prone to chemical and structural changes when recycled. Glass, on the other hand, is known to experience minute changes in its chemical composition after being recycled [12]. The possible utilization of WG in ordinary concrete has been studied by a number of researchers [12-19]. Crushed WG has been recycled for ornamental concrete, and literature reports the WG employed as coarse aggregate in the batching of the conventional concrete. The incorporation of WG as an aggregate has shown a reduction in the workability, compressive ( $f_c'$ ), and tensile strengths [20]. WGP shows promise as an SCM given the high quantity of silica content present in it [7]. As an amorphous material, glass has a high content of silica which renders it a pozzolanic material provided that its particle size can be maintained at 75  $\mu\text{m}$  or less. Results of the study conducted by Du and Tan have concluded that finely milled WG does not contribute to the alkali-silica reaction [17]. The effect of the use of pozzolanic materials on the durability of concrete has been established [21]. Glass powder has demonstrated pozzolanic properties under various curing temperatures [13] hence encouraging researchers to explore its use as an SCM.

As mentioned earlier, several studies have been conducted to explore the utilization of WGP as an SCM/pozzolanic material. However, these studies have been focused on the use of a certain type of glass, having a particular chemical composition and crystalline structure, such as Soda-lime silica, Boro-silicate, Lead crystal, and Aluminosilicate, to name a few [references]. The use of a particular type of glass will have serious implications on the industrial application of glass infused concrete. This study, on the other hand, utilizes the generally available WG consisting of different types of glasses that have been ground without sorting. Furthermore, the earlier studies on the utilization of waste glass powder have been limited to evaluating the mechanical properties of glass powder concrete at the standard age of 28 days, as recommended by ASTM [22]. However, the pozzolanic materials have been known to contribute to mechanical properties when cured for a prolonged period of time since the pozzolanic activity is influenced by the presence or absence of water, affecting the density of the concrete and consequently resulting in improved mechanical behaviour [23]. This study has been carried on concrete samples that have been evaluated for their mechanical properties when cured for a short-term, standard duration, and prolonged periods.

## 2. Material Characterization

The WGP was partially substituted within the limit of 10 to 35 percent of ordinary Portland cement (OPC) by weight and mix design has been carried up for each mix. American Concrete Institute (ACI) Absolute Volume Method (ACI 211.1-91) of Concrete Mix Design was used to develop the mix design. The following are the material details used in this study.

### 2.1. Cement

The cement that was used was manufactured by the Cherat cement factory. The cement complies with the requirements of ASTM C150 [25]. It comprises of 95% clinker. The coarse aggregate utilized in the current experimental program came from a local quarry of "Margalla Hills". The bulk specific gravity, bulk specific gravity (in saturated surface dry condition), and water absorption (%) was calculated as per ASTM C127 [26] and were found to be 2.641, 2.67, and 1.03, respectively. The chemical properties of cement are reported in Table 1.

Table 1. Chemical Properties of Cement

S/N	Property	ASTM C-150 Standard Specification for Portland Cement 2011	Manufacturers: (Cherat Cement)
1	Soundness (mm)	<10	2.1
2	Fineness	<10	7
3	Insoluble Residue( I. R) %	0.75 (Max)	0
4	Loss on Ignition (LOI) %	3 (Max)	2.1
5	Magnesium Oxide (MgO) %	6 (Max)	1
6	Sulphuric Anhydride (SO <sub>3</sub> )	3.5 (Max)	2

### 2.2. Coarse Aggregate

The nominal maximum size of coarse aggregate (inch) was  $\frac{3}{4}$  inch down, the value was calculated using ASTM C136 [27]. The unit weight of the aggregate was calculated in accordance with ASTM C29 [28] and was found to be 100.09 lb/ft<sup>3</sup>. Various tests were performed on coarse aggregate conformed to specifications of ASTM standards are reported in Table 2 and Figure 1.

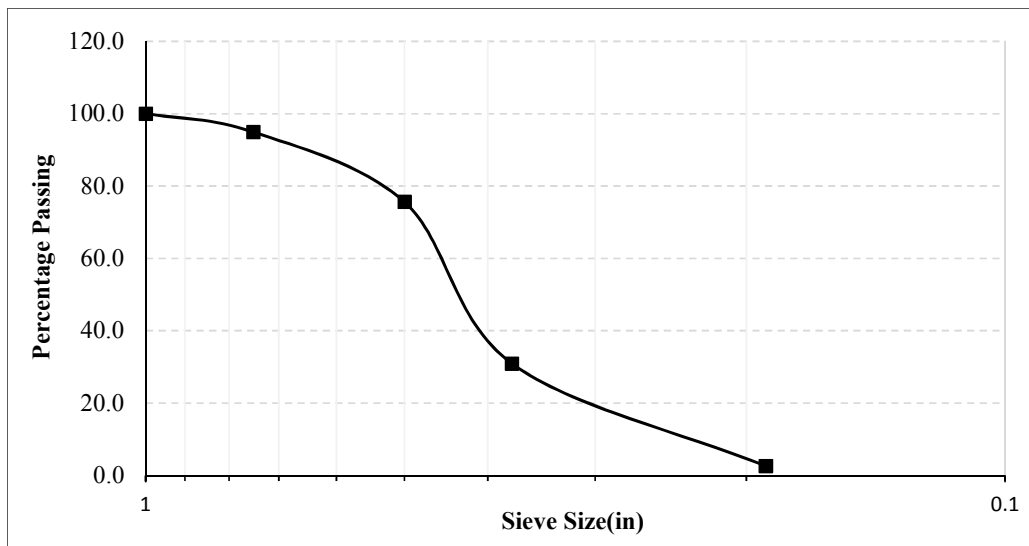


Figure 1. Coarse Aggregate gradation curves

Table 2. Physical properties of coarse aggregate

Description	ASTM Standard	Value
Bulk Specific Gravity	ASTM C127	2.65
Bulk Specific Gravity (S.S.D)	ASTM C127	2.66
Water Absorption (%)	ASTM C127	1.04
Available Moisture Content (%)	ASTM C566	1.01
Rodded Unit Weight (lb/ft <sup>3</sup> )	ASTM C29	100.1
Nominal max. Size of Coarse Aggregate (inch)	ASTM C136	3/4

### 2.3. Fine Aggregate

The sand was from a local source of Lawrencepur, located in Pakistan. The sand fineness modulus was calculated to 2.51 as per ASTM C136 [27]. The available moisture absorption (%), available moisture content (%), bulk specific gravity (g/cc), and apparent specific gravity (g/cc) were calculated using ASTM C127 [29] and was found to be 1.46, 1.09, 2.639 and 2.703 respectively. To check the sand for organic impurities the sand was tested and it observed lighter color when compared with the standard solution prepared as per ASTM C87 [30]. The gradation curves and physical properties of sand are shown in Figure 2 and Table 3, respectively.

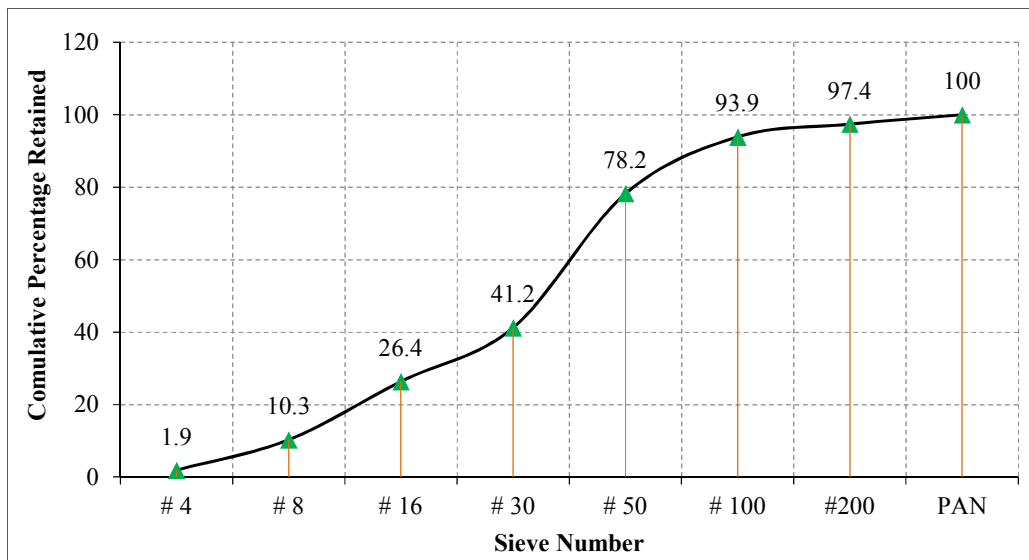


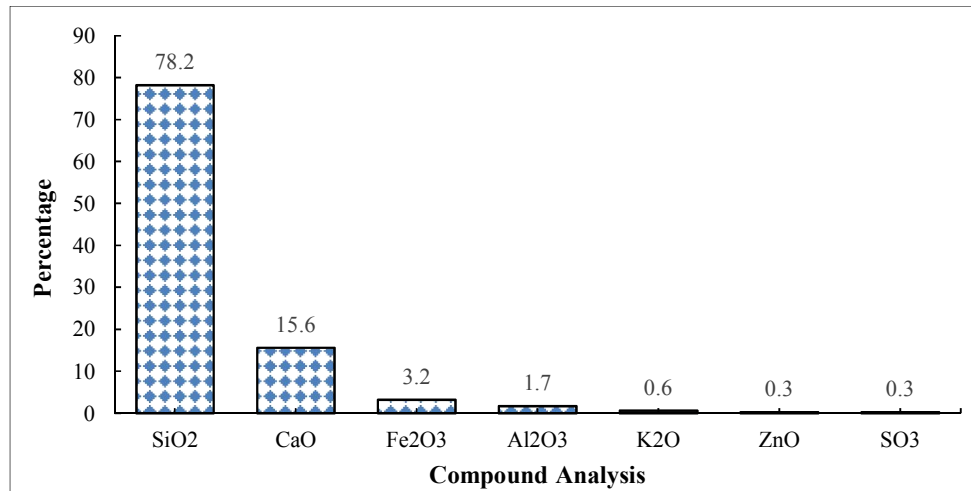
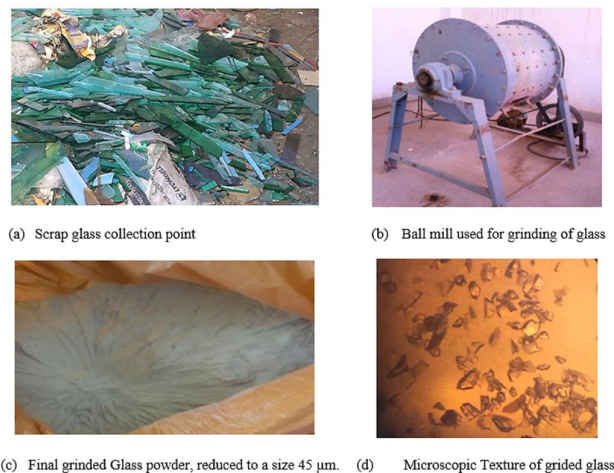
Figure 2. Fine Aggregate Gradation Curves

**Table 3. Properties of Lawrencepur Sand**

Description	ASTM Standard	Value
Moisture Absorption (%)	ASTM C128	1.45
Moisture Content (%)	ASTM C128	1.08
Bulk Specific Gravity (oven dry) (g/cc)	ASTM C128	2.60
Bulk Specific Gravity (SSD)(g/cc)	ASTM C128	2.63
Apparent Specific Gravity(g/cc)	ASTM C128	2.70
Fineness Modulus	ASTM C136	2.52
Organic Impurities	ASTM C87	Lighter Colour than standard

#### 2.4. Waste Glass Powder

In this study, cement was replaced with WGP having a fragment size of less than 45  $\mu\text{m}$ . The locally available waste glass was collected from scrap dealers (Figure 4a) and ground with the help of a ball mill (Figure 4b) to get the desired particle size i.e. less than 45  $\mu\text{m}$  [17] as shown in Figure 4c. After grinding of the glass, the WGP was checked under the microscope to analyze its texture, the microscopic images of the powder showed that the powder was in the form of an angular broken glass piece (Figure 4d). To examine the chemical composition of the WGP, X-Ray Fluorescence (XRF) was performed and its results are shown in Figure 3. The presence of  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{Al}_2\text{O}_3$  in large amounts indicates that the material has some pozzolanic properties due to which it can be used as a partial replacement of cement in concrete [24]. Moreover, the presence of these chemical compounds is also indicative of the ability of WGPC in gaining strength.

**Figure 3. Chemical analysis of waste glass powder**

**Figure 4. Various Stages of Glass Powder Preparation: (a) Showing the waste glass collection site; (b) The grinding equipment Used for grinding the WG to the required size; (c) The WGP having a size less than 45  $\mu\text{m}$ ; (d) The microscopic image of the glass powder showing its texture.**

## 2.5. Water

The water consumed for concrete batching and curing was clean and portable. All standards of ASTM 1602 [31] were taken into consideration while selecting the source of water.

## 2.6. Concrete Mixtures Configuration

The concrete mix ratio of the control concrete mixture was 1:2:2.61 by weight of OPC, fine aggregate, and coarse aggregate, respectively. The estimated quantity of OPC come about 375 kg/m<sup>3</sup>. WGPC samples were batched by substitution of cement with 0% to 35% by weight of the glass powder with 5% increments in the quantity of waste glass powder. Table 4 reports the mix design for each type of mix used in this research. Standard cylinders specimen and beams were produced for every mix proportion for subsequent testing under compression and in tension

**Table 4. Mix design specifications (for 1 m<sup>3</sup> of concrete)**

Material	CM** (0%)	MWG***-10 (10%)	MWG-15 (15%)	MWG-20 (20%)	MWG-25 (25%)	MWG-30 (30%)	MWG-35 (35%)
Cement, (kg)	375	337.5	318.7	300	218.2	262.5	243.75
Fine Aggregate, (kg)	761	761	761	761	761	761	761
Coarse Aggregate, (kg)	979	979	979	979	979	979	979
Water, (kg)	206	206	206	206	206	206	206
Glass Powder, (kg)	0	37.5	56.3	75	93.8	112.5	131.25

\* Water to Cement Ratio (w/c) = 0.55 was used for all Mix  
 \*\*Control Mix- CM  
 \*\*\* Mix having Waste Glass-MWG

## 2.7. Tests on Concrete in the Fresh State

### 2.7.1. Workability

A slump test was performed at the site for all the concrete mixes according to ASTM-C143 [32], their results are presented in Table 5. A clear decrease was observed in a slump from test results which shows that the addition of WGP considerably changed the slump of concrete. The workability level is assessed by the extent of slump value achieved; hence, a more quantity of water is needed to achieve a comparable extent of workability like that of the CM. The reason for this is the greater surface area and angular shape of the WGP particles [8] (Figure 4d). It was observed that, besides the reduction of the workability, the bleeding in the concrete amplified with the rise in the WGP percentage. It remained due to the fundamental smooth surface of WGP, due to which very little amount was entrapped at the surface of WGP, which resulted in the reduction in the cohesive forces in the varying mixes of concrete which in turn resulted in the bleeding of the concrete. With the incorporation of 35 % WGP in the concrete mix, there was a 90% reduction in workability was observed.

**Table 5. Slump values for the fresh concrete**

Mix Designation	Slump (mm)
CM	109.22
MWG-10	99.06
MWG-15	88.9
MWG-20	76.2
MWG-25	45.72
MWG-30	40.64
MWG-35	10.16

### 2.7.2. Normal Consistency Test

The normal consistency of the cement past and other WGP mix were evaluated with the help of ASTM C187 [33]. The result of the test is shown in Figure 5. The WGP-cement mix requires more quantity of water to reach its normal consistency level. The incorporation of WGP powder up to 10 % does not affect the consistency of the cement paste. With the increase of incorporation of WGP by 15%, the water demand increases by 1% percent to reach the normal consistency of the paste. With the increase in the WGP by 20% to 35% the water requirement for normal consistency increase by 2, 2.5, 3.5 and 5 % respectively.

### 2.7.3. Initial and Final Setting Time

To analyze the influence of WGP on the initial and final setting times of the cement paste, the test was conducted as per ASTM C191 [34]. The result of the test is shown in Figure 6. The cement used under the research program showed the initial and final setting time of 157 and 283 minutes, respectively. The incorporation of WGP in the cement paste within the percentage of 10 to 35 percent there was a trend of delay in the initial and final setting time was observed. At 35% replacement, the initial setting time and final setting time showed a delayed by 43 minutes each.

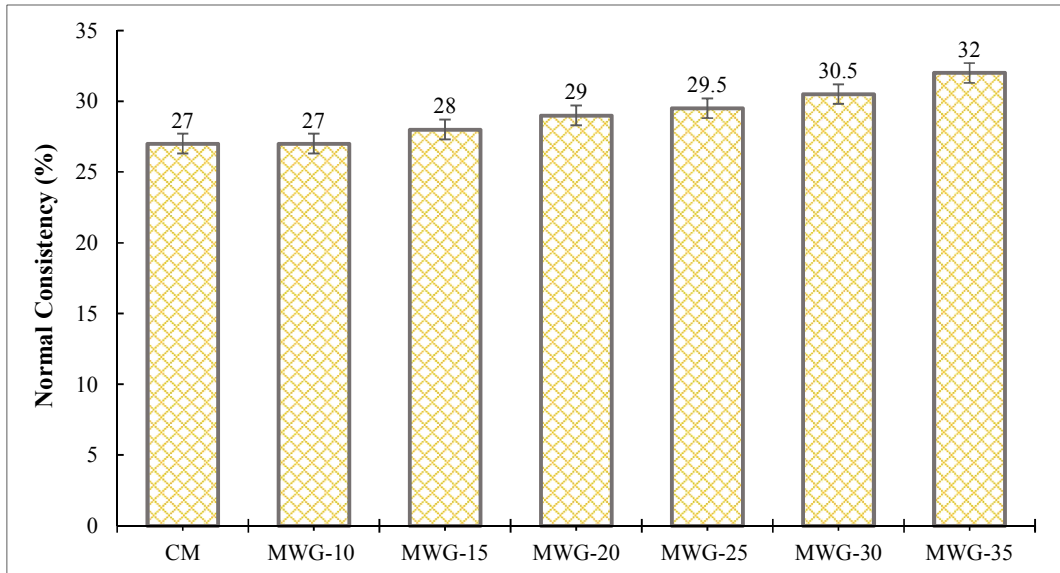


Figure 5. Normal Consistency of mix with the variation of WGP percentages

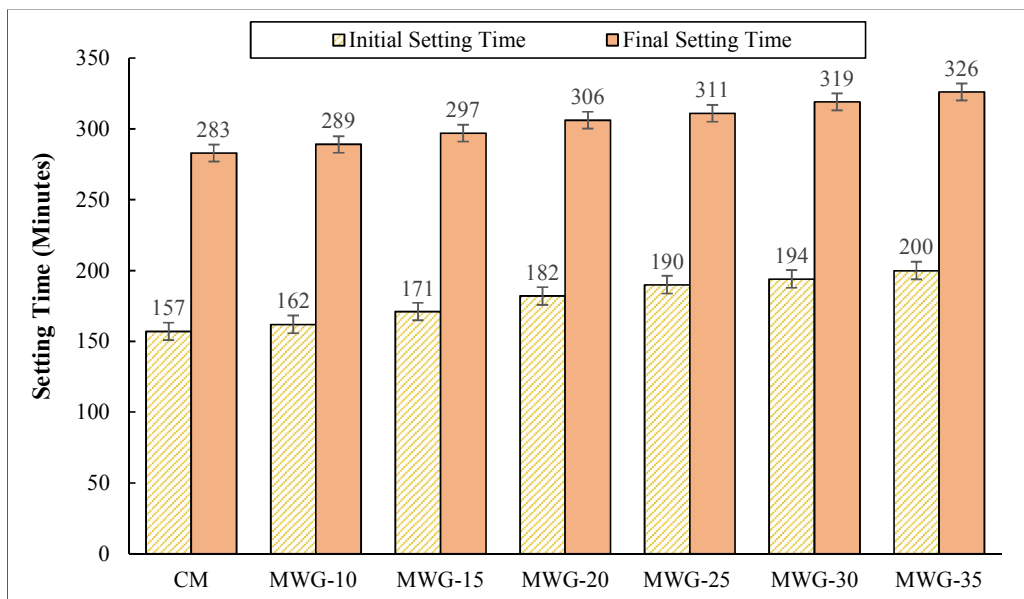


Figure 6. Initial and final setting time of cement paste with the variation of WGP percentages

## 2.8. Concrete Hardened State Properties

### 2.8.1. Unit Weight of Concrete

Concrete cylinder specimens were cast and cured for 28 days as per ASTM C192 [22]. The unit weight of these specimens was determined. The results shown are shown in Figure 7, which indicates a reduction of unit weight of concrete, with the increase in WGP. When compared with the traditional concrete, the unit weight of the MWG-35 decreased by up to 2%. The normal unit weight of concrete is approximately equal to 2,400 kg per cubic meter. The concrete density varies reliant on numerous factors, the quantity and density of the aggregate, how much air is entrapped or purposely entrained, the cement concentration, and the maximum size of aggregate used. The density of



the concrete that was produced was the same as that of normal concrete with some minor decrease and increase but the average value observed was between 2350 kg/m<sup>3</sup>.

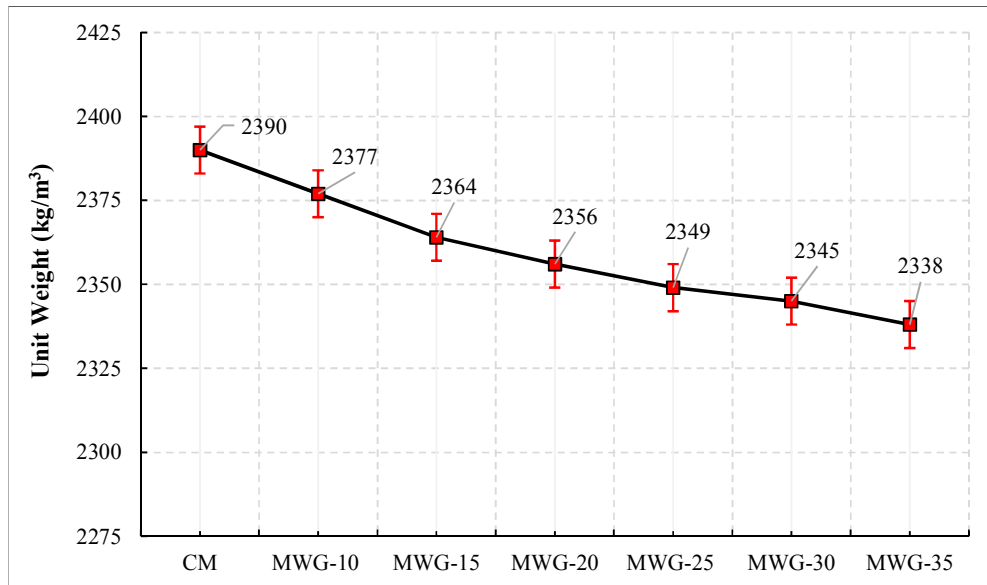


Figure 7. Unit Weight of Concrete at 28 days of Curing

### 2.8.2. Compressive Strength Sample Description & Testing Protocol

For the compressive strength ( $f_c'$ ), samples were cured for 28 days while being submerged in a tank of portable water confirming to ASTM standard. The capping of each cylinder was done as per ASTM C617 [35] before the compressive test (Figure 8) so that the load is applied uniformly to the complete area of the cylinder exposed to loading. To check the trend of the compressive strength gain by the concrete in the initial days 3, 7 and 14 days tests were also conducted, which are shown in Figure 10.

To examine the impact of prolonging curing on the compressive strength of the concrete containing WGP, other samples of cylinders were cast having a diameter of 152.4 mm and height of 304.8 mm were prepared and their preparation was as per ASTM C192 [22] but the curing condition was prolonged instead of 28 days one set was cured for 56 days and other was cured for 84 days.



Figure 8. (a) Compressive strength test specimens for the experimental program after curing for 28 days, (b) The capped cylinder under compressive loading in the universal testing machine (UTM)

### 2.8.3. Modulus of Rupture Sample's Description & Testing Protocol

The beams having dimensions of 152.4 mm wide  $\times$  152.4 mm deep  $\times$  762 mm-long beams were cast for the calculation of the modulus of rupture. These beams were cast and tested as per ASTM C78 standard [36]. The test setup is shown in Figure 9.

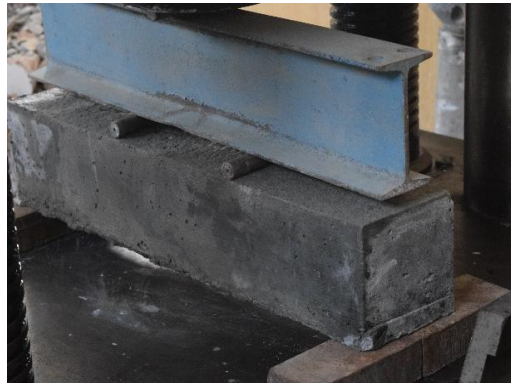


Figure 9. 152.4 mm wide × 152.4 mm deep × 762 mm-long beam testing for Modulus of Rupture using third point loading method [36]

### 3. Results and Discussion

#### 3.1. Compressive Strength

##### 3.1.1. 28 Days Normally Cured Concrete Specimens

A decrease in the compressive strength of the concrete was observed during the first 14 days. The drop of compressive strength on 14 days varied between 15 to 55% when compared with the conventional concrete mix (CM). The initial drop of the compressive strength may be attributed to the reduction of the cement content in the mixes and incorporation of WGP. The 28 days of testing showed that the compressive strength of concrete in with the varying amount of WGP showed a loss in strength which was in between, 17 to 55% in comparison to CM (Figure 10). This percent loss in the compressive strength was the same as observed at the early age testing of the cylinders. At 56 days, the compressive strength improved as the pozzolanic reaction of WGP starts, and the internal structure starts to consume the added glass powder. The loss of compressive strength, when compared to conventional concrete, was reduced to between a range of 11% to 53%, and at 84 days of testing this range further decrease to 11% to 41%. Those mixes that contained more amount of WGP showed more loss in strength as compared to those which had less amount of WGP replaced as cement during the initial days. The compressive strength for all the mixes was calculated and the results indicated a decrease in compressive strength at an early age of concrete due to the reduced amount of binding material used and replaced with WGP. This phenomenon was observed in all the concrete mix used. The compressive strength evaluated at 84 days showed different results compared to concrete at a relatively younger age. The compressive strength of mix MGW-10, MGW-15, MGW-20, and MGW-25 reached up to approximately 88% of the control mix due to the pozzolanic reaction [5, 17, 37, 38] of glass powder, thus representing an optimum limit if glass powder replacement up to 20% of cement without losing considerable strength.

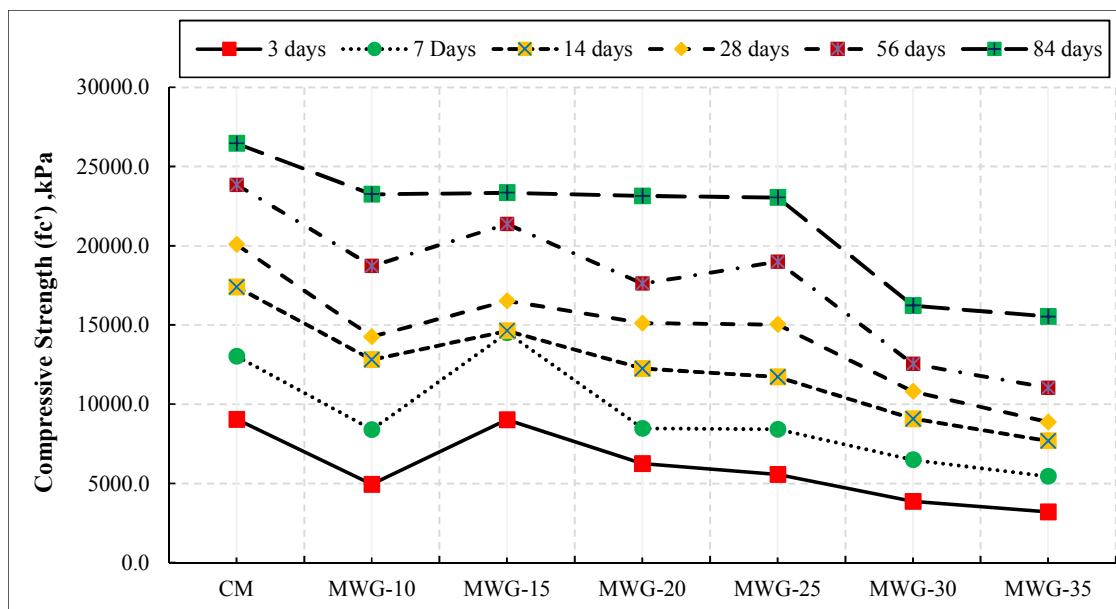


Figure 10. Compressive strength of concrete cylinder specimens at various ages



### 3.1.2. Prolong Cured Concrete Specimens up to 84 Days

As the pozzolanic activity [39] takes place in the abundance of water, so the specimens were cured to check the compressive strength of high volume WGP concrete compressive strength results. The result of the prolonged cured concrete with varying percentages of WGP is shown in Figure 11. The result shows that with the prolonged curing up to 56 days can increase the compressive strength of concrete and when compared to the previous data shown above, it is concluded that the strength decrease observed previously was improved within the range of 5 to 33%. At 84 days of curing this range became 5 to 22%. The effect of prolonging curing was more in those mix in which greater amount of WGP was used.

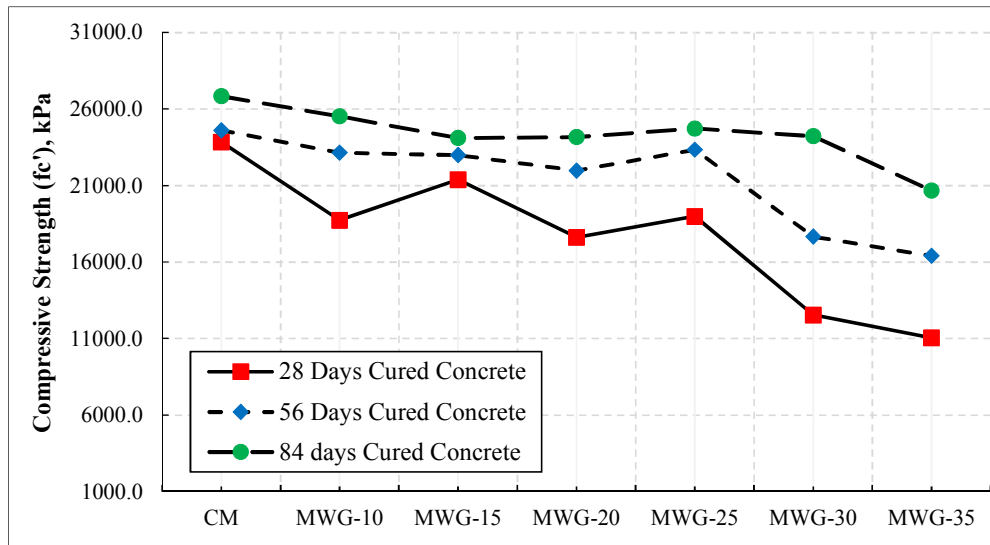


Figure 11. Compressive strength of prolonged cure concrete containing the varying percentage of WGP

### 3.2. Modulus of Rupture

The test trial is presented to determine the evaluation of the maximum load upon which the structural beam may crack in the tension zone due to the bending action and it also gives an estimate of the tensile strength as well. The tensile strength of the structural concrete in the bending situation can be referred to as its flexural strength, and thus flexural strength of concrete is also known as the modulus of rupture of concrete [36]. The experimental test setup of the beam is shown in Figures 9 and 12 shows the result of modulus rupture at various days of testing. The results revealed an increase in modulus of rupture for later ages, i.e. 56 and 84 days. A higher value was observed at 56 but at 84 days the strength gain when compared with conventional concrete was only approximate 2% higher was recorded for 25% replacement. The modulus of rupture value of the concrete with varying percentage of WGP between 10 to 25% showed good result when compared with the conventional concrete.

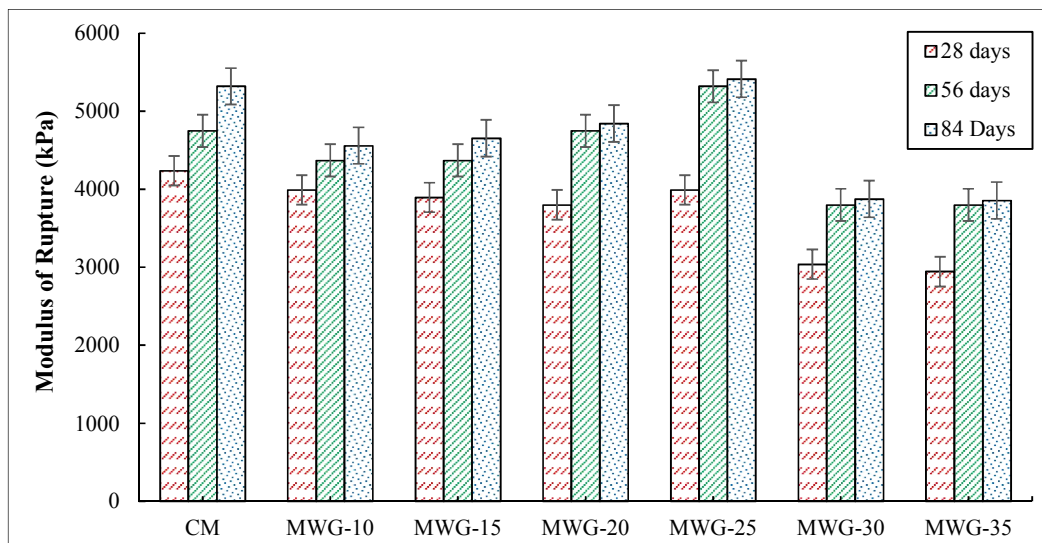


Figure 12. Modulus of rupture at various ages

## 4. Conclusions

This research study focused on the experimental evaluation of various concrete parameters after a partial replacement of cement with WGP. The following conclusions can be drawn from the analysis of test results.

- The addition of WGP decreases the workability and hence more water is required to obtain concrete of the desired workability. The slump was decreased by more than 60% with the addition of more than 25% WGP. This is attributed to the smaller particle size and angular texture of WGP.
- The initial and final setting time of the cement paste increased with an increasing quantity of WGP. The gradual increase of WGP from 10% to 35% caused an increase of 3% to 27% in the initial setting time and 2% to 15% in final setting time as compared to conventional cement paste.
- A gradual decrease in the compressive strength of concrete was observed with the addition of an increasing quantity of WGP. For example, the loss in strength ranges from 17% to 55% with 10 to 35% replacement of cement with WGP. However, the decrease in strength is more at early ages i.e. there is a greater drop in strength in specimens with 3 days curing as compared to 7 days curing and so on. A 35% replacement of cement with WGP caused a decrease of 65%, 59%, 56%, and 55% at 3, 7, 14, and 28 days curing, respectively.
- The drop in strength with an increasing quantity of WGP ranges from 5 to 33% and 5 to 22% for 56 and 84-days curing, respectively. This shows an improved strength at higher levels of WGP with prolonged curing. The compressive strength improved with prolonged curing as the pozzolanic reaction of WGP starts and the internal structure starts to consume the added glass powder.
- With 28 days of curing, a reduction in modulus of rupture within the range of 5 to 30% was observed depending on the amount of WGP replacement. At 56 days, the maximum reduction in modulus rupture was 20%. At 84 days of testing, a 25% replacement specimen showed approximately 2% higher value than the control mix. Based on the results obtained, a 25% replacement of cement with WGP is recommended.

## 5. Conflicts of Interest

The authors declare no conflict of interest.

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