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Effect of Waste Glass Powder (WGP) on the Mechanical Properties of Concrete

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ABSTRACT: *Waste glass is a major component of the solid waste stream in many countries. It can be found in many forms, including container glass and flat glass. Normally, waste glass has no harm on the environment in any way due to its non-degradable nature, but if disposed of improperly it may cause harm to both humans and animals. This study investigates the mechanical properties; compressive strength and flexural strength of concrete incorporating waste glass powder (WGP) as partial cement replacement . Waste glass was obtained, washed and carefully prepared to give WGP used in preparing concrete specimens. To function properly, the glass was sieved to particle sizes of less than 300 µm. A nominal mix design of 1:2:4 was adopted with a water to cementitious material ratio of 0.6. The contents of cement and WGP were adjusted such that as cement content reduces, WGP increases by 10%. Hence, specimens prepared and tested included a control mix (with 0% WGP), 10%, 20%, and 30% WGP-containing concrete. Test specimens were prepared and tested according to standard requirements. The test results show 10% replacement of cement using waste glass powder gave quite impressive results for compressive strength and flexural strength although the pozzolanic effect of WGP was not very significant. In conclusion, the optimal replacement level of WGP in concrete according to this research is 10%. To yield more impressive results however, it is recommended that finer glass powder of grain sizes not greater than 10 µm be used.*

Keywords: *compressive strength, flexural strength, waste glass powder (WGP), pozzolan, cement.*

I. INTRODUCTION

1.1 BACKGROUND TO STUDY

Concrete is the second most consumed material on the planet, second only to water, and it is the most used construction material in the world. Concrete is a versatile material which is capable of being poured and molded into any required shape, and hence is employed in a wide variety of applications. In its simplest form, concrete is a composition of paste (water and cement) and aggregates, or rocks. From the breakdown of the constituents of concrete, it is evident that cement is a key ingredient of the concrete matrix as it is the binder of every other constituent in the makeup, constituting 7 – 15% of it.

By 2050, nearly 70 per cent of countries or areas in the world are projected to be more than 60 per cent urban and 38 per cent will be at least 80 per cent urban. The urban areas of Africa and Asia will absorb nearly all of the projected growth of the world population. Of the 2.5 billion new urban dwellers anticipated by 2050, 90 per cent will live in Africa and Asia. Just three countries – India, China and Nigeria – together are expected to account for more than one third of global urban population growth (United Nations, Department of Economic and Social Affairs, Population Division, 2014). Urbanization would definitely be accompanied by provision of both adequate construction and sustainable infrastructure.

It is well known that Portland cement production is an energy intensive industry, being responsible for about 5% of the global anthropogenic CO_2 emissions worldwide (Martos and Sousa-Coutinho, 2012). It is estimated that about 0.9 – 1.0 tons of CO_2 are produced for a ton of (cement) clinker depending on the type of fuels used. According to scientists, the greatest environmental challenge today is that of man-made climate change due to global warming, which is caused by the steadily rising concentration of greenhouse gasses (which carbon dioxide is an example of) in the earth's atmosphere during the past 100 years (Mehta, 2002). Among other environmental implications of cement production process are quarry-plant water run-off, emissions of dust and carcinogenic kiln bricks.If this level of degenerative effectsare not reduced, the world as we know it is likely to deteriorate faster than envisaged.

The American Concrete Institute concrete terminology 2013 defines a supplementary cementitious material as inorganic material such as fly ash, silica fume, metakaolin, or slag cement that reacts pozzolanically or hydraulically. Supplementary cementitious materials are often incorporated in the concrete mix to reduce cement contents, improve workability, increase strength and enhance durability(Nuewald, 2004).

To control such environment-depleting situations, solid industrial by-products, such as siliceous and aluminous materials, as well as some pozzolanic (i.e. supplementary cementitious) materials are increasingly being used in the cement and concrete industry. The incorporation of these materials in concrete has been giving encouraging results regarding the mechanical and durability properties of concrete(Papadakis and Tsimas, 2002). Examples of these materials are furnace slag, fly ash, silica fume, slag, and waste glass, and agricultural residue such as rice husk.

Waste glass is a major component of the solid waste stream in many countries (Shao*et al.*, 2000). It can be found in many forms, including container glass, flat glass such as windows, bulb glass and cathode ray tube glass.

Normally, waste glass has no harm on the environment in any way due to its non-degradable nature, but if disposed of improperly it may cause harm to both humans and animals.However, glass is a 100% recyclable material with high performances and unique aesthetic properties, which make it suitable for wide-spread uses. For reasons based on the chemical interaction and activity of crushed glass in alkali-aggregates reaction that leads to weakening of concrete matrix, it is only appropriate to reduce the glass to powdery form i.e. Waste Glass Powder (WGP), in order to obtain more reasonably satisfactory results.

The use of supplementary cementitious materials (SCMs), recycled aggregates and other industrial wastes could reduce the environmental impacts of concrete production (Lepech*et al.*, 2008). With little or no emission of pollutants involved in its preparation (i.e. reduction of glass into powder), WGP presents itself as a viable partial replacement for cement in concrete. However, as much as using waste glass powder as a pozzolan in concrete contributes significantly towards sustainability in construction on one end, mechanical properties of the concrete consisting WGP is also a necessity to cater for on the other end. Before building high hopes on WGP, it is important that the effect of WGP on some of the mechanical properties of concrete be investigated.

Basically, there are four (4) raw materials necessary for cement production. These include lime (CaO), silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3). The restructuring of these raw materials in the kiln and the interaction that occurs (known as calcination) produces the four main compounds present in cement. These are summarily presented in the Table.1 below;

However, in addition to the main compounds presented in Table 1, there are minor compounds, such as magnesium oxide, titanium oxide, manganese oxide, sodium oxide and potassium oxide. Although, these compounds are minor in quantity, they are not insignificant in importance. Sodium oxide (Na_2O) and potassium oxide (K_2O) are two alkalis and are examples of minor compounds with marked significance in Portland cement behavior in concrete makeup. These alkalis react with silica in some aggregates causing the disintegration of concrete and affecting the rate of strength development.

Table 1 Chemical composition of Portland cement

Compound	Chemical Formula	Cement Chemists' Notation*	Usual Range by Weight (%)
Tricalcium Silicate (Alite)	3 CaO. SiO_2	C_3S	45-60
Dicalcium Silicate (Belite)	2 CaO. SiO_2	C_2S	15-30
Tricalcium Aluminate (Aluminate)	3 CaO. Al_2O_3	C_3A	6-12
TetracalciumAluminoferrite (Ferrite)	4 CaO. Al2O3. Fe2O3	C_4AF	6-8
* The cement industry uses shorthand notation (CCN) for chemical formulas: C = Calcium oxide, S = silicon dioxide, A = Aluminium oxide, and F = Iron oxide.			

Source: Mamlouk and Zaniewski, 2011

Glass is a very useful member in the family of wastes found in most urban environments as well as some rural settlements. It is a result of several inorganic mineral raw materials, which after undergoing a process of controlled cooling becomes a hard homogenous, stable, inert, amorphous and isotropic material (Frederico and Chidiac, 2009). Presently, glass is being reused in several applications apart from its uses in the concrete and cement industry. This include majorly industrial (– as filler in paints and other products, agricultural fertilizers, fiber glass insulation etc.) and craft applications (– as in making of jewelries, vases, and other visually pleasing pieces by glass fusing).

Waste glass, however, is majorly post-consumer glass and industrial waste glasses. Post- consumer glass can be found in various colours (especially green, brown and clear) and this affects the recycling process of waste glass as there is no economically friendly and automated equipment to sort the various colours. The difficulty of separating waste glass from other materials such as plastic bottles, ceramic plates and undifferentiated trash and more so into various colours has discouraged recycling glass into new containers.

This situation led to the bulk of waste glass being disposed of in landfills, which is not only undesirable but also inefficient for such valuable material.
Waste Glass Powder is fine, superfine or powdered glass obtained by necessary preparation of waste glass from landfills, dumpsites or other waste disposal environments. This preparation involves washing, crushing, grinding and milling of waste glass to give the powder of required fineness.
Glass contains relatively large amount of silicon and calcium. Hence, it is, in theory pozzolanic in nature when it is finely ground and thus can be used as a cement replacement in Portland cement concrete (Shi and Zheng, 2007). Amongst other factors, fineness of glass powder affects its performance as a pozzolan. It has been observed after careful study that pozzolanic properties of glass are first notable at particle sizes below approximately 300 µm (Papadakis and Tsimas, 2002). Although, smaller grain sizes reacts faster and gives better result. Table 2 below shows the chemical composition of typical glass powder compared to cement and silica fume

Table 2 Chemical composition of cement, glass powder and silica fume

Contents	Cement	Silica fume	Glass powder
SiO_2	21.0	85 – 96	71.4
Al_2O_3	5.9	-	1.4
Fe_2O_3	3.4	-	0.2
CaO	64.7	-	10.6
MgO	0.9	-	2.5
Na_2O	-	-	12.7
K_2O	-	-	0.5
Ti_2O	-	-	-
SO_3	2.6	0.3 – 0.7	0.1
Loss on ignition	1.2	3.5	0.4

Source: Kou and Xing, 2012

There are different methods of producing glass powder (WGP) from waste glass for cement and concrete works but the method described here is that patented in the United States of America Patent No. US7413602B2 (2008). As explained in the patent, to produce glass powder from unsorted dirty post-consumer glass, four basic steps are followed;

1. Employing glass-pulverizing equipment to reduce waste glass to small fragments, allowing removal of trash,
2. Employing a multistep washing process to clean the glass fragments in the preferred embodiment using aggregate cleaning equipment,
3. Drying the fragments, preferably using fluidized bed techniques, and
4. Grinding the glass to a desired particle size, preferably using a ball mill, in conjunction with an air classification step to produce a glass powder of uniform size.

It has been found out by the authors that powdered glass made according to the process as described in detail may be used as a replacement for up to 40%. Another method is the more common method which involves loading a bottle supply hopper with the glass trash (e.g. bottles, offcuts of glass louvre blades etc.) where it is transported into the crusher. In the crusher, glass is reduced to crushed glass or cullet which is further passed on to the cullet mill where it is ground even finer to powder. The powder is then sifted to attain uniform particle size.

According to literature, this is not the first time glass is being used in concrete. Glass has a good history as replacement for concrete constituents in the recent past. Glass is known for its aesthetic appearance and durability in concrete. It is also known for improving some mechanical properties of concrete. Crushed glass has been used as replacement for coarse aggregate in concrete and its effect reported (Topçu and Canbaz,2004). Also, the effect of replacement of sand with glass cullet or ground glass has been investigated by Park*et al.*(2004), Pereira de Oliveira *et al.* (2008), Ali and Al-Tersawy(2012)and others.

However,a major concern regarding the use of glass in concrete is the chemical reaction that takes place between the silica-rich glass particles and the alkali in the pore solution of concrete, i.e., alkali-silicareaction (ASR). This reaction can be very detrimental to the stability of concrete, unless appropriate precautions are taken to minimize its effects. The susceptibility of glass to alkali implies that coarse glass or glass fibres could undergo ASR in concrete, possibly with deleterious effects(Shayan and Xu, 2004; Rajabipour*et al.*, 2010). The chemical reaction between silica-rich glass and alkali was a major concern when using glass in concrete (Batayneh *et al.*, 2007). This led to further research to address the effect of alkali silica reaction of glass in concrete which resulted in the conclusion that when in powdered form, glass shows pozzolanic characteristics and does not show deteriorating effects on concrete (Shi and Zheng, 2007).

Although there have been previous research on the pozzolanic effect of glass in concrete as far back as about a decade ago (Shayan and Xu, 2006), more recently, there have been other reports that also support the findings of Shi and Zheng (2007). In fact, a review of the utilization of waste glass of different particlesizes in concrete was carried out by Jani and Hogland (2014). Also, Bhat and Bhavanishankar(2014) reported the result of their study of effect of partial cement replacement with waste glass powder on the compressive strength of concrete.
However, this report addresses the effect of waste glass powder on the mechanical properties (i.e. compressive strength and flexural strength) of concrete and compares the result with respective properties of control concrete samples.

II. METHODOLOGY

2.1 MATERIALS USED FOR THE CONCRETE PROCESSING

The materials used in this study include 42.5R grade Portland cement (Dangote 3X), coarse aggregate (of nominal size 20mm), fine aggregate (sharp sand), and potable mixing water. Lastly, waste glass (processed to powder) that was used as pozzolan. Each of these materials are briefly discussed in the following sections.

PORTLAND CEMENT

Dangote 3X Portland cement (CEM II) with a grade of 42.5 and which sets rapidly was obtained from a dealer at Bodija market, Ibadan, Nigeria. The cement used conforms to BS EN 197 – 1 in terms of its composition and other criteria stated in the code.

COARSE AGGREGATES

The coarse aggregate used was of maximum size of 20 mm obtained from a site at the Faculty of Technology, University of Ibadan, Nigeria. It was sufficiently washed to rid every dirt and organic matter which may affect its performance in concrete.

2.1.3 FINE AGGREGATES

Sharp sand is the fine aggregate used for the study. It was obtained from a clean drainage deposit at UI central mosque, Ibadan, Nigeria. To achieve the standard requirements for fine aggregates, British Standard sieve sizes of 4.75 mm and 200 µm were used in preparing the used samples. The fine aggregates used were those passing through the 4.75 mm but retained on the 200 µm.

2.1.4 MIXING WATER

Water, free from organic matter and other objectionable material was obtained from a clean source behind Egbogha Building, Civil Engineering department, Faculty of Technology, University of Ibadan, Ibadan, Nigeria.

2.1.5 WASTE GLASS COLLECTION AND PROCESSING TO WASTE GLASS POWDER

The waste glass was obtained, as readily crushed (or broken) glass,from a glass (louvre blade) cutter at Iwo-Road, Ibadan, Nigeria. The waste glass was processed to meet the fineness prescription given by Papadakis and Tsimas (2002). About 30 kgof dirty brownwaste glasswas obtained for processing to obtain waste glass powder (WGP). It was then taken to an experienced contractor at the Department of Geology, University of Ibadan, to be processed accordingly.

In order to obtain WGP, waste glass was washed with an unreactive chemical and water to remove soil and other impure attachments. Afterwards, the glass was allowed to dry naturally. The dry glass was then ground to very fine size. Although the fine glass produced were of relatively small grain sizes, only particle sizes of less than 300 µm were obtained using British standard sieve of mesh size 300 µm. The portion retained (can also be ground to become finer to yield more WGP but) was disposed of and was not used (plates1&2).

Plate 1 Obtained broken waste glass

Plate 2 Waste glass in ground fine form after processing

MIX PROPORTIONING

To achieve the desired concrete grade of C20/25 (expected for the control mix) using the purchased cement, a mix ratio of 1:2:4 (Cementitious Material: Fine aggregates: Coarse aggregates) was adopted in casting concrete cubes and prisms (Table 3).

The batching method used in this study is by weight. Water to cementitious binder ratio of 0.60 was adopted. The WGP obtained was used as a replacement in 10%, 20% and 30% replacement levels by weight of cement content respectively with replacement of cement by WGP in the proportion percentages stated earlier. Also, sets of specimens (cubes and prisms) with 0% WGP were cast to serve as control. Slump test was also carried out on mixes of the different replacement levels to investigate the effect of WGP on the consistence of concrete.

Twelve cubes, used to determine the compressive strength at 7, 14, 21, and 28 days, were cast for each replacement level. Also, three prisms (used to determine flexural strength, only for 28 days) were cast for each replacement level.

For the casting, wooden moulds of size 100 × 100 × 100 mm for concrete cubes were used. For prisms, moulds of 500 × 100 × 100 mm size were used.

Table 3 Mix proportion for prepared samples

Replacement (%)	Water/Binder	Cementitious materials (kg/m^3)		Water (kg/m^3)	Fine Aggregates (Sand) (kg/m^3)	Coarse Aggregate (kg/m^3)
		OPC	WGP			
0	0.6	342.86	0	205.71	685.71	1371.43
10	0.6	308.57	34.29	205.71	685.71	1371.43
20	0.6	274.29	68.57	205.71	685.71	1371.43
30	0.6	240.00	102.86	205.71	685.71	1371.43

COMPRESSIVE STRENGTH TEST

The compressive strength test was done in accordance with BS EN 12390-3:2009

FLEXURAL STRENGTH TEST

The flexural strength test was done in accordance with BS EN 12390-5:2009

III. RESULT AND DISCUSSION

SLUMP TEST RESULT

The slump test result for 0, 10, 20 and 30% levels of WGP replacement are presented in table 4

Table 4 Slump test for various WGP replacement levels

Mix replacement level (%)	Slump measurement (mm)
0	41
10	36
20	28
30	21

A. COMPRESSIVE AND FLEXURAL STRENGTH RESULTS

The results of strength testing of cured cubes are presented in table 5. The strength values reported are the average of three test results.Figures 1 -3 show the graphical behavior of the specimens in compression and flexure.

Table 5 Compressive and flexural strengths concrete test specimens

WGP Replacement (%)	Property				
	Average compressive strength (N/mm^2) Average strength*				flexural (N/mm^2)
	7 days	**14 days**	**21 days**	**28 days**	**28 days**
0	23.17	27.26	28.52	33.28	7.63
10	16.63	21.46	22.09	24.47	7.20
20	11.21	12.14	17.07	17.71	6.87
30	12.33	13.16	15.39	15.48	5.61

* Minimum flexural strength requirement by standard is 3.35 N/mm^2.

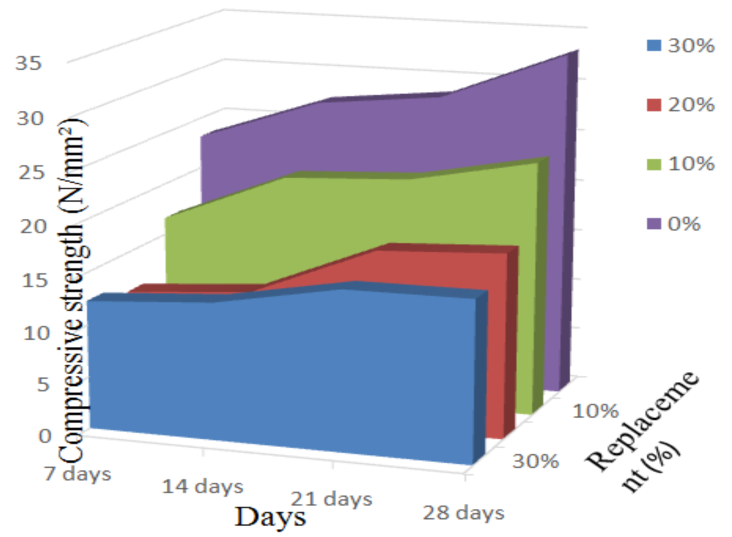

Figure.1 Compressive Strength variation of concrete containing WGP with days for each replacement level.

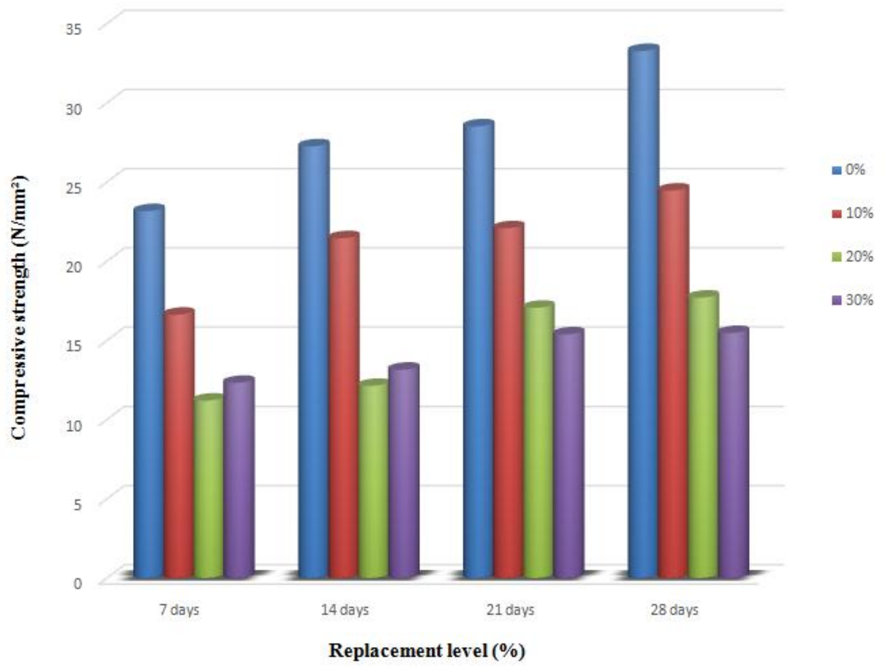

Figure2 Comparison of 7, 14, 21 and 28 day compressive strength with different % replacement of waste glass powder

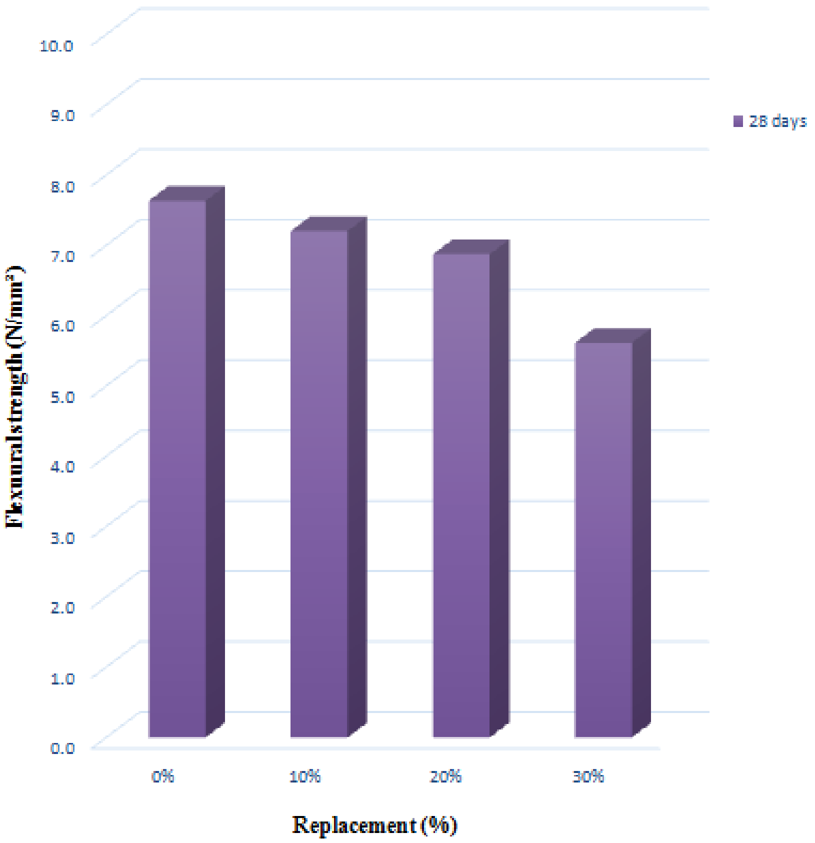

Figure3 Variation of 28-day flexural strength with % replacement of waste glass powder

SLUMP TEST

Slump results table shows that the control mix has the highest slump with mixes containing WGP showing decreasing slump values with increasing replacement percentage. The decrease in slump with increasing WGP content in concrete shows that concrete containing WGP is less workable than plain concrete. However, the slump values for the mixes range from 20 – 45 mm showing low workability. The decrease in slump can be related to the angular shape of glass powder particles. Also, the mass per unit volume of glass powder in concrete is relatively higher than that of cement and since glass powder in itself is not cementitious, excess of it does not add to the binding property of fresh concrete and hence makes concrete less workable. In other words, the excessive amount of glass powder and reduced cement content makes the mix harsh to work and compact.

COMPARISON OF COMPRESSIVE STRENGTHS AND FLEXURAL STRENGTHS

The minimum cube crushing strength (of 25 MPa at 28 days) targeted was well exceeded by the control mix with an average 28-day strength of 33.28 MPa. Although, mixes containing WGP did not meet the target 28 day strength, it is worthy of note to point that 10 % replacement showed an impressive strength value of 24.47 MPa, almost the target strength. Generally, the reduction in the 28 days strength, may likely be a short-term effect because in such short periods the pozzolanic effects would not become evident. However, the scope of this research was limited to a maximum curing period of 28 days.

As expected, the concrete samples for the control as well as each replacement level gained strength as the time of curing increases notwithstanding the effect of glass powder content on the mixes. However, the 7 days and 14 days compressive strengths of 20% WGP replacement concrete show only a slightly low rate of strength gain within that period when compared with the rate of strength gain of mixes containing 10% and 30% of WGP.

The early strength gain rate of 20% and 30% WGP which are observed from Figure 4.1 shows slow strength development. This agrees with the observation of Mehta and Monteiro (2006) that when a pozzolan is used in concrete, the reaction is slow; therefore, the rates of heat liberation and strength developmentwillbe accordingly slow.

In the case of flexural strength, the standard requirement of 3.35 N/mm^2 (obtained in Art. 3.54) was surpassed by all the samples (as shown in the table) with the lowest flexural strength of 5.61 N/mm^2 being that of 30% WGP replacement, although the flexural strength of concrete reduced with increase in percentage replacement of WGP. Consequently, amongst the replacement levels, 10% glass powder mix had a very close flexural strength compared to the control mix, with only a difference of 0.43 N/mm^2. Since the flexural strength is also an important property of concrete as a building material, this is a significant result concerning the usage of WGP as a replacement material in concrete.

From the presented results above, the significant effect of waste glass powder on the compressive strength of concrete can be said to be felt optimally at 10% replacement level. This might be due to the fact that the amount of silica present in 10% WGP is just adequate to exhaust the lime produced during hydration. This places optimal addition at 10%. Beyond 10% WGP replacement, there is a reduction in the compressive strength of concrete.

IV. CONCLUSION

From the research work performed, the following conclusions can be reached.

1. Waste glass powder is potentially pozzolanic and, if well prepared, can be used as a cementitious material.
2. The workability of concrete reduces as the percentage replacement increases.
3. The strength of concrete can be improved by replacement of cement with waste glass powder of adequate replacement level.
4. The optimum replacement level of glass powder for cement in concrete is 10%.

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