Characteristics of concrete with waste glass as fine aggregate replacement

Sadoon Abdallah, Mizi Fan

***Abstract*— This paper systematically investigates the characteristics of concrete containing fine crushed glass during its process, the best ratio of fine crushed glass which leads to higher strength of concrete in order to produce concrete blocks, and the effect of waste glass replacement on the expansion caused by Alkali-silica reaction (ASR). The slump, unit weight, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, ultrasonic pulse velocity, dry density, water absorption and Alkali-silica reaction (ASR) were analyzed in terms of waste glass content (0%, 5%, 15% and 20%) under different curing age of 7, 14 and 28 days. It was found that the slump of concrete containing waste glass as fine aggregate replacement decreased with increases in the waste glass content but without loss of workability. The compressive, splitting tensile and flexural strength of concrete with 20% waste glass content increased by 5.28 %, 18.38% and 8.92% respectively at 28 days. The mixes with waste glass replacement showed a denser internal concrete structure or more consistent structure under ultrasonic pulse velocity assessment. There was a clear decrease in the water absorption with an increase of waste glass aggregate ratio, and a clear reduction in the expansion of the waste glass concrete, showing an alkali–silica reaction in concrete which occurred between the active silica of waste glass and alkali of cement paste.**

***Index Terms*— Waste glass; Concrete; Properties; Alkali-silica reaction.**

I. Introduction

The reuse of waste glass is one of the most important issues around the world due to the increase of solid wastes in the landfill and non-degradable nature of its disposal. The use of recycled waste glass in concrete has attracted much interest worldwide and numerous researches have been carried out, showing the possibility of use of waste glass as building materials by partially replacing concrete mixtures (Pike et al.1960; Schmidt and Saia 1963; Phillips and Cahn 1973; Jonhston 1974; Shi and Zheng 2007). Nevertheless, the research could be categorized as follows:

One of the research fields is for glass cullet in pavement materials; the glass cullet has been exploited as road construction aggregate for asphalt paving (Reindl 2003). American Association of State Highways and Transportation Officials (AASHTO) had recognized the use of recycled materials in pavement and created a new specification titled "Glass cullet use for soil aggregate base course". The specification illustrates that when properly processed, the glass cullet can be expected to provide adequate stability and load support for use as road or highway bases. Crushed glass cullet that has been used as aggregate in road construction or bituminous concrete pavement is popularly known as "glassphalt". A number of field trials of glassphalt pavement have been carried out since 1971. It was observed that it can hold heat longer than conventional asphalt. This may be advantageous when road work is carried out in cold weather or when long transport distances are required. Furthermore, the glass particles could increase the reflectivity of the road surface and such improve the night-time road visibility (AASHTO 2011). The crushed waste glass pavement also has a good resistance for abrasion, lower shrinkage in dry situation and lower water absorption compared with plain concrete (Concrete Technology Unit 2004).

The second area of studies is for the recycled glass particle (sand) as aggregate for concrete in building construction. The use 30–70% of waste glass as a fine aggregate, up to 100μm, in concrete has been trialed, showing no deleterious effect at macroscopic level, rather an improvement of the mortar mechanical performance (Corinaldesi et al. 2005). Shehata et al.(2005) reported that using waste glass as partial volume replacement of fine aggregate resulted in a higher modulus of rupture values for all glascrete mixes compared to reference mix. It was found that using waste glass as a fine aggregate can achieve good interfacial bonding between cement paste and glass aggregates and that the glass aggregates act as crack arrestors, preventing cracks from propagating through them. The presence of recycled glass sand particles (RGS) can also reduce the permeability of the concrete and the amount of water used in concrete (Taha and Nounu 2008).

The third area of studies is for the recycled glass as pozzolanic replacement. The waste that contains a high content of silica (SiO2) could be added to cement as a pozzolanic constituent. Finely ground glass of appropriate amorphous silica (SiO2) can react with the dissolved calcium hydroxide in the presence of water, consequently forming hydrated compounds in a similar way to pozzolanic materials, such as pulverized-fuel ash (PFA), ground-granulated blast furnace slag (GGBS) and silica fume (SF). Pozzolanicity of glass powder (GP) was first studied in 1973 (Reindl 2003), but a major progress has been achieved in the last 10 years. Published research work has shown that glass powder could react in a pozzolanic manner in the cementitious systems and contribute to the strength development of concrete (Reindl 2003; Shi and Zheng 2007). It was also reported that the pozzolanic reactivity increases with fineness increased. Smaller glass particle size led to a

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Sadoon Abdallah, Civil Engineering Department, School of Engineering and Design, Brunel University,UB8 3PH, UK

Mizi Fan, Professor Mizi Fan, Head of Research, Civil Engineering, Brunel University, United Kingdom, UB8 3PH

higher compressive strength and lower expansion in their concrete composites at both early and late age compared with concrete containing fly ash (Shao et al. 2000). However, it may be noted that the highest rate of heat evolution drops as the Portland cement content is reduced. This is because the pozzolanic reaction occurred at later stage and evolved only minor quantities of heat at early stage of hydration (Dyer and Dhir 2001). Shayan and Xu (2004) observed that a decrement in compressive strength of GP mixes was due to the lower cement content rather than the nature of GP. He also indicated that when 30% of sand was replaced by GP, the 90-day compressive strength was similar to that of SF specimens.

The fourth area of studies is for colour glass aggregate. Jin et al. (2000) have conducted a study to use colour glass aggregate as a partial replacement of fine and coarse aggregate. It was reported that the concrete with non-colour waste glass had larger expansion caused by ASR reaction compared with concrete with colour waste glass. Moreover, the presence of colour glass as aggregate can affect the slump and mechanical properties of concrete with glass content increased due to the lower adhesion and bond strength between glass aggregate and cement paste resulted from the relatively smooth surfaces of glass comparing with relatively rough surfaces of natural aggregate (Meyer 2003; Park et al. 2004; Topçu and Canbaz 2004; Taha and Nounu 2008). Shayan and Xu (2004) pointed out that no more than 50% by weight of the normal aggregate could be replaced with a mixture of coarse and fine glass aggregate for structural and non-structural applications. Terro (2006) also reported that the compressive strength of concrete made with colour waste glass decreased up to 20% of its original value when temperature increased up to 700°C.

The fifth area of research work is on the reaction of glass with cement. While the role of aggregate in concrete was originally perceived to be entirely mechanical, and aggregate particles are thought to be unaffected by the cement paste and selected on the basis of their physical properties, there are chemical reactions (i.e. alkali-silica reaction) that can take place between some reactive aggregates and cement paste Hadlington (2002). It is generally believed that glass is unstable in the alkaline environment of the concrete. Although both sand and glass consist mostly of silica, they behave differently. The main reason for this difference in behavior is attributed to the nature of the silica in sand which has a regular crystalline structure, is relatively stable and resistant to chemical influences, whereas the same silica in the amorphous form in glass is not (Meyer 2003). Phillips and Cahn (1973) have shown that up to 35% of glass cullet could be used in concrete in combination with low-alkali cement (cement limited with 0.60% on the Na2Oeq in accordance with ASTM-C150) without detrimental effects. However, some specifying agencies indicated that the use of low-alkali cement does not guarantee that concrete containing reactive aggregates will not produce excessive expansion, i.e. increasing the cement content with low-alkali cement may increase the alkali concentration of the concrete pore solution and may cause deleterious expansion. However, Shayan and Xu (2004) showed that the use of up to 30% glass aggregate in concrete might not cause deleterious effects, particularly if the alkali content of the concrete is below 3 kg/m3. Another important issue that was under misgiving and argumentations was the large soda content of the glass (around 13%). It was reported that replacing 10% of the natural aggregate with clear glass can lead twice expansion (14 days) that of the ASTM limit of 0.1%, and bars with 100% glass aggregate exhibited the extraordinary expansion of 1.4%. On the other hand, Smith (2004) indicated that ground glass could be added to clay during manufacturing of brick to save energy costs and produces bricks that are more resistant to frost damage. The manufactured brick has also proved lower water absorption and higher compressive strength.

It is apparent that while some research has been carried out in the above five areas, there is few report of consistent data across the process of waste glass concrete or specific effects of using waste glass, such to give an accurate account of potential replacement of a fine aggregate in concrete. There are also major concerns regarding the use of glass in concrete due to the chemical reaction that takes place between the silica-rich glass particles and the alkali in cement i.e. alkali-silica reaction (ASR), which forms gel, leads to swelling in presence of moisture, causes expansions and results in a damage to the concrete. This study aims to systematically investigate the characteristics of concrete containing fine crushed glass, the best ratio of fine crushed glass which leads to higher strength of concrete in order to produce concrete blocks, and the effect of that ratio on the expansion caused by Alkali-silica reaction (ASR).

II. MATERIALS

Ordinary Portland cement used in the study was the Blue Lion brand and the chemical and physical properties are summarised in Table 1. The fine aggregates were the natural sand of the maximum size 4.75mm and natural quartzitic gravel of maximum size 20mm with a bulk density 1530kg/m^3. The waste glass of the used windows was used as a replacement of fine aggregate and was analyzed in terms of physical properties such as sieve analysis and particle size (Table 2).

Table 1. Chemical and phyiscal properties of cement

Chemical composition of cement	
Oxide	***Content %***
CaO	63.17
SiO2	19.98
Al2O3	5.17
Fe2O3	3.27
MgO	0.79
SO3	2.38
Total Alkalis	0.9
L. O. I.	1.88
I. R.	1.47
L. S. F.	0.87
Main Compounds (Bogue's equations)	
C3S	59.09
C2S	12.71
C3A	8.18
C4AF	9.94

Table 2. Grading of glass aggregate

Sieve size(mm)	Mass Retained (gms)	Retained%	Passing%	Cumulative Retained %	ASTM Standard Specification
4.75	0	0	100	0	95-100
2.36	1.7	0.17	99.83	0.17	80-100
1.18	357.7	35.77	64.04	35.94	50-85
0.60	230.9	23.09	40.97	59.03	25-60
0.30	200.2	20.02	20.95	79.05	5-30
0.15	113.2	11.32	9.63	90.37	0-10
Pan	96.3	9.63	0	0	0
Fineness modulus of glass, ΣF/100 = 264.56/100 = 2.64				264.56	

III. Experimental Procedures

A. Mixture

Four types of concrete mixes were prepared for this study. The controlled concrete mix ratio is 1:2.2:2.7 (cement: fine aggregate: coarse aggregate) with the water-cement ratio of 0.55. The glass concrete mixes were summarised in Table 3 with 5, 15 and 20% partial replacement for the sand. Three specimens were prepared for each test and all concrete specimens were cured for 7, 14, and 28 days.

Table 3. Mixes of concrete with waste glass

Mix	**W/C**	**Amount of cement Kg/m^3**	**Coarse aggregate Kg/m^3**	**Fine aggregate Kg/m^3**	**Fine aggregate glass Kg/m^3**
Control	0.55	363.3	979	812.2	0
5% WG	0.55	363.3	979	771.59	40.61
15% WG	0.55	363.3	979	690.37	121.83
20% WG	0.55	363.3	979	649.76	162.44

Table 4. Tests and sample parameters

No	**Test Name**	**standard**	**Specimen size**
1	Slump	B.S.1881.Part 2:1970	Cone: Top, bot and high= 10cm, 20cm and 30cm
2	Unit weight	B.S.1881:1952	Cylindrical pan: 200 mm dia., x 320 mm
3	Dry density	B.S.1881:1952	Cube: 100x100x100 mm
4	Compressive strength	B.S.1610: part 1 : 1992	Cube: 100x100x100 mm
5	Spiliting tensile strength	ASTM C496-96	Cylinder: 100 mm dia., x 200 mm high
6	Flexural strength	B.S.1610: part 1: 1992	Prisms: 100x100x500 mm
7	Modulus of elasticity	ASTM-C-469	Cylinder: 100 mm dia., x 200 mm high
8	Water absorption and Porosity	ASTM C-642	Cylinder: 10 cm dia., x 3.5 cm high
9	Ultrasonic pulse velocity (UPV)	BS 1881: Part 203	Prisms: 100x100x500 mm
10	Alkali-silica reaction(ASR)	ASTM C1260	Prisms: 30x30x300 mm

B. Fabrication and testing

The moulds were coated with oil coating to ensure that no water escaped during filling and to prevent any adhesion of cement. A cube mould of 100x100x100mm, cylindrical mould of 200 (diameter)x100 (length) mm, prism mould of 100 x 100 x 500 mm and 30x30x 300mm were used for various samples for both destructive and non-destructive tests. Casting, compaction and curing were carried out in accordance with BS1881:1952 and other relevant standards. The tests, sample sizes and the applied standards are summarized in Table 4.

IV. Results and Discussion

A. Effect of waste glass on mix fluidity

The results of the slump tests are illustrated in Figure 1. It can be seen that the slump values decrease as the waste glass content increases. The level of decrease seems logarithmic with a high degree of fit. The values of slump test were 65, 56.5 and 52mm for the concretes with 5%, 15% and 20% of waste glass respectively, representing a reduction of 19, 29 and 35% respectively in comparison with 80mm for the control concrete. This is due to more sharper and irregular geometric forms of the glass particles compared to sand particles, which may give rise to high friction and such resulted in less fluidity. In comparison with the results of previous work, which showed that increasing the ratio of waste glass by 30%, 50% and 70% as aggregate resulted in a decrease in the slump by 19.6 –26.9%, 30.1–34.6% and 38.5–44.3% respectively, compared with control mix [19], it seems that a reduction in fluidity could be significant although depending on surface property of the waste glass particles.

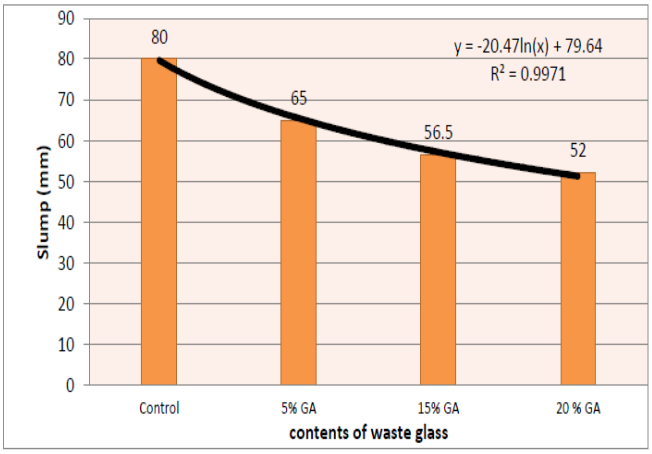

Figure 1. Slump in relation to waste glass

B. Effect of waste glass on unit weight and density of concrete

The concrete samples from the above pastes are subjected to further process and testing. It is evident that an addition of waste glass resulted in a slight weight reduction due to the lower specific gravity of glass aggregate as compared with sand. The fresh density of the mixes was 2442, 2426, 2405 and 2399kg/m^3 respectively for the control, 5%, 15% and 20% waste glass replacement mixes.

The dry density for all mixes at 7, 14 and 28-day curing ages is given in Table 5. The results demonstrate the decreasing tendency of the dry density as the waste glass ratio increases compared with controlled mix. This is again attributed to a lower density of glass aggregate compared to that of natural sand. This can be further confirmed by the similar increase in the density of all concretes with curing time: the density increased by 1.4%, 0.7%, 0.47% and 0.37% respectively for control, 5%, 15% and 20% waste glass replacement mixes when comparing 7 days with 28 days concretes. It is most interesting that the degree of increase in density with hydration time decreases with the increase of waste glass content. The continuing process of hydration of cement should lead to the formation of hydration products that might fill some of existing voids and hence the density increased of paste. The less increase in density with time due to the increase of waste content indicates that there may be less further hydration occurred or the effect of waste glass on the micro voids of cement paste.

Table 5. Density of waste glass concrete

Mix	Dry density kg/m³ at ages of		
	7 days	**14 day**	**28 day**
Control	2365	2378.6	2398
5% WG	2358.5	2364.3	2374.2
15% WG	2354.8	2362.9	2366.1
20% WG	2351.4	2359.7	2360.2

C. Effect of waste glass on compressive strength of concrete

The compressive strength of the control and waste glass concretes at 7, 14, and 28 days are given in Figure 2. It can be seen that the addition of waste glass resulted in a slight increase in compressive strength (Figure 2). The highest 28-day compressive strength is 34.22MPa for the concrete mix made of 20% waste glass fine aggregate, which represents an increase in the compressive strength of up to 5.28 % as compared to the control mixes. It can also be observed that the percentage increases in compressive strength with age overall increased with the increment of glass aggregate replacements. This may be attributed to the Pozzolanic reaction that appears to offset this trend at a later stage of hardening and such contributes to an improvement in the compressive strength at 28 days. A similar observation was reported by Metwally (2007).

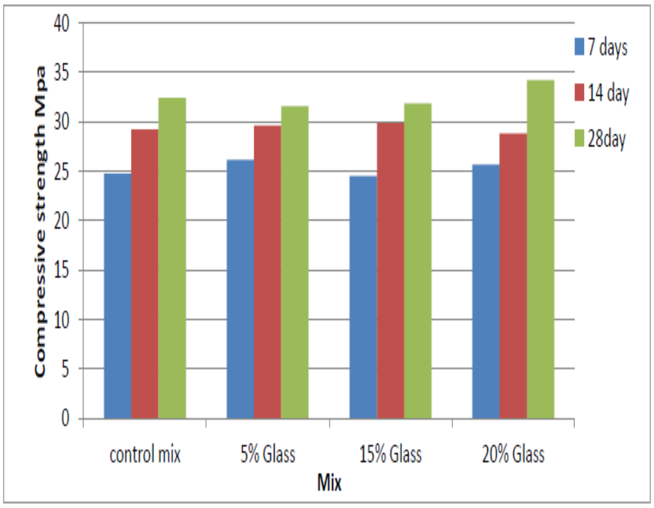

Figure 2. Compressive strength of various mixes

D. Effect of glass concentration on the splitting tensile strength

The splitting tensile strength for all mixes after being cured for 7, 14, and 28 day is given in Figure 3. The results show that overall the tensile strength increased with the increase of curing time for all mixes. A scrutiny of the tensile strength between different mixes indicates that a 5% replacement of waste glass had little effect on the tensile strength, but further increase of replacement resulted in a significant influence on the tensile strength at the early curing age, while an opposite effect for a mature concretes, i.e. the tensile strength of 20% replacement of sand with waste glass was much higher than that of the control concrete at 28 day curing time. The 28-day splitting tensile strength was 3.122MPa for 20% glass replacement concrete, which is an increase up to 18.38% compared to the controlled mix. This may be attributed to the progress of hydration and decrease in the permeability of glass mixed concrete, and the good bond strength between glass aggregate and the surrounding cement paste because of irregular geometry of glass. The pozzolanic reaction may also offset this trend at a later stage of hardening and help improve the splitting tensile strength at 28 days.

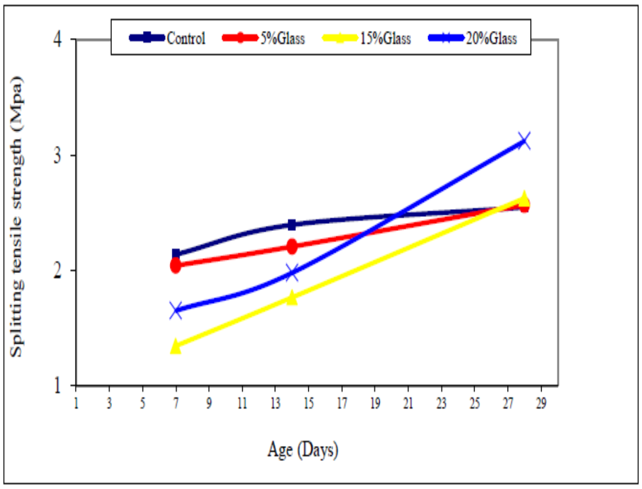

Figure 3. Splitting tensile strength with glass concentration

E. Effect of waste glass on flexural strength and stiffness

Overall the flexural strength increased with the addition of waste glass, whether 7, 14 and 28-day test results. Again it is clear that all mixes show a continuous increase in flexural strength with age. After 28-day, the flexural strength increased by 3.54%, 5.03 % and 8.92% respectively when the waste glass content increased by 5%, 15% and 20%. This could be attributed to pozzolanic reactions which appear to accelerate with time, and offset hardening process and help improve the flexural strength. A similar behaviour was also reported by Shehata et al (2005). It must be noted that higher waste glass replacement may have an adverse effect on the flexural strength at early stage, for example, at 14 days, the flexural strength of concretes was 4.2MPa for 20% replacement compared to 4.3MPa for 15% and 4.4MPa for 5% replacement (Figure 4).

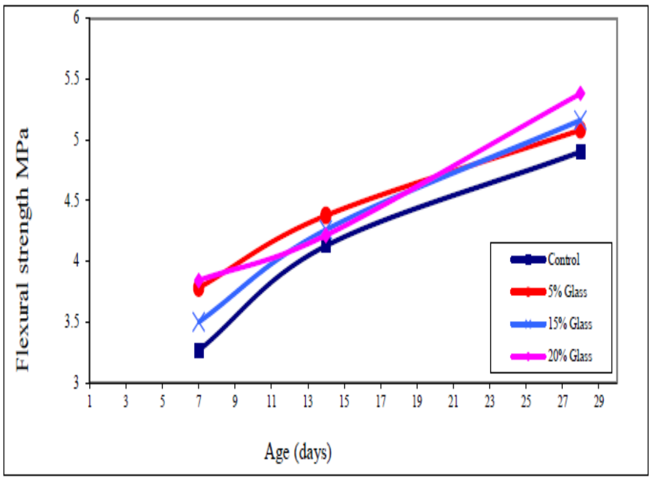

Figure 4. Flexural strength with waste glace replacement

The modulus of elasticity (MOE) of the waste glass concretes at 7, 14 and 28 days curing is shown in Figure 5. Overall, the trend of change in the MOE is very similar to that of MOR. After 28-day curing, MOE increased by 2.54%, 5.45% and 9.75% respectively as the waste glass content increased by 5%,15% and 20%. In addition to the mechanisms discussed above, this could also be attributed to a high modulus elasticity of glass compared to that of natural sand.

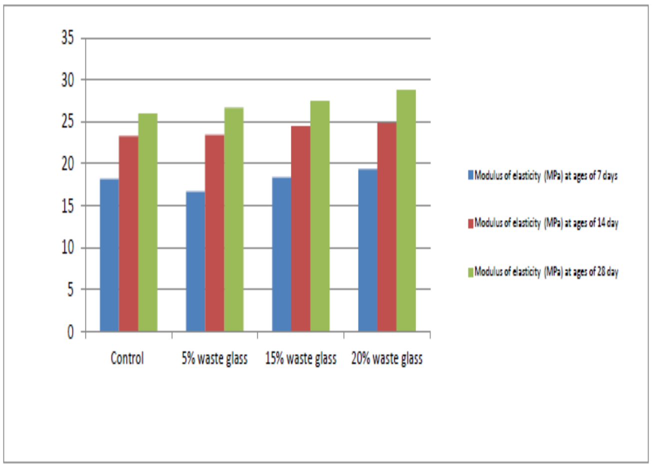

Figure 5. Comparison of MOE for different mixes

F. Ultrasonic pulse velocity (UPV) test

The ultrasonic pulse velocity (UPV) test is an important tool for the assessment of uniformity of concrete quality, detecting the existence of voids, cavities and crack in concretes, and monitoring strength development of concrete. It is apparent that UPV increased with age due mainly to the increase in the density of concretes with consistent hydration and reduction in void content and discontinuity points within the concretes. It seems that a small amount of waste glass replacement (5%) resulted in a higher UPV, which may indicate a more compact or consistent structure of waste glass concretes. However, further increase in the percentage of waste glass resulted in a decrease in UPV (Figure 6). This may be attributed to the lower specific gravity of glass particles in comparison to that of sand. High content of irregular waste glass may also result in 'bridge' of irregular particles or inconsistent structures.

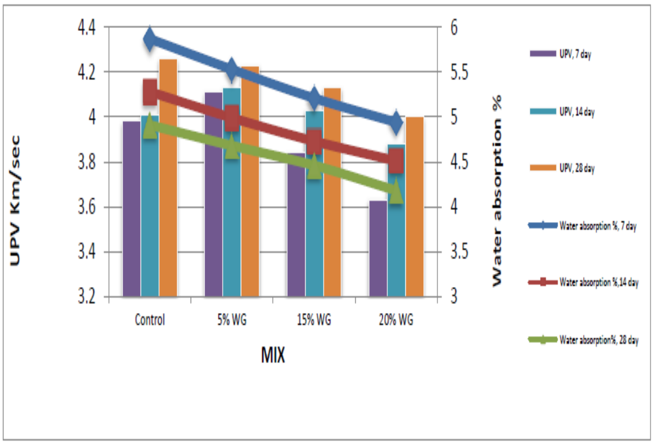

Figure 6. Correlation between UPV and water absorption of waste glass concretes

G. Effect of waste glass on water absorption

An increase of the glass aggregate in mixes led to a decrease of water absorption whether for all curing ages (Figure 6). A decrease of water absorption with age is well known because a continuous hydration process will produce concrete with lower porosity and hydration products fill the pore between cement particle and aggregate to reduce the average pore diameter. However, a reduction in the water absorption with an increase of the waste glass replacement may be attributed to the impermeable nature of glass aggregate compared with sand and irregular geometry of waste glass which may be more accessible to the deposition of the hydrated concrete products. A similar observation was reported by previous worker [18]. At 28 days, the percentages of reduction in water absorption for mixes containing 5%, 15% and 20% of waste glass are 4.68%, 9.16 % and 14.86 % respectively compared to the controlled mixes.

H. ASR

The Alkali–silica reaction (ASR) is used to determine any adverse reaction in concrete which occurs between the active silica that resides sometimes in aggregates and alkali that exists in cement. This reaction was discovered in 1940 by Stanton. The reaction occurs between the hydroxide ions associated with the dissolved salts of sodium and potassium and the silica molecules of certain imperfectly crystallized siliceous rocks. In fact the alkalis do not actually attack the reactive silica. The importance of the alkalis is that their presence in high concentrations in the pore solution results in an equally high concentration of OH^- ions (to maintain charge equilibrium). It is this high OH^- concentration, and thus high pH value, that leads to the initial breakdown of reactive silica components in the aggregates. The reaction produces a silica gel that will expand in the presence of moisture. The gel that is formed at the aggregate surface and before hardening is high-lime gels that are thought to be innocuous and unable to expand. It is of special interest to know that although, the alkali-silica reaction is very detrimental to the concrete stability, this chemical reaction can to some extent increase the strength of the concrete. This increase in strength is usually due to the filling of bond-area with cementitious reaction products that have not caused any deleterious expansion. This process may be considered similar to the pozzolanic reaction in concrete (Hadlington, 2002).

The expansion values of the waste glass mixes at 3, 7 and 14 days age are shown in Figure 7. It is very interesting that with the increase in waste glass contents to 20%, there is a clear reduction in the expansion of the specimen. The percentage reductions in expansion at 14-day age for 5%, 15% and 20% compared to the controlled mix are 20%, 56% and 70% respectively. This decrease in the expansion of the mixes containing waste glass as aggregate replacement may be attributed to the reduction of available alkali due to the consumption of lime by reaction with finely waste glass and the expected reduction of the system alkalinity. The degree of ASR for all mixes also increases with the hydration process, showing a polynomial progression of expansion (Table 6). However, a scrutiny of the coefficients 'a', 'b' and 'c' indicates that the level of polynomial progression decreases with the content of waste glass increases in the mixes.

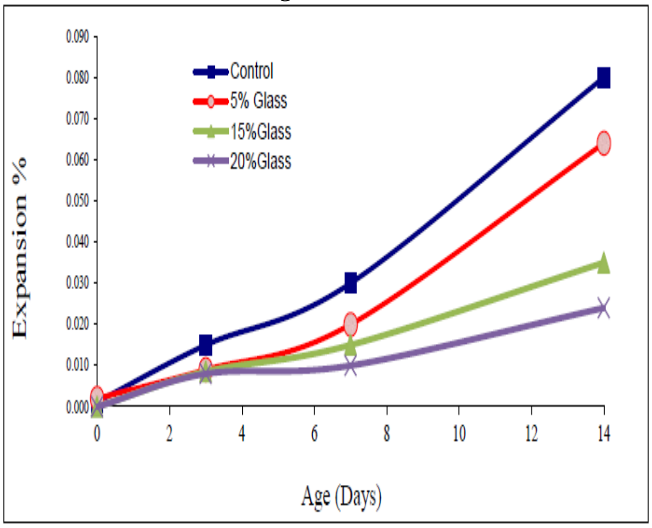

Figure 7. Expansion of waste glass mixes

Table 6. Polynomial fit of expansion with hydration time (y=ax2+bx+c)

Waste glass (%)	a	b	c	R2
Control	0.0002	0.0029	0.0023	0.9972
5	0.0002	0.0009	0.0027	0.9984
15	0.00003	0.0002	0.0007	0.9935
20	0.00001	0.0014	0.0011	0.9646

V. Conclusions

- The slump of concrete containing waste glass as fine aggregate replacement decreased with increases in the waste glass content, but in spite of this decline in the slump, the mixes remained good workability.
- Compressive strength of the concrete with partial replacement of sand by finely crushed waste glass increased with the increment ratio of waste glass, especially at the later ages, with compressive strength at 28 days being 5.28% higher compressive strength for 20% replacement compared to controlled concrete, which also indicated the contribution of pozzolanic reaction.
- Water absorption decreased with increase waste glass aggregate ratio. The highest reduction was obtained with 20% of glass aggregate replacement with a reduction of 14.68% at 28-day age compared to control.
- The ultrasonic pulse velocity for mixes containing different ratios of waste glass as aggregate replacement showed slightly lower than those of the controlled mix and pulse velocity for all mixes at -28 days age were higher than 4 km/s, which qualified these as good concrete, indicating a denser internal concrete structure or more consistent structure.
- There was a clear reduction in the expansion of the waste glass concrete. The maximum expansion was recorded with reference mix at 14-days, on other hand the percentage of reduction in expansion at-14 days for 20% of glass aggregate is 70% compared with controlled mix, showing an alkali–silica reaction in concrete which occurred between the active silica of waste glass and alkali of cement paste.

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