Effect of Particle Size of Waste Glass on Mechanical Properties of Concrete

Hassan Juma Abd   Riyadh Ibrahim Atiyah   Abdaljaleel Mohammed Hashim
Directorate of Research and Nuclear Applications
Ministry of Science and Technology, Baghdad-Iraq
hassanjabd@yahoo.com

Abstract

Three groups of concrete containing waste glass of various particles sizes were prepared, Group A (19- 4.75) mm, Group B (4.75- 0.15) mm, and Group C (< 75) μm. The waste glass was used to replace coarse aggregate in one group and fine aggregate in two groups in proportions of (10%, 20%, 30%, and 40%) by weight. All the mixtures were proportioned with a constant water to cement ratio (w/c) of 0.4 by weight, In this research the specimens were investigated to specify the effects of the particles sizes of waste glass and the content of waste glass on compressive strength, flexural strength, and water absorption at (7 and 14) days of immersion, compared with ordinary specimen. The experimental results showed that the compressive strength and flexural strength increased with the increase of waste glass content up to 30%, and the maximum values were with particles sizes (< 75) μm, at (14) days. While the water absorption was decreased with increased of waste glass content and decreasing the particles sizes, and the minimum values were with particles sizes (< 75) μm, at (14) days. Therefore, the addition of waste glass was improved the mechanical properties of concrete.

Keywords: Concrete, Waste Glass, Compressive Strength, Flexural Strength, and Absorption.

تاثير الحَجم الحُبيبي لمُخلفات الزُجاج على الخَواص الميكانيكية للخرسانة

حسن جمعة عبد   رياض ابراهيم عطية   عبد الجليل محمد هاشم
مديرية البحوث والتطبيقات النووية
وزارة العلوم والتكنولوجيا، بغداد - العراق

الخلاصة

تم تحضير ثلاث مجاميع من الخرسانة تحتوي على نفايات الزجاج بأحجام حبيبية مختلفة وهي مجموعة A (19-4.75 mm) ومجموعة B (4.75- 0.15 mm) ومجموعة C (< 75 μm) ، حيث تم أستخدام نفايات الزجاج بدلاً من الركام الناعم (الرمل) في مجموعة (B) و (C) والركام الخشن (الحصى) في مجموعة (A) وبالنسب (10%, 20%, 30%, and 40%) مع ثبات نسبة الماء الى السمنت (w/c) ولجميع العينات وهي (0.4) وزنياً، تم في هذا البحث دراسة تاثير الحجم الحبيبي لنفايات الزجاج ومحتوى نفايات الزجاج على بعض الخواص الميكانيكية للخرسانة مثل مقاومة الأنضغاطية ومقاومة الأنثناء وأمتصاصية الماء لعمر

أنضاج (7 أو 14) يوم. بينت النتائج العملية زيادة كل من مقاومة الأنضغاط ومقاومة الأنثناء بزيادة محتوى نفايات الزجاج الى النسبة 30% وكانت أعلى قيم عند (14) يوم عندما كان الحجم الحبيبي لنفايات الزجاج أقل من (75) µm ، بينما أنخفضت الأمتصاصية للماء بزيادة محتوى نفايات الزجاج ونعومة الحجم الحبيبي لها، وكانت اقل قيم للأمتصاصية عند (14) يوم عندما كان الحجم الحبيبي لنفايات الزجاج أقل من (75) µm . لذا فان اضافة نفايات الزجاج أدى الى تحسن الخواص الميكانيكية للخرسانة.

الكلمات المفتاحية: الخرسانة، نفايات الزجاج، مقاومة الأنضغاطية، مقاومة الأنثناء ، الأمتصاصية.

Introduction

Glass recycling is the process of turning waste glass into usable products. A glass is defined as an inorganic product of fusion which has been cooled to a rigid condition without crystallization. Traditional methods of waste glass recycling need to melt the waste glass to reproduce new glass containers; this technique has greatly reduced the energy needed in the furnace, the application of glass in architectural concrete still needs improvement [1]. The collected waste glass is usually colour mixed and with the presence of dirt which are barriers for its reuse for glass manufacturing. Comparatively, mechanically crushing of large quantities of waste glass into cullet and reuse as aggregate substitutes in concrete is a much more economical way for waste glass recycling. In addition, the cleanliness requirements of waste glass cullet to be used in concrete are also relatively lower compared with the traditional recycling method. There are many studies about using waste glass in concrete: M. Mageswari and B.Vidivelli investigated the possibility of using SGP (Sheet glass powder) as a replacement in fine aggregate for a new concrete. Natural sand was partially replaced (10%, 20%, 30%, 40% and 50%) with SGP -Sheet glass powder- The test results indicate that it is possible to manufacture concrete containing Sheet glass powder (SGP) with characteristics similar to those of natural sand aggregate concrete provided that the percentage of SGP as fine aggregate is limited to 10-20%, respectively [2], Edson Jansen, et al. show that the use of flat glass powder in place of sand in 5%, 10% and 20% percentages, at w/c (water/cement) ratios of 0.50, 0.55 and 0.58 is feasible for the production of an environmentally appropriate and structurally applicable concrete [3]. Vikas Srivastava, et al. indicated that Waste glass can effectively be used as coarse aggregate replacement (up to 50%) without substantial change in strength [4]. Zhitong Yao, et al. their work presents a comprehensive overview of literature reporting on the reuse of cathode ray tube CRT glass to prepare glass-ceramics; cement mortar, paste, and concrete. CRT glass possesses reasonable intrinsic strength, low water absorption and rich in silica, which makes the glass suitable for use as sand or pozzolan in construction materials [5]. Saman Rahat, et al. demonstrate that waste glass was used to replace fine and coarse aggregate in proportions of 0%, 5%, 10%, 15% and 20%.The experimental results showed that the workability improved with the increase of waste glass content. In addition, the results prove that glass as aggregates have enhanced the mechanical properties and water absorption [6]. D Rajitha, et al. they utilized of waste glass as fine total and coarse totals substitution in concrete. The examination showed that 5% Waste glass can viably be utilized as fine aggregate and coarse aggregate substitution without generous change in quality [7]. Abdelmaseeh and Gailan were used windows waste glass as a partial replacement of coarse aggregates with 0, 20, 25, and 30 percentages of replacement by weight. The best effect on the mechanical properties was observed at 25% WG percentage, and the increases in compressive, splitting tensile and flexural strengths at 28-day age were 30%, 38% and 31 %, respectively [8]. Mohajerani, et al. from the literature review conducted, they concluded that crushed waste glass CWG has potential use as an aggregate in construction materials, such as in concrete and asphalt mixtures [9]. In this work, we will study the effects of waste glass as a fine aggregate and coarse aggregate partial replacement materials at different particles sizes in concrete on the mechanical properties of concrete.

Experimental Part

In this research waste glass was assembled of repeatedly washed with water and dried at 80^0 C for 24hr. then crushing, grinding and sieving into three different particles sizes groups, namely: Group A (19- 4.75) mm, Group B (4.75- 0.15) mm, and Group C (< 75) µm, as shown in figure (1).

To study the effect of particle size of waste glass on mechanical properties of concrete we used Portland cement with the specific gravity of 2.6 gm/cm^3, the crushed stone with nominal maximum size of (5-19 mm) was used as the coarse aggregate, and the sand was used as the fine aggregate in the concrete mixtures, with particle size less than (4.75 mm) [10]. The control mix of the concrete was designed with a mix ratio of (1:2:4) of (cement: sand: coarse aggregate) by weight with (0.4) of water-cement (w/c) ratio according to ACI 211.1 with compressive strength 30-35 MPa, the chemical composition of waste glass, sand and cement by using Spectro analytical instruments model XEPOS fluorescent x-ray (XRF) is presented in table (1).

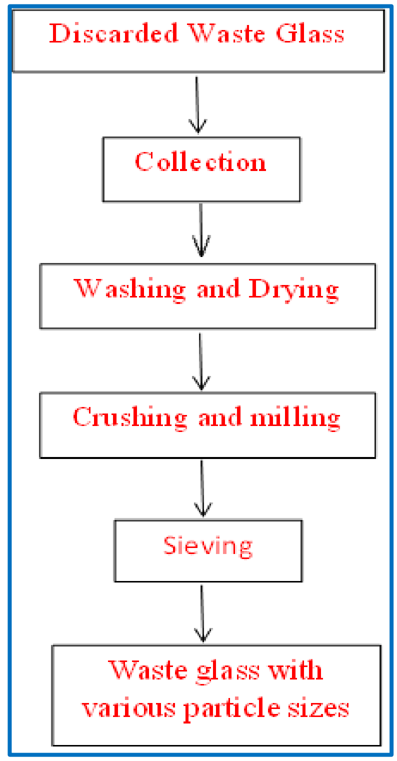


Figure (1) Process of waste glass preparation.

Table (1) Chemical Composition of Waste Glass, Sand and Cement by using (XRF).

No.	symbol	Concentration of waste glass %	Concentration of sand %	Concentration of cement %
1	Na	< 0.22	< 0.30	< 0.29
2	Mg	0.096	0.099	< 0.042
3	Al	< 0.0100	0.0766	0.1505
4	Si	8.826	3.421	2.033
5	P	0.00544	0.01230	0.00463
6	S	0.00160	0.2609	0.4213
7	Cl	< 0.00006	< 0.00020	< 0.00031
8	K	0.0177	0.2710	0.6501
9	Ca	5.532	8.851	38.35
10	Ti	0.06297	0.03233	0.1135
11	V	< 0.00091	< 0.00097	< 0.0028
12	Cr	0.00194	0.0065	0.0321
13	Mn	0.00164	0.01003	0.1162
14	Fe	0.02220	0.6795	2.940
15	Co	0.00128	0.00110	0.0086
16	Ni	0.00113	0.00161	0.01696
17	Cu	0.06202	0.00036	0.00259
18	Zn	0.02804	0.00098	0.00551
19	Ga	< 0.00013	< 0.00015	0.00047
20	Ge	< 0.00011	< 0.00014	< 0.00024
21	As	< 0.00014	0.00008	< 0.00063
22	Se	< 0.00007	0.00012	< 0.00016
23	Br	0.00009	0.00010	0.00020
24	Rb	0.00013	0.00098	0.00251
25	Sr	0.00694	0.03320	0.05402
26	Y	0.00136	0.00158	0.00185
27	Mo	< 0.0022	< 0.0021	< 0.0043
28	Ag	< 0.00039	< 0.00046	< 0.00066
29	Cd	< 0.00046	< 0.00048	< 0.00060
30	Sn	0.00469	< 0.00084	< 0.00070
31	Sb	< 0.00073	< 0.00073	0.00079
32	Te	0.00209	< 0.00075	< 0.0013
33	I	0.00259	< 0.0016	< 0.0023
34	Ba	< 0.0032	< 0.0024	0.0614
35	W	< 0.00086	< 0.00051	< 0.0010
36	Hg	< 0.00018	0.00032	0.00045
37	Ti	< 0.00017	< 0.00018	< 0.00046
38	Pb	0.00276	0.00064	0.02275
39	Bi	< 0.00015	0.00016	0.00070
40	Th	< 0.00015	0.00045	< 0.00034
41	U	< 0.00015	0.00031	< 0.00038

Waste glass was used to replace fine aggregate (sand) and coarse aggregate in proportions of (10%, 20%, 30% or 40%) by weight, beside one mix without waste glass as reference. Table (2) shows the concrete mix compositions for the samples.

Table (2) The mix designs concrete samples.

group		waste glass %	(gm/cm^3)					w/c
			Cement	Coarse aggregate	Fine aggregate (sand)	Waste glass	Water	
A	A0	0	288	1152	576	0	115.2	0.4
	A10	10	288	1036.8	576	115.2	115.2	0.4
	A20	20	288	921.6	576	230.4	115.2	0.4
	A30	30	288	806.4	576	345.6	115.2	0.4
	A40	40	288	691.2	576	460.8	115.2	0.4
B	B10	10	288	1152	518.4	57.6	115.2	0.4
	B20	20	288	1152	460,8	115.2	115.2	0.4
	B30	30	288	1152	403.2	172.8	115.2	0.4
	B40	40	288	1152	345.6	230.4	115.2	0.4
C	C10	10	288	1152	518.4	57.6	115.2	0.4
	C20	20	288	1152	460,8	115.2	115.2	0.4
	C30	30	288	1152	403.2	172.8	115.2	0.4
	C40	40	288	1152	345.6	230.4	115.2	0.4

Specimens were prepared with the geometry of (100×100×100) mm for compressive strength test (ELE-international-2000 KN) and (20×20×70) mm for flexural strength test (Tinus Olsen model H50KT). Figure (2) shows the specimens after removing from curing cabinet before testing.

After removed from the curing cabinet, the specimens were dried for 24 hours and then dipped with water for 7 days or 14 days according to ASTM C31/C31M. The compressive strengths and flexural strengths of various concrete mixtures were determined at 7 or 14 days. Figure (3) shows the specimens after testing.

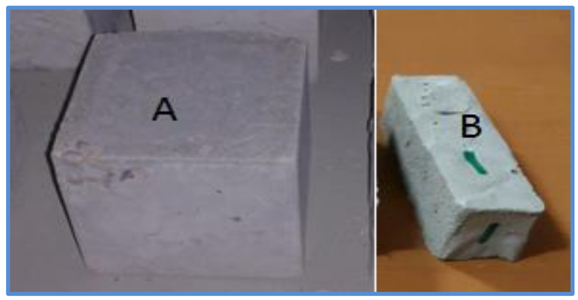


Figure (2) The specimens before testing: (A) concrete cubes (100x100x100) mm for compressive strength, and (B) concrete prisms (20x20x70) mm for flexural strength

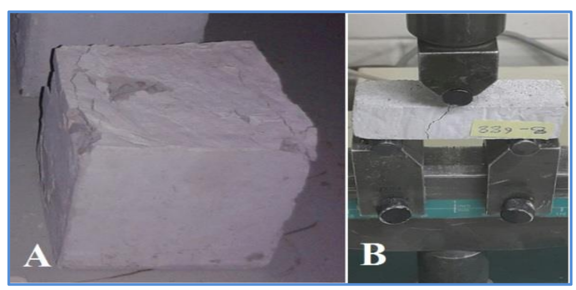


Figure (3) The specimens after testing: (A) concrete cubes (100x100x100) mm for compressive strength, and (B) concrete prisms (20x20x70) mm for flexural strength.

The water absorption of concrete cubes (100x100x100) mm was calculated through Eq. (1).

$$Wa(\%) = \left(\frac{W_2 - W_1}{W_1}\right) X100 \quad \dots (1)$$

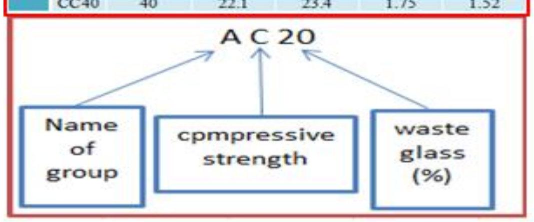
Where: W_a is the water absorption, W_1 is the weight before dipped, and W_2 is the weight after dipped [11].

Results and Discussion

The compressive strength and the water absorption of the concrete cubes specimens (100x100x100) mm after (7 or 14) days are summarized in Table (3). Each presented value is the average of three measurements. The particle size of waste glass was in variation of three groups, Group A (19- 4.75) mm, Group B (4.75- 0.15) mm, and Group C (< 75) µm, and the content of waste glass replaced fine aggregate (sand) and coarse aggregate was in proportions of (10%, 20%, 30% or 40%).

Table (3) Results of compressive strength and water absorption for cubic specimens of size (100x100x100) mm, after (7 or 14) days

group		Glass %	Compressive strength (N/mm²)		Water absorption %	
			7 day	14 day	7 day	14 day
A	AC0	0	18.4	21.2	2.40	2.31
	AC10	10	20.2	23.1	2.31	2.24
	AC20	20	22.6	25.2	2.23	2.10
	AC30	30	24.3	27.3	2.05	1.82
	AC40	40	21.2	22.4	1.9	1.73
B	BC10	10	20.8	23.2	2.20	2.17
	BC20	20	23.2	25.4	2.15	2.01
	BC30	30	24.6	27.6	1.92	1.85
	BC40	40	21.9	22.8	1.83	1.63
C	CC10	10	21.4	24.2	2.13	2.05
	CC20	20	24.2	25.6	2.04	1.95
	CC30	30	25.3	28.2	1.83	1.63
	CC40	40	22.1	23.4	1.75	1.52



Compressive strength is typically the most important mechanical property of concrete, because it correlates strongly with other properties such as tensile strength and many durability properties. Figures (4) and (5) illustrate the effect of the particle size of waste glass and the content of waste glass into the concrete mix after (7 or 14) days on the compressive strength and water absorption of concrete. Fig. (4) indicates increasing in compressive strength with decreasing the particles size and increasing in the content of waste glass up to 30% after (7 or 14) days. This result agreed with the results of Bhandari, et al. which demonstrate that the Fine aggregates were replaced by waste glass aggregate as 10%, 20% and 30% by weight, where fine glass aggregate of size 600µm – 1.18mm, and coarse glass aggregate of size 1.18mm – 4.75mm, they concluded that the particle size less than 1.18 mm get higher strength than that of particle size ranges from 4.75 mm to 1.18 mm [12]. Also, Shayan and Xu found that 30% glass powder could be incorporated as aggregate or cement replacement in concrete without any long term detrimental effects glass is unstable in the alkaline environment of concrete and could cause deleterious alkali-silica reaction problems. This property has been used to advantage by grinding it into a fine glass powder (GLP) for incorporation into concrete as a pozzolonic material [10], the increasing in the content of waste glass lead to appear an internal chemical reaction between the alkaline components in the cement and active silica-based mineral constituents of some aggregates. The reaction results in the formation of a gel that absorbs water, expand, and therefore exerts internal pressure which sometimes can be far in excess of what concrete can sustain, thereby causing the formation of micro-cracks [13, 14]. The maximum compressive strength was (1.63 N/mm^2) of sample CC30 at (14 days) when the waste glass content was 30%, and the particles size C (< 75) µm. It can be observed from figure (4) that compressive strength for waste glass concrete like normal concrete increases with curing age comparing with sample AC0 which contents zero percentage of waste glass.

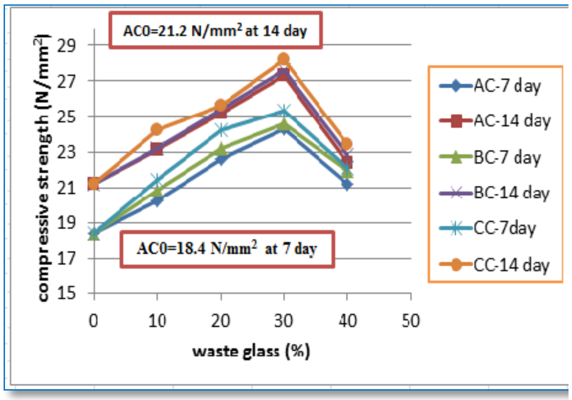


Figure (4) Variation in compressive strength vs. waste glass content and particles sizes of cubic specimens (100x100x100) mm after (7 or 14) days.

Figure (5) shows decreasing in water absorption with increasing of waste glass content and decreasing particles sizes, this result agrees with the study of M. Iqbal Malik et al. that fine aggregates were replaced by waste glass powder as 10%, 20%, 30% and 40% by weight, the results concluded the permissibility of using waste glass powder as partial replacement of fine aggregates up to 30% by weight for particle size of range 0-1.18mm, and with increase in waste glass content, percentage water absorption decreases [15].

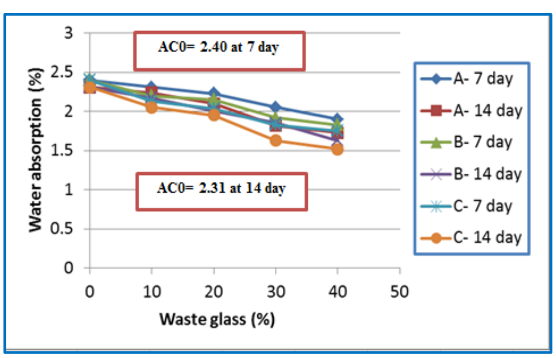
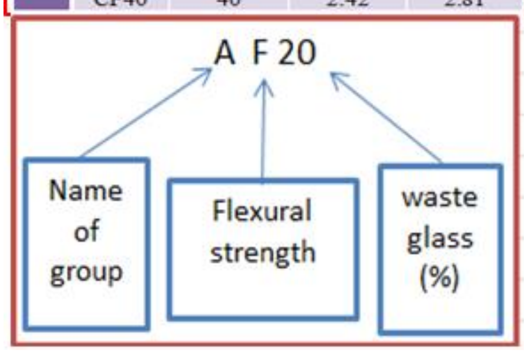


Figure (5) Variation of water absorption with waste glass content and particles sizes of cubic specimens (100x100x100) mm after (7 or 14) days.

The results of Flexural Strength with waste glass content and particles sizes of prisms specimens (20x20x70) mm after (7 or 14) days are summarized in Table (4). The specimen (CF30) which contents 30% waste glass and particle size Group C (< 75) µm, have Flexural strength (3.41 N/mm^2) after 7 days of immersion and (3.85 N/mm^2) after 14 days of immersion, as shown in figures (6) and (7). The values of Flexural strength were measured by using test (Tinus Olsen model H50KT).

Table (4) Results of Flexural Strength of waste glass content and particles sizes of prisms specimens of size (20x20x70) mm, after (7 or 14) days.

group		Glass %	Flexural strength (N/mm²)	
			7 day	14 day
A	AF0	0	1.62	1.93
	AF10	10	1.95	2.21
	AF20	20	2.31	2.32
	AF30	30	2.52	2.65
	AF40	40	1.73	1.95
B	BF10	10	2.33	2.53
	BF20	20	2.62	2.85
	BF30	30	3.04	3.26
	BF40	40	2.10	2.30
C	CF10	10	2.63	2.84
	CF20	20	3.22	3.65
	CF30	30	3.41	3.85
	CF40	40	2.42	2.81



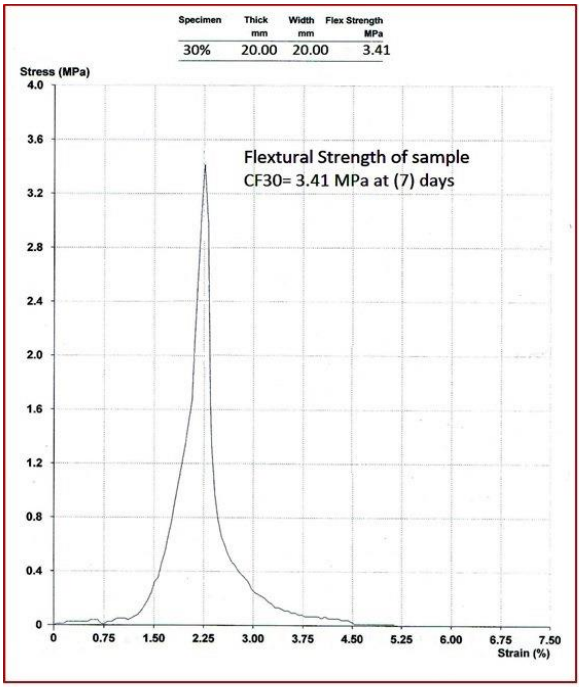


Figure (6) Flexural strength of the sample CF30=3.41 MPa after (7 days) water immersion by using test (Tinus Olsen model H50KT).

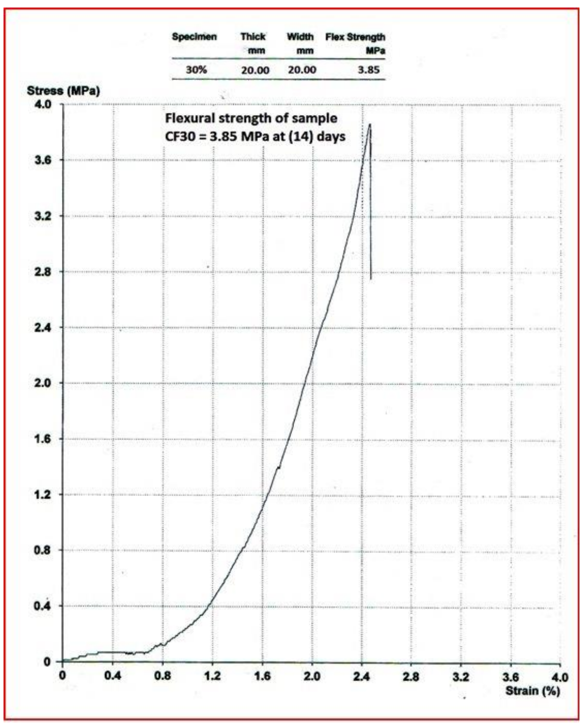


Figure (7) Flexural strength of the sample CF30=3.85 MPa after (14 days) water immersion by using test (Tinus Olsen model H50KT).

Fig.(8) illustrates increasing in Flexural Strength with decreasing in the particles size and increasing in the content of waste glass up to 30% after 7 or 14 days where the maximum value of Flexural Strength was (3.85N/mm^2) of the sample (CF30) after (14 days) when the waste glass content is 30% and the particle size Group C (< 75) µm.

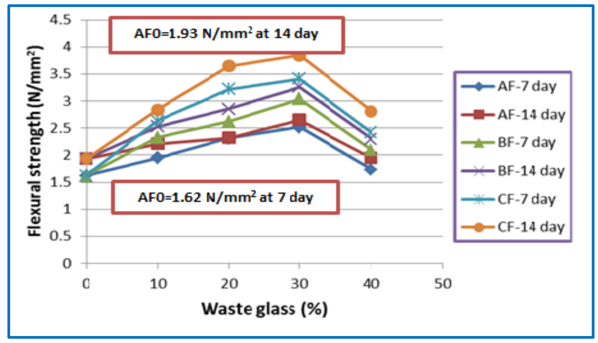


Figure (8) Variation in Flexural Strength vs. waste glass content and particles sizes of prisms specimens (20x20x70) mm after (7 or 14) days.

It can be observed from figure (8) that Flexural Strength of waste glass concrete like normal concrete increases with curing age comparing with sample AF0. The results of Compressive Strength and Flexural Strength of waste glass concrete of all specimens after 30% glass were decreasing due to the damaging expansion in the concrete caused by ASR (Alkali Silica Reaction) between high-alkali pore water in cement paste and reactive silica in the waste glasses. The chemical reaction between the alkali in Portland cement and the silica in aggregates forms silica gel that not only caused crack upon expansion, but also weakened the concrete and shortens its life, Mavroulidou et al. show that fine glass cullet aggregate in concrete was used together with binders partially replacing ordinary Portland cement (OPC) so that alkali-silica reaction problems are overcome, and they was concluded that fine glass cullet can be used as a substitute to fine concrete aggregate without apparent problems for resulting concrete [16]. ChangLi et al. show that fine lightweight aggregate (FLWAs) may be a possible solution for ASR mitigation. The study investigated how commonly used FLWAs, expanded slate, shale, and clay can mitigate and reduce ASR in concrete using the accelerated mortar bar test (AMBT), concrete prism test (CPT), pore solution analysis and scanning electron microscope (SEM) analysis [17]. However, we use waste glass in concrete and within a limited range as a partial substitute so as not to appear strong effects of the reaction of alkali-silica and give negative results of concrete properties, and to be a partial solution for the disposal of waste glass in an environmentally friendly method.

Conclusions

1- At the rate of 30% waste glass replacement of sand and coarse aggregate meets maximum values of compressive and flexural strengths as compared to that of control sample and other percentage of replacement of sand and coarse aggregate. The increasing of waste glass caused an internal chemical reaction between the alkaline components in the cement and active silica--based mineral constituents of some aggregates. The reaction results in the formation of a gel that absorbs water expand, and therefore exerts internal pressure which sometimes can be far in excess of what concrete can sustain, thereby causing the formation of micro-cracks.

2-With increase in waste glass content, percentage water absorption decreased.

3-With decrease in the particle size of waste glass, percentage water absorption decreased.

4-From results, it is concluded that particle size less than 75 µm (group C) get higher strength than that of particle size of group A (19- 4.75) mm, and group B (4.75- 0.15) mm,

5-Use of waste glass in concrete will eradicate the disposal problem of waste glass.

References

1. S.P. Gautam, Vikas Srivastava and V.C. Agarwal, (2012) “Use of glass wastes as fine aggregate in Concrete”. J. Acad. Indus. Res. 1(6): 320-322.
2. M. Mageswari1, and Dr. B. Vidivelli (2010) “The Use of Sheet Glass Powder as Fine Aggregate Replacement in Concrete”. Open Civil Eng. J. 4, pp. 65-71.
3. Edson Jansen Pedrosa de Miranda Júnior, Helton de Jesus Costa Leite Bezerra, Flávio Salgado Politi, and Antônio Ernandes Macêdo Paiva (2014). “Increasing the Compressive Strength of Portland cement Concrete Using Flat Glass Powder”. Mater. Res. 17(1), pp. 45-50.
4. Vikas Srivastava , S. P. Gautam, V. C. Agarwal , P. K. Mehta, (2014) “Glass Wastes as Coarse Aggregate in Concrete”J.Environ. Nanotechnology, Vol. 3(1), pp. 67-71.
5. Zhitong Yao, Tung-Chai Ling, P.K. Sarker, Weiping Su, Jie Liu, Weihong Wu, Junhong Tang, (2018) "Recycling difficult-to-treat e-waste cathode-ray-tube glass as construction and building materials: A critical review" Renewable and Sustainable Energy Reviews 81 (2018) 595–604.
6. Saman Rahat Dahmardeh, Mohammad Hassan Mirabi Moghaddam, and Mohammad Saleh Sargazi Moghaddam, (2014) "Investigate Fresh and Hardened Properties of Self-Compacting Concrete Containing Waste Glass" American Journal of Civil and Structural Engineering (AJCSE), 1(3), pp. 81-87
7. D Rajitha, V Srinivas, and M Zoheb Nawaz (2017) "experimental study on partial replacement of fine and coarse aggregate with waste glass"

International Journal of Civil Engineering and Technology (IJCIET), Volume 8, Issue 10, October 2017, pp. 1521–1525.

8. Abdelmaseeh Bakos Keryou and Gailan Jibrael Ibrahim, (2014) " Effect of Using Windows Waste Glass as Coarse Aggregate on some Properties of Concrete" Eng. & Tech. Journal ,Vol.32, Part (A), No.6, pp.1519-1529.
9. Abbas Mohajerani John Vajna ,Tsz Ho Homan Cheung, Halenur Kurmus, Arul Arulrajah , Suksun Horpibulsuk (2017) "Practical recycling applications of crushed waste glass in construction materials: A review" Construction and Building Materials, Volume 156, 15 December 2017, Pages 443-467
10. Ahmad Shayan, and Xu A. (2004) "Value-added utilization of waste glass in concrete". Cement Concrete Res. 34 (1): 81–89.
11. Liang Hong, Zhu Huiying, and Byars Ewan A. "Use of waste glass as aggregate in concrete" 7th UK CARE Annual General Meeting, UK Chinese Association of Resources and Environment, Greenwich, 15 September 2007, pages 1-7.
12. Bhandari P.S., Dhale S.A., Mr. Ghutke V.S., and Mrs. Pathan V.G., (2014) "Influence of Fine Glass Aggregate on Cement Mortar". Int. J. Eng. Computer Sci. 3(1): 3607-3610.
13. H. Marzouk, and S. Langdon, "The effect of alkali-aggregate reactivity on the mechanical properties of high and normal strength concrete" Cement & Concrete Composites 25, (2003) pp. 549–556
14. R.N. Swamy, (2003) "The Alkali-Silica Reaction in Concrete" British Library Cataloguing in Publication Data ISBN 0-203-03663-8 Master e-book ISBN.
15. M. Iqbal Malik, Muzafar Bashir, Sajad Ahmad, Tabish Tariq, and Umar Chowdhary (2013). "Study of Concrete Involving Use of Waste Glass as Partial Replacement of Fine Aggregates". IOSR J. Eng. 6(7), pp. 8-13.
16. Mavroulidou, M. Candengue, D. and Ramachandran, S. (2011) "use of glass cullet aggregate in concrete with binders counteracting Alkali-Silica reaction" proceedings of the 12th international conference on environmental science and technology, Rhodes, Greece 8-10 September 2011, pp A-1202— A-1209.
17. ChangLi,Michael D.A. Thomas, Jason H.Ideker," A mechanistic study on mitigation of alkali-silica reaction by fine lightweight aggregates" Cement and Concrete ResearchVolume 104, February 2018, Pages 13-24.