Wasit Journal of Engineering Sciences
VOLUME: (6), NO. : (2) 2018

Partial and Full Replacement of Silica Sand by Fine Recycled Glass in Cementitious Composites

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Submitted: 21/5/2018
Accepted: 6/6/2018

Abstract— One of the major concerns currently and within the close future is the adequate management and efficient reuse and recycling of wastes, which reduces the natural sources and energy consumption. Millions of tons of waste glass are discharged around the world annually. One of the successful policies of the recycling of waste glass is the use in the construction industry where it can be used as aggregate or cement replacement. In the current study, fine recycled glass with granular size of 0.075 to 0.3 mm was used as silica sand replacement in cementitious composites incorporated fly ash and no coarse aggregate. Cube and prism specimens were prepared with four replacement ratios of 0, 25, 50, and 100% to evaluate the compressive strength, the modulus of rupture, and the expansion. The test results showed that 50% and 100% replacements of silica sand by fine glass enhanced both the compressive strength and the modulus of rupture. For mixtures with 100% fine recycle glass, the compressive strength and the modulus of rupture increased by 25% and 33.6%, respectively, compared to mixtures with 100% silica sand. Moreover, the expansion was found to be reduced by approximately 30% as the silica sand was fully replaced by fine glass.

Keywords— *Recycled glass, fine glass, silica sand, cementitious composites*

الإستبدال الجزئي والكلي لرمل السيليكا في المركبات الأسمنتية بزجاج ناعم معاد

صلال راشد عبد، *ياسر حسين دايخ ، سجاد حسين علي ، احمد لطيف كاظم*

الخلاصة :إحدى أهم المشاكل الحالية وفي المستقبل القريب هي الإدارة السليمة والتدوير وإعادة الاستخدام الكفوءة لمخلفات المدن والذي يؤدي الى تقليل استهلاك الموارد والطاقة. في كل عام يتم طرح ملايين الأطنان من مخلفات الزجاج حول العالم. إحدى أهم السياسات في تدوير مخلفات الزجاج تكمن في إستخدامها في الصناعات الإنشائية حيث يمكن إستخدامها كتعويض عن الركام او الأسمنت. تم إستخدام ركام زجاج ناعم بقياس ٠.٠٧٥ الى ٠.٣ ملم في هذه الدراسة كتعويض عن رمل السيليكا في المركبات الأسمنتية التي تحوي رماد متطاير ولا تحوي ركام خشن . تم إعداد نماذج مكعبة وموشورية بأربعة نسب تعويض تساوي ٠، ٢٥، ٥٠ و ١٠٠% لدراسة مقاومة الانضغاط، معاير الكسر والتمدد. بينت نتائج الفحوصات أن تعويض رمل السيليكا بركام الزجاج الناعم بنسب تساوي ٥٠ و ١٠٠% حسنت كل من مقاومة الإنضغاط و معاير الكسر . في الخلطات التي تحوي على ١٠٠% ركام الزجاج الناعم إزدادت مقاومة الإنضغاط ومعاير الكسر بمقدار ٢٥% و ٣٣.٦% على التوالي مقارنة مع الخلطات التي تحوي ١٠٠% رمل السيليكا. بالإضافة الى ذلك فإن التمدد قل بما يقارب ٣٠% في حالة التعويض الكامل لرمل السيليكا بركام الزجاج الناعم.

I. INTRODUCTION

As the population of world increases, the need for residence buildings, schools, hospitals, roads, and other municipal facilities boosts. Thus, the construction industry consumes more and more natural resources and energy. Every year, an average of about 3,000 million tons of constructional materials is used in the construction industry [1]. The industry and transportation of such amount of materials consume huge amount of energy, which is estimated to reach 7% of the total world consumed energy [2]. The production of cement only is responsible of approximately 8% of the global CO_2 emission [3]. On the other hand, in many of the leading countries in waste materials and recycling management, the construction industry is one of the most active fields where the recycled materials are efficiently reused. The recycling of construction and demolition waste is a priority in construction industry. However, other waste materials such as fly ash, blast furnace slag, and glass can also be efficiently recycled as useful minerals in concrete industry.

The recycling, reuse, and management of waste glass, which is mainly represented by container glass, became one of main problems in large cities. The annual waste container glass discharge of the United States, for example, is more than 8 million tons [4]. In Hong Kong, approximately 3.7% of the total municipal solid waste was waste glass [2], with approximately 370 tons daily discharge of container glass only [5]. In the United Kingdom, more than 6% of the house hold waste is glass containers, which is approximately 1.6 million tons in 2001/2002 [6]. The annual output of waste glass in Egypt is approximately 3.5 million tons [3].

Effective scientific researches on the use of glass waste in concrete is returned to the early 1960's, where many researchers [7-9] tried to study the mechanical properties of concrete containing glass aggregate. These researches led to one main conclusion, which is the brittle behavior of such concretes. Within the approaching of the new century, and due to the serious problems of municipal waste and recycling management, the use of glass waste in concrete became the focus of attention. Since that, many researches [10-18] were conducted to deeply investigate the use of waste glass as aggregate. As waste glass contains large quantities of silica and calcium, it has thus pozzolanic properties and hence can be used as a cementitious material. Many previous researches were conducted during the last 15 years to utilize glass powder from waste glass as partial cement replacement [19-25].

This paper presents a part of an experimental program directed to investigate the effect of fine recycled glass on the mechanical properties and durability of cementitious composites. In this paper, the fine glass was used as partial and full replacement of silica sand in cementitious mixes incorporated Portland cement and fly ash. Cubes and prisms were cast to evaluate the compressive strength and modulus of rupture in addition to expansion. To the best of the authors' search and knowledge, no previous researches were found in the literature on such mixes.

II. Required Review of Literature

In literature, there was no complete agreement about the effect of the use of recycled glass both as filler or binder. Some researchers showed positive impact, others showed that the use of recycle glass leads to unfavorable results. Before reviewing some of the experimental literature on this subject, it should be mentioned that waste glass has several forms, each contains different ingredients that can play important role in the microstructural behavior of the concrete mix. However, the one that composes more than 80% of the total glass waste is the soda-lime glass [26]. This type is the mostly used in the production of container glass. The soda-lime glass composes of 66-75% of SiO_2, 12-16% of Na_2O, and 6-12% of CaO, in addition to smaller amounts of Al_2O_3, K_2O, and MgO [27].

The recycled glass can be used as fine aggregate or can be crushed to finer grain sizes and used as partial cement replacement. However, since the glass is rich of silica, the alkali-silica reaction is the main concern facing the potential use of recycled glass in concrete, which makes the concrete more expansive. A literature review carried out by Shi and Zheng [26] summarizes the results of many researches on the expansion of concrete incorporated glass aggregate and glass powder. The review showed that the expansion depends mainly on the type of recycled glass, its color, and its grain size. The green soda-glass was found to cause more expansion than amber glass, while clear soda-glass was reported to be the most reactive [26]. Shao et al. [19] showed that glass with grain size larger than 75 microns is too coarse to afford the minimum required pozzolanic requirements. Researchers at the University of Colombia [28, 29] showed that the increase of expansion due to the alkali-silica reaction increases as the size of particles decrease due to the increase of the surface area-to-volume ratio of these particles, which results in more reaction. However, this observation was found to be true down to a specific particle size, smaller than which, the opposite holds where expansion tends to decrease and compressive strength tends to increase. This size for soda-lime container glass is 1.18 mm [29].

A recent research by Aliabdo et al. [3] attempted to use different levels of replacement (5% to 25%) of glass powder (0.0015-0.07 mm) as cement replacement in normal concrete. They found that the glass powder fulfills the physical, mechanical, and chemical requirements of ASTM C818 for pozzolanic materials. They also found that the use of glass powder up to 15% increases the compressive and tensile strength of cement mortars and concrete .The replacement of cement by 10% of glass powder led to an increase in compressive strength of mortar by 9%. On the other hand, the use of 20% and more of glass powder decreased the compressive strength. Another finding is that the slump is increased by approximately 10 mm for each 5% use of glass powder.

Most recently and most closely to the current research, Soliman and Tagnit-Hamou [30] carried out an experimental study to evaluate the potential of using of glass sand as a replacement of quartz sand in Ultra-High Performance Concrete (UHPC). They found that the optimum mean grain size of glass sand in UHPC is 275 microns. They also found that the use of glass sand can increase the workability of such concrete by approximately 10%. This finding confirms the findings of Aliabdo et al. [3], while it contradicts with findings of former researches [11, 12] who found that glass aggregate leads to lower workability and slump. On the other hand, Soliman and Tagnit-Hamou [30] found that glass sand decreases the compressive strength by approximately 13%.

III. Experimental Program

The experimental program of the current research composes of preparing, casting, and testing of cube and prism specimens of a cementitious mix. Six cubes and three prisms were prepared from each mix. The cubes were 70 mm in side length and were used to evaluate the compressive strength, while the prisms were 70×70×260 mm and were used to evaluate both the expansion and the modulus of rupture. The expansion was tested using a mechanical extensometer with a measurement length of 100 mm. After casting, all specimens were kept in temperature-controlled water containers for curing purposes. The expansion was tested at ages of 1, 2, 3, 4, 5, 6, 7, and 14 days, while the compressive strength and the modulus of rupture were tested at age of 28 days. The central deflection of the prisms was also investigated during the flexural test of the prisms, which was a third-point loading test conforms to ASTM C-78.

The used mix was developed by Victor Li [31] in Michigan University under the name of Engineering Cementitious Composites (ECC). However, the original mix contains 2% PVA fibers, while the current mix does not include any type of fiber. This mix is known to involve self-compacting properties. A rich review about this mix can be found in the literature [31]. In addition to Portland cement, fly ash is also used as binder in this mix with fly ash/cement content of 1.2. Table 1 shows the physical and chemical properties of the used cement and fly ash. The filler of this mix is fine silica sand with filler/binder content of 0.8, while the water/binder content is 0.27. The silica sand used in the current work is produced by Sika with granular size ranging from 0.08 to 0.2 mm and density of 1500 kg/m^3. On the other hand, Sika ViscoCrete-5930 is the high range water reducer additive used in the current mix.

A recycled container glass (bottle glass) was used in this research as a replacement of the silica sand. After collecting the required quantity, the glass bottles were cleaned using tap water and dried in the laboratory environment. Then after, the crushing of these bottles was carried out in two stages. At the first, the glass bottles were crashed using the Los Angeles abrasion machine to particles with maximum size of approximately 5 mm. In the second stage, the crushed quantity was sieved and the fine materials (less than 1.18 mm) were crushed in another crushing machine with fine grinding grips to have the desired granular size. After crushing, the fine materials were sieved to three sizes 0.075, 0.15, and 0.3 mm. Coarse glass grains can cause unfavorable alkali-silica reaction, on the other hand, with grain sizes less than 75 microns, the glass works as pozzolanic material, which is not the goal of this research. Therefore, the materials having granular size larger than 0.3 mm or smaller than 0.075mm were excluded. The fine recycled glass that was used in the mix is 70% of the material retained on the 150 microns sieve and 30% of the material retained on the 75 microns sieve. Fig. 1 shows the second crushing stage of the recycled glass, while Fig. 2 shows a quantity of the fine recycled glass after crushing and sieving.

TABLE 1.CHARACTERISTICS OF CEMENT AND FLY ASH USED IN THIS STUDY

No	Oxide (%)	Cement	Fly ash
1	SiO_2	21.04	56.00
2	Fe_2O_3	5.46	24.81
3	Al_2O_3	2.98	5.3
4	CaO	63.56	4.8
5	MgO	2.52	1.48
6	SO_3	2.01	0.36
7	f-CaO	0.76	-
8	Loss on ignition (%)	1.38	5.78
9	Specific surfaces (m^2/kg)	362	-
10	Specific gravity	3.15	2.20
11	Fineness (% retain in 45 μm)	-	28.99

Fig. 1. Second stage crushing of the recycled glass

Fig. 2. The used recycled glass after crushing

Four mixes were considered in this study, each with different percentage replacement of silica sand by fine recycled waste glass. In the first mix, the filler of the mix was 100% silica sand. This is the reference mix, to which the percentage enhancement or decay of the investigated properties are measured. In the following three mixes, the silica sand was replaced by 25, 50, and 100% of fine glass.

IV. RESULTS AND DISCUSSION

As stated previously, the compressive strength, the modulus of rupture, and the expansion of the four mixes were tested in this study. The following sections summarize the results obtained from the tested specimens.

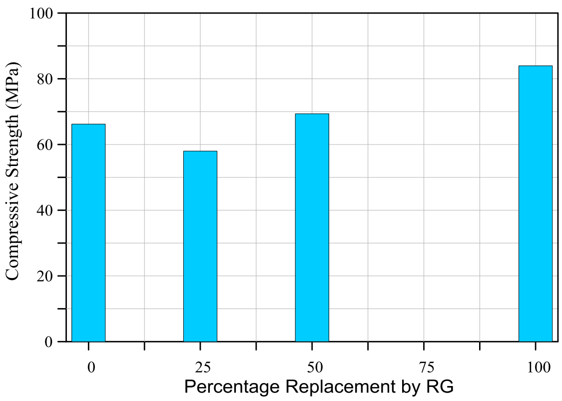

Fig. 3. Effect of replacement of silica sand by recycled glass (RG) on compressive strength

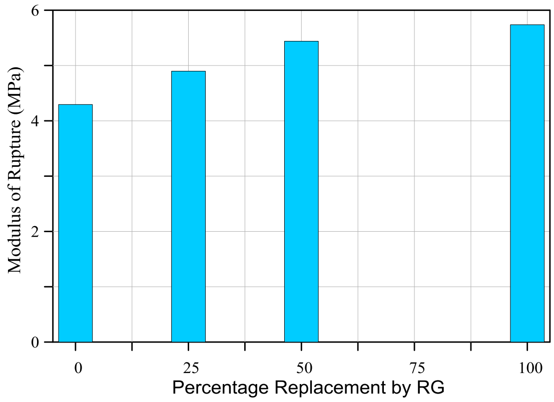

Fig. 4. Effect of replacement of silica sand by recycled glass (RG) on modulus of rupture

A. Compressive Strength

As presented in Fig. 3, the experimental results show that the effect of recycled glass on the compressive strength is dependent of the percentage replacement. The use of low replacement percentage of 25% decreased the compressive strength from 66.2 MPa to 58 MPa, hence, resulted in more than 10% decay. This result confirms the result of Soliman and Tagnit-Hamou [30] who found that fine glass sand causes a 13% decrease in compressive strength. On the other hand, the replacement of 50% of the silica sand by the fine recycled glass increased the compressive strength to 69.3 MPa, which is almost the same as the original strength before replacement (66.2 MPa) with minor increase of less than 5%. The best improvement was obtained when the silica sand was completely replaced by fine glass (100% replacement) as shown in Fig. 3. For the fourth mix where the recycled glass composes 100% of the filler, the compressive strength jumped to 83.9 MPa. This means that the recycled fine glass could enhances the compressive strength by more than 25%.

B. Modulus of Rupture

It is clear from the observation of Fig. 4 that modulus of rupture and hence tensile strength increases as the percentage of recycled glass increase in the mix. The modulus of rupture values of the four cementitious mixes with 0, 25, 50, and 100% replacement of silica sand by fine glass were 4.3, 4.9, 5.4, and 5.7 MPa, respectively. Thus, the percentage increase in modulus of rupture for replacements of 25, 50, and 100 % compared to the reference specimens were 14, 26.6, and 33.6%, respectively. Fig. 5 shows the load-central deflection of the tested prisms. In this figure, two reference specimens were presented against one specimen from each of the rest three mixes. The most deviated two specimens of the reference mix were selected to illustrate the margins of load-deflection behavior of the non-glass mix to evaluate comparatively the load-deflection behaviors of the other three mixes. It is shown that the deflections at each load step of the three specimens with glass fall within the margins of the reference specimens. This means that according to this test, which is not originally directed to evaluate load-deflection behavior of concrete, the effect of glass is insignificant here. However, it should be mentioned that the deflection at each load step increased as the percentage replacement increased and that the specimens with 50% and 100% glass exhibited higher failure load and total deflection. This may lead to a conclusion that the use of glass in favor of silica sand may enhance the ductility. Further tests on thin plates or longer span beams are required to deeply investigate this point.

C. Expansion

The expansion of the 70×70×260 mm prisms was measured in this research using a 100 mm gage length extensometer. This is not the standard method to evaluate the expansion of glass-incorporated mortars, where alkali-silica reaction is the point of investigation. The expansion is measured either using the ASTM C227 bar method, or the ASTM C1260 accelerated bar method. In both methods, 25×25×285 mm mortar bars are placed in NaOH solution (1N NaOH for ASTM C1260) for a specific period and at a specific temperature. The temperature in the accelerated bar method is 80 ^{o}C, while it is 38 ^{o}C in ASTM C227. Therefore, the specimens are measured up to age of 14 days in the accelerated bar method compared to six months in the bar method. In the current study, to better capture the expansion behavior of the specimens, the measurements should last for six months, or at least 3 months. However, due to the short available time for graduation projects, the measurements were stopped after the 14 days records.

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Fig. 6 shows that the four groups of specimens have similar behaviors with time. The increase in expansion during the first week is noticeable, while slower rate is shown during the second week. Another important notice is that the expansion of the reference specimens, specimens with 25% glass, and specimens with 50% glass are approximately the same. At age of 7 days, the three groups expanded by 50 microns, while at age of 14 days, the expansion was 55, 55, and 60 micros, respectively. These values are shown in Figure 6 as the percentage expansion related to the gage length, which is 100 mm.

The distinguishable finding here is that the 100% replacement of the silica sand by recycled glass led to about 30% decrease in expansion. The expansions of the specimens with 100% recycled glass were 35 and 40 microns at ages of 7 and 14 days. Although of the different test method and

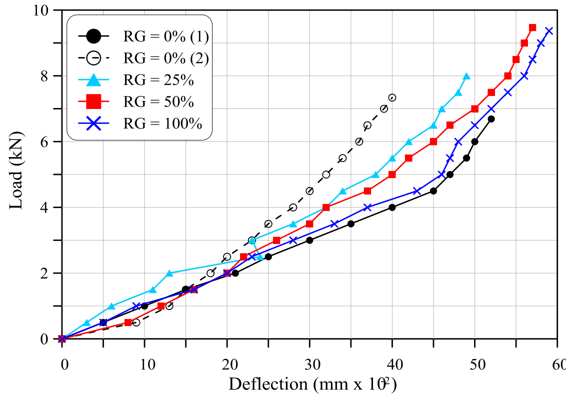

Fig. 5. Load-deflection curves for different recycled glass (RG) replacement ratios

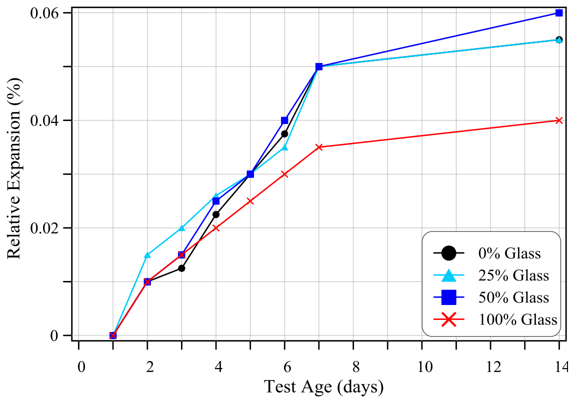

Fig. 6. Percentage relative expansion for different recycled glass (RG) replacement ratios

conditions, the specimen size, and the mix ingredients, it is worthy to discuss the current research results with those from literature. The expansion results of the experimental research program conducted in Colombia University [29] showed that the expansion depends on the particle size and the color of the glass as stated previously in section three. The same study also showed that the expansion increases as the percentage replacement by aggregate increase, where mixes with 100% glass showed approximately 40% extra expansion compared to those with 50% glass for fixed granular size. These results contradict with the results obtained in this study. However, in these tests, blue nonreactive circle sand was mixed with clear soda-lime glass, while the used reference sand in this study is fine silica sand. Moreover, it wasn't specified in the mentioned paper [29], what is the granular size of the used glass. These two points are questionable and may alter the results significantly. Noting that the same study [29] showed that glass with fine size similar to that used in this study exhibited significantly lower expansion values. Liu et al. [32] showed that glass powder when used as cement replacement has inhibitory effect on alkali-silica reaction because of the pozzolanic activity [32], which reduces the expansion compared to reference specimens. This may explains the lower expansion of the 100% glass mix recorded in this study because the used fine glass was all finer than 300 microns with some percentage less than 100 microns, which may exhibits pozzolanic activity.

V. Conclusions

Based on the test results of this study and within the limitations of the investigated parameters, the following can be concluded.

- Fine recycled glass with grading of 0.075 to 0.3 mm can be used efficiently as partial or full replacement of silica sand in cementitious composites incorporated no coarse aggregate. The compressive strength was increased by approximately 25% for specimens with 100% fine glass compared to the reference specimens without glass (100% silica sand). However, the replacement of 50% of the silica sand by fine glass was found to have no significant effect on compressive strength.
- The modulus of rupture was found to increase as the percentage replacement of silica sand by fine glass increase. The percentage increase in the modulus of rupture ranged from approximately14% for 25% fine glass to more than 30% for 100% fine glass.
- Expansion measurements on prism specimens cured in water under standard conditions showed that the expansion trend is approximately the same for specimens with fine glass replacements of 0, 25, and 50%, while the expansion was approximately 30% lower for specimens with 100% fine glass.

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