Optimization of glass powder content in self-compacting concrete as partial replacement of cement

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Abstract—The main aim of the present work is to investigate the fresh and hardened properties of self-compacting concrete by utilization recycled glass powder as partial replacement material for cement and to specify the optimum percent from performance and sustainability point of views. In this study, five mixes were designed with different percentage of grinded glass powder used as cement replacement at 0%, 10%, 20%, 30%, and 40% by weight. Slump flow diameter, time needed to achieve a flow diameter of 500 mm, sieve segregation resistance and L-box height ratio were utilized to examine the rheological properties of the produced self-compacting concrete. For the main mechanical properties, compressive strength at 7, 28, 56 days, splitting tensile, and flexural strengths test at 28 day were conducted. The test results illustrate that the increase in the partial replacement of cement by glass powder led to keep flow ability and caused small decrease in T500 mm time. However, there was slight decrease in the passing ability and better performance in segregation resistance compared to the mix without glass powder. The mechanical properties of the produced mixes increased up to the replacement level of 30%. However, the optimization results using Minitab 18 statistical software deduced that the optimum percent is 24% to achieve optimum performance in terms tested properties and evaluated sustainability aspects.

Keywords—self-compacting concrete, Glass powder, fresh properties, mechanical properties.

1. INTRODUCTION

Self-compacting concrete (SCC) is recognized as a new type of concrete, which provides many important benefits. It is produced with fully compaction under its own weight without the need for external vibration [1]. It has environmental, social and economic benefits as compared with conventionally vibrated concrete and it can be considered as a more sustainable type [2]. In addition, it provides many advantages like a good finishing surface, an excellent construction quality, a short time required for casting, a reduced labor cost and without noise pollution, an ease to cast in congested areas of steel reinforcement which allows more choices in the design of the construction systems [3, 4]. This type of concrete is produced from the same fundamental ingredients as conventional vibrated concrete, i.e. cement, water, aggregate, additives or admixtures [1]. However, the use of high volume of binder content and the need for chemical admixtures to improve the fresh properties might increase in initial cost and prone of initial cracking. The use of high quantities of cement in self-compacting concrete SCC can cause an increment in its tendency to the risk of shrinkage cracking[5]. It was found that the reduction of cement content in SCC (use of alternative materials) can develop concrete precast technology and on-site concrete applications with more economical cost and minimum dosage of superplasticizer [6]. Therefore, one of the main problems in the production of SCC is the high initial cost due to use a high content of cement and
Several extensive studies have been conducted in order to use alternative materials for Portland cement, for example fly ash, silica fume, ground granulated blast slag and metakaolin. Various types of industrial by products and recycled waste materials are used to produce environmentally friendly materials at a more competitive cost to replace the traditional building materials [7]. The quantities of waste glass that are continuously generated due to the significant improvement in the lifestyles and the increase in industrialization increased significantly. Consequently, from viewpoint of an environmental and economical, the utilization of these wastes in production of modern concrete has attracted great interest all over the world. Recently several studies have investigated the employment of milled waste glass as a cement alternative in construction industry[8,9]. To some extent, recent work has indicated that the recycled glass milled down to small size particles exhibited a level of pozzolanic activity in concrete [10]. The finely ground particles of waste glass are believed to act as pozzolanic material to form new gel (calcium-silicate hydrates) with high amount of hydration products[10]. The typical pozzolanic material in concrete should contain high silica content, which should be amorphous with a vast surface area. It is believed that the glass powder has an adequate amount of amorphous silica content to stimulate the pozzolanic behavior if grinded to very small sizes[11].

Yassen et al.[12] studied the behavior of normal concrete with partial cement replacement by glass powder into concrete mixes. Their investigation was carried out to examine the hardened properties in term of compression strength, splitting strength, unit weight test and ultrasonic test. They concluded that the partial replacements of (10-25%) by weight contributed to produce an eco-friendly normal concrete and improved all the hardened properties. Vanjare and Mahure [13] studied the fresh and mechanical properties of SCC having glass powder as a partial cement replacement of 5%, 10%, and 15% by weight. They concluded that the rheological and mechanical properties decreased with increasing the glass content. Tejaswi et al. [14] studied the possibility of producing eco-friendly normal sustainable concrete by using different levels of glass waste (10, 20, 30, 40, and 50) % by weight as a partial replacement of cement and sand. They claim that these replacements can effectively contribute in reducing carbon dioxide emissions from the cement industry. Laboratory tests such as residual compressive strength were carried out after heating the samples for different periods. They observed that 20% replacement showed the highest residual strength and almost equal to the reference concrete mix. Ali and Al-Tersawy [15] evaluated the performance of self-compacting glass concrete by replacing part of fine aggregate (10-50%) by weight of recycled glass on the workability and mechanical characteristics of concrete. For this purposes, 18 concrete mixes were conducted with different content of cement (350, 400, 450) kg/m$^3$ at the same w/c ratio. It was concluded that an increase in the glass content led to an increase in the slump flow. However, the compressive, splitting tensile and flexural strengths decreased.

According to the above reviewed works. The researchers specified the best performance according to the experimental results only. In other words, they determine the best (not the optimum) percent of glass powder replacement depending on an already assumed percentage. Therefore, the aim of this paper is not only to specify the best performance but also to give the exact optimum percent by optimizing the experimental results. This is from both the performance in terms of fresh and hardened states and sustainability points of view as well in terms CO$ _2$ emission, and cost of production.

2. EXPERIMENTAL PROGRAM

A. Materials

1) Cement and waste glass powder

Ordinary Portland cement (OPC) type 1 with fineness and specific gravity of 325 m$^2$/kg and 3.15 respectively was used to cast all the concrete mixes in the present investigation. This cement confirms the limitation of the Iraqi specification No.5/1984 [16]. The chemical properties were illustrated in Table I for the used cement.
The broken and discarded glass windows were collected from the local glass processing shops and then crushed and grinded into powder before the use in the concrete mixes. Fig.1 shows the preparation of glass powder using in this study. The strength activity index was 102% of the glass powder used in this study, which was conducted according to the requirements of the strength activity index of ASTMC311_05 [17].

2) Aggregate

Crushed gravel was used in this study as coarse aggregate with a max. Size of 10 mm. The water absorption and specific gravity of this type were 0.53% and 2.65 respectively. Locally available natural fine sand was also employed as fine aggregate with a maximum particle size of 4.75 mm. The water absorption of this sand is 0.77% with specific gravity of 2.63. The sieve analysis was shown in Table II for the two types, which confirm the limitation of ASTMC33[18].

3) Superplasticizer

In this experimental work aqueous solution of polycarboxylic (sika viscocrete – 5930) type F was used as superplasticizer, which meets the ASTM C 494 limitation [19].

| Chemical compositions % by weight | Cement |
|-----------------------------------|--------|
| CaO                               | 61.95  |
| SiO₂                              | 20.91  |
| Al₂O₃                             | 5.31   |
| Fe₂O₃                             | 3.33   |
| SO₃                               | 2.5    |
| MgO                               | 2.35   |
| K₂O                               | 0.92   |
| Na₂O                              | 0.17   |
| Loss On ignition                  | 2.08   |

| Cumulative passing % | Natural coarse aggregate | Natural fine aggregate |
|----------------------|--------------------------|------------------------|
| Sieve size (mm)      |                          |                        |
| 12.5                 | 100                      | ---                    |
| 9.5                  | 86.76                    | ---                    |
| 4.75                 | 14.12                    | 95.3                   |
| 2.36                 | 0.16                     | 85.9                   |
| 1.18                 | ---                      | 77.3                   |
| 0.6                  | ---                      | 62.4                   |
| 0.3                  | ---                      | 16.8                   |
| 0.15                 | ---                      | 2.0                    |
| 0.075                | ---                      | 0.005                  |
B. Mix Proportion

Several trial mixes were conducted in the laboratory to design the final proportion of the reference mix (without glass powder), which designed by following trial and error method to obtain the best rheological and mechanical properties of SCC without segregation and bleeding. The guidelines of EFNARC was used as reference to design the control mix [20]. For this investigation, five mixes were made with the same water/powder ratio of 0.365 and dosage of super plasticizer of 0.86% by weight of powder. Four mixes were carried out by partial replacing of cement content 465 kg/m³ with different proportion of glass powder ranging from (10 - 40%) by weight. The mix proportions of all mixes are shown in Table III.

![TABLE III. MIX PROPORTIONS](image)

| Mix  | W/b | Binder content | Natural aggregate | Water | HRWRA |
|------|-----|----------------|-------------------|-------|-------|
|      |     | Cement         | Glass powder      | coarse | Fine |       |
| M0   | 0.365 | 465           | 0                 | 800    | 870   | 170   | 4    |
| M10  | 0.365 | 418.5         | 46.5              | 800    | 870   | 170   | 4    |
| M20  | 0.365 | 372           | 93                | 800    | 870   | 170   | 4    |
| M30  | 0.365 | 325.5         | 139.5             | 800    | 870   | 170   | 4    |
| M40  | 0.365 | 279           | 186               | 800    | 870   | 170   | 4    |

C. Mixing procedure

The mixing process was done with the same procedure for preparing all mixtures. In sequence, the ingredients were put into the laboratory mixer. Initially the dry mixing coarse and fine aggregate mixed about one minute and then the cement blended with the replacing ratio of the glass powder for several minutes in a separate vessel, then added to the aggregate and mixed until the mixture becomes homogeneous. Finally, the mixing water containing SP was gradually added to the dry mixing, and the wet mixture continued for approximately 5 minutes.

D. Testing Program

Slump flow test was carried out to evaluate flow ability of fresh concrete using slump flow diameter and time T500mm in unconfined conditions. Visual inspecting during the test as well as measurement of arrival time T500mm to may give additional indications about the segregation resistance of SCC. L-box test is performed to estimate the passing ability of SCC using blocking ratio h2/h1 through confined area and narrow opening during spaces congested with reinforcement steel. The L-box value index is measured as the ratio between the concrete elevations in the horizontal dimension h2 to the remaining concrete elevation in the vertical dimension h1. Sieve segregation test was conducted to determine the segregation resistance of fresh concrete mix. Due to high slump flow or low viscosity leads to settle down some coarse aggregate particles and then separated from the mixture. Thus, it negatively effects on the stability of the mixture. The segregation index is a tool that indicates to the stability of the mix or not, which is determined by dividing the passing concrete mass from the sieve opening by the total poured concrete mass. All concrete fresh tests were performed as stated by guideline EFNARC [20].

Mechanical properties of hardened concrete were performed under the same laboratory conditions, where the recorded results were obtained by taking the mean for three samples at each age.

Compressive strength test was conducted according to BS EN 12390-3:2002 [21] using nine cubes 100mm at 7, 28, 56 days. Three (100×200 mm) cylinders were made to calculate splitting tensile strength at 28 day with respect to the standard ASTMC496 [22]. According to this standard ASTM C78 [23], three (400×100×100) mm prisms at 28 day were casted in order to calculate the flexural strength. The photograph in Fig2 shows the all conducted tests in this study.
3. RESULTS AND DISCUSSION

A. Experimental results

The flow charts in Figs. 4, 5, 6 and 7 show the results of fresh concrete tests, which must meet acceptance ranges for SCC mix according to EFNARC [20,24]. As it can be seen from these figures, results of slump flow diameter, slump flow time T_500mm, L-box test and segregation resistance were in a range of 770-780 mm, 2-2.96 second, 0.9-0.88 and 9.5-10.7 respectively. Fig.4 provides the final flow diameter, as it was found practically that partial replacement of cement with glass powder up to 30%, maintains the same final spread diameter for the control mixture. It is believed that the interpretation of this result is that particle size distribution of ground glass powder and cement is somewhat similar except for the replacement rate of 40%, where there is a slight decrease in workability. It represents the largest amount of glass powder that can increase the possibility of the non-spherical and rough milled particles to decrease the workability [25]. Fig.5 displays the obtained time of flow T_500mm in seconds for all concrete mixes. T_500mm can be used to assess viscosity in concrete mixes, and its values range from 2-5 mm as stated by European guidelines EFNARC [20].
The L-box blocking value $H_2/H_1$ ratios of produced SCC are shown in Fig.6. This value must range from 0.8 - 1 indicating that the self-compacting concrete mixes have good passing ability. From the figure, all the performed mixes satisfied the requirements of EFNARC [20]. It has also been noticed from the results that the blocking value follows a decreasing trend when the replacement ratio of glass powder increased by 1.11%, 1.11%, 2.22% and 3.33% for M10, M20, M30 and M40 compared to control mix. This result is consistent with the conclusions of Vanjare, & Mahure [13].

Compared to the reference mix as shown in Fig.7, it was found that the increase in the replacement level of milled glass leads to a decrease in segregation index by approximately 1.3%, 2.98%, 6.89%, and 11.55% for M10, M20, M30, M40 mixes respectively. These results explain that the use of glass powder as a partial alternative to cement led to an increase in the viscosity of the mix that contributed to segregate lower[26].

Fig.8, 9 and 10 present the results of compressive, tensile and flexural strengths respectively. Fig.6 shows that the measured compressive strength was ranged from 54-42.21 MPa, 62.75-52.5 MPa and 71.34-61 MPa for 7, 28 and 56 day respectively. It can be concluded from the results that replacement of a glass powder as part of cement caused a gradual increase in the strength up to 30% by (6.3%, 5.6%) at 7 day, (14.3%, 5.51%) at 28 day and (7.2%, 1.6%) at 56 day for M10 and M20 respectively. Then strength decreased with increasing the replacement level by (9%, 21.8%) at 7 day, (6.8%, 16.33%) at 28 day and (7%, 15.6%) at 56 day for M30 and M40 respectively as compared to the control mix. The enhancement of strength might be attributed to the pozzolanic activity, where very fine particle of glass powder can contribute to enhance reaction with cement hydrates to form new gel. It is also can block the capillary pores in the concrete, making pores smaller and not connected to make the SCC more dense[7].

For other mechanical properties, Figs.9 and 10 show the results of splitting tensile and flexural strength tests. These properties follow a similar trend comparable to the results of compressive strength at the same replacement ratios. Splitting tensile and flexural strength increased up to 30% by approximate (1.78%, 1.11%) and (7.6%, 10.6%) for M10, M20 respectively. Then they decreasing by (4.44%, 6.67%) and (1.5%, 3.03%) for M30 and M40 respectively as compared to the control mix.

B. Optimization results

Based on the experimental investigation results and evaluated sustainability aspects in terms of CO2 emission and cost of production, optimization was made by the statistical regression model to determine the optimal content of glass powder as partial replacement of cement. The desirability function technique was used to simulate optimizing the responses (tested properties).

In this model analysis, the major sustainable variable in term of CO2 emission and cost of production as well as the SCC properties were employed as the response variables (dependent factors) while percent of grinded glass powder was appointed as the independent factors. The aim from optimization process is to obtain the optimal value that yields the best properties. Individual desirability values (d) for four response parameters were calculated to determine the overall desirability (D) using MINITAB software. The dependent variables were optimized to achieve the best response by using minimize goal of sustainable responses and maximum goal of SCC responses. Fig.3 illustrates the measured overall and individual desirability and the variables acquired at optimal properties. From Fig.3, the optimum percent of glass powder needed to acquire the SCC optimal properties was 24%.
4. CONCLUSIONS

Based on the present investigation, the following concluding remarks can be drawn:

- All mixes tested in this work exhibited good rheological properties by means flow ability, passing ability, and segregation resistance in terms of slump flow diameter, flow time $T_{500mm}$, L-box height ratio and segregation index.

- All the fresh concrete results above satisfied the limitations of SCC as stated by EFNARC.

- High viscosity of the self-compacting glass concrete caused reduction in the blocking value $H_2/H_1$ and sieve segregation. Therefore, segregation resistance and flow time $T_{500mm}$ increase with increasing in the overall replacement level of glass powder as compared to control mix.

- The compressive strength, splitting tensile and flexural strength increased when the partial replacement of cement with glass powder up to 30% and they decreased behind this as compared to control mix.

- From the experimental results, at the level 10% of replacement cement by glass powder gave the maximum values of compressive strength and 28 day splitting tensile strength, however, the higher flexural strength is achieved at a level of 20% at 28 day.

- The statistical model was derived from the major sustainable factors and SCC properties. Where the analysis of this model demonstrate that it can be used to derive the best properties of SCC.

- Based on the desirability function technique, the optimum percent of glass powder needed to acquire the desirable properties in terms of performance and sustainability was 24%.
Fig. 4. Slump flow diameter of fresh concrete

Fig. 5. T500 of fresh concrete
Fig. 6. Blocking ratio ($H_2/H_1$)

Fig. 7. Segregation Index of fresh concrete
Fig. 8. Compressive strength of hardened concrete

Fig. 9. Splitting tensile strength of hardened concrete
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