International Scientific Journal of Civil and Infrastructure Engineering (ISJCIE), May 2023, Vol.1, Issue1, pp.1-13, ISSN: Pending (Online), Australia, DOI: https://doi.org/10.56601/ISJCIE
Infrastructure, Construction, Concrete, Geotechnic, Earthquake, Environment.

Combined Effects of Waste Glass and Nano-Silica Powder on Workability, Durability and Mechanical Properties of Fiber-Reinforced Self-Compacting Mortar

Maryam Monazami, Shahrood University of Technology, Iran
Farshid Jandaghi Alaee*, Shahrood University of Technology, Iran
Ashkan Abedian, Shahrood University of Technology, Iran

* Corresponding Author, fjalaee@shahroodut.ac.ir, Received: Aug 2022, Accepted: Sep 2022

ABSTRACT: This research aims to combine the effects of waste glass and Nano-silica powder on the properties of fiber-reinforced self- compacting mortar. A detailed study was undertaken to investigate the effect of different glass powder contents as cement replacement on the behavior of mortar. For this purpose, Portland cement was partially replaced by 10%, 15%, and 20% waste glass powder alone, and then in combination with 2% substitution levels for Nano-silica. The amount of water-binder ratio and cementitious materials content were considered constant. Fresh properties of specimens were determined using slump flow, and v-funnel flow time tests, mechanical properties were determined by compressive strength, and tensile strength tests, and durability characteristics evaluated by water absorption, and resistance to sulfuric acid attack. Microstructural morphology of specimens was also assessed by scanning electron microscopy. It was observed that the workability slightly decreased and improved mechanical and durability properties could be achieved. The SEM micrographs illustrated more densified pore structure of the mortars containing waste glass powder which leads to increase in strength and durability of specimens.

Keywords: Waste glass; Nano-silica; Durability; Mechanical properties; Workability; Self-compacting mortar

1. Introduction

Glass waste is representing environmental problems all over the world. These materials occupy huge parts of the landfill spaces, due to the non-biodegradable nature of glass, and causing serious environmental pollutions. Also, the lack of spaces for new landfills is a problem facing the dense population cities in different countries. The best solution to overcome over the environmental impact of these glass wastes is to reuse them. The chemical composition of waste glass shows that glass has a large quantity of silicon and calcium and with amorphous structure; glass has the ability to be a pozzolanic or even a cementitious material [1].

Different studies have been made for the use of waste glass in cement and concrete industries. Some of these studies used waste glass as an aggregate; others used it as a cement replacement and some studies used it as aggregate and as a cement replacement in the same mixture. The use of waste glass as a coarse and fine aggregate in the production of concrete was very limited and did not show satisfactory results because of the alkali-silica destructive reaction between the cement and the waste glass aggregate and the low performance of the produced concrete. It was found that the particle size of the waste glass aggregate is playing a vital role in alkali-silica harmful reaction [1].

The pozzolanic properties of glass aroused the idea of using the waste glass as a cementitious material or as partial replacement of cement in the production of concrete. The pozzolanic properties of glass are highly affected by the particle sizes of glass [2]. Different studies have been done to investigate the optimum particle size and percentage of waste glass that can be used as a partial replacement to cement to produce concrete. Table 1 shows a summary of some research for the use of waste glass as a partial replacement to cement.

Table 1 Summary of all the research for the use of waste glass as a partial replacement to cement [1]

Type of waste glass	**% Waste glass studied**	**Particle sizes studied**	**Optimum % waste glass**	**Optimum particle size**	**Reference**
Fluorescent lamps glass (soda-lime)	30	38-150 μm	30	38 μm	[2]
Glass beads (soda-lime)	20	10-700 μm	20	30-100 μm	[3]
Window plate glass (soda-lime)	0-20	1-100 μm	10	1-100 μm	[4]
Bottles (soda-lime glass)	0-23	13-25 μm	20	13-25 μm	[5]
Container (soda-lime glass)	20	20-100 μm	20	20 μm	[6,7]
Recycled waste glass (soda-lime)	0-20	0.1-100 μm	20	0.1-100 μm	[8]

Although considerable research has been devoted to the use of waste glass as an aggregate or as a cement replacement in traditional vibrated concrete (TVC), rather less attention has been paid to the use of waste glass in self-compacting concrete (SCC). Self-compacting concrete or self-consolidating concrete is highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation [9]. Originally developed in Japan with the first significant applications in early 1990s, it has rapidly been adopted worldwide in construction [10].

SCC is composed of Portland cement, fine aggregate, coarse aggregate, water, chemical admixtures, and typically supplementary cementitious materials such as fly ash, slag, silica fume, and metakaolin. In some cases, mineral fillers such as limestone powder or very fine sands are used to increase the mixture's powder or fine material content. Aside from mineral fillers, the materials used to produce SCC are the same as those common to the production of conventional concrete [11]. In various parts of the world, different concepts might be followed for the proportioning of SCC and are referred to as 'powder-type SCC', 'viscosity-modifying admixture (VMA)-type SCC', or 'mixed-type SCC' [12].

It is the fresh, plastic properties of SCC that differentiate the material from conventional concrete. Workability of SCC is described in terms of filling ability (unconfined flowability), passing ability (confined flowability), and stability (segregation resistance), and is characterized by specific testing methods. For SCC, it is important to seek a combination of constituents that provide the mortar the appropriate yield stress for the application while maintaining adequate viscosity to ensure passing ability and segregation resistance [9]. As a result, it is attractive to consider the extent to which waste materials with suitable particle sizes can be incorporated.

In an attempt to enhance the knowledge of using waste materials in SCC, a detailed study was undertaken to investigate the effect of different glass powder contents as cement replacement on the behavior of mortar. The mechanical, physical and microstructural performances of mortars were investigated based on 10%, 15%, and 20% substitution levels for waste glass alone, and then in combination with 2% substitution levels for Nano- silica.

2. Experimental Program

2.1 Materials

The materials used in this study will be discussed in the following sections.

2.1.1 Portland cement

An ordinary type II Portland cement that complies with the requirements of specification ASTM C150 [13] was used as a testing cement. Table 2 shows the chemical composition and physical properties of cement, as supplied by the manufactures.

Table 2 Chemical and physical characteristics of Portland cement

Chemical composition, %	**Cement**
SiO_2	21.56
Al_2O_3	6.67
Fe_2O_3	6.17
CaO	49.88
MgO	4.51
SO_3	2.75
K_2O	0.76
Na_2O	0.43
LOI	2.79
Physical properties	
Specific gravity, g/cm^3	3.05
Specific surface area, cm^2/g	3250
Blaine fineness, m^2/kg	285
Autoclave expansion, %	0.017

2.1.2 Fine aggregate

The natural fine aggregate used in this study was river sand from a local source. A series of laboratory tests were conducted to assess the properties of fine aggregate. Table 3 shows the results of these tests. Fine aggregate gradation shall meet the requirements of ASTM C33 [17] as illustrated in Figure 1.

2.1.3 Glass powder

Mixed color ground glass supplied by a local source was used in this study without any treatment, washing or sorting. The distribution of glass particles was determined by using a particle-size analyzer device. Figure 2 shows the variation between the normalized particle amounts versus particle diameter. It can be realized from this figure that the particle diameters are in the range of 0.297-153.42 µm.

2.1.4 Nano-silica

Silicon dioxide Nanoparticle (Nano-SiO2) in dispersed suspension form with an average particle size of 11- 13 nm, specific surface area of 200 m2/g and purity of higher than 99% was used in this study.

Table 3 Review of laboratory tests for fine aggregate

		Test method
Apparent relative density	2.76	ASTM C128 [14]
Relative density (SSD)	2.69	ASTM C128 [14]
Total evaporable moisture content, %	2.2	ASTM C566 [15]
Sieve Analysis		ASTM C136 [16]
Sieve No.	%, Passing	
#4	100	
#8	92	
#16	72	
#30	40	
#50	15.8	
#100	3.8	
Pan	0.0	
Fineness modulus	2.68	

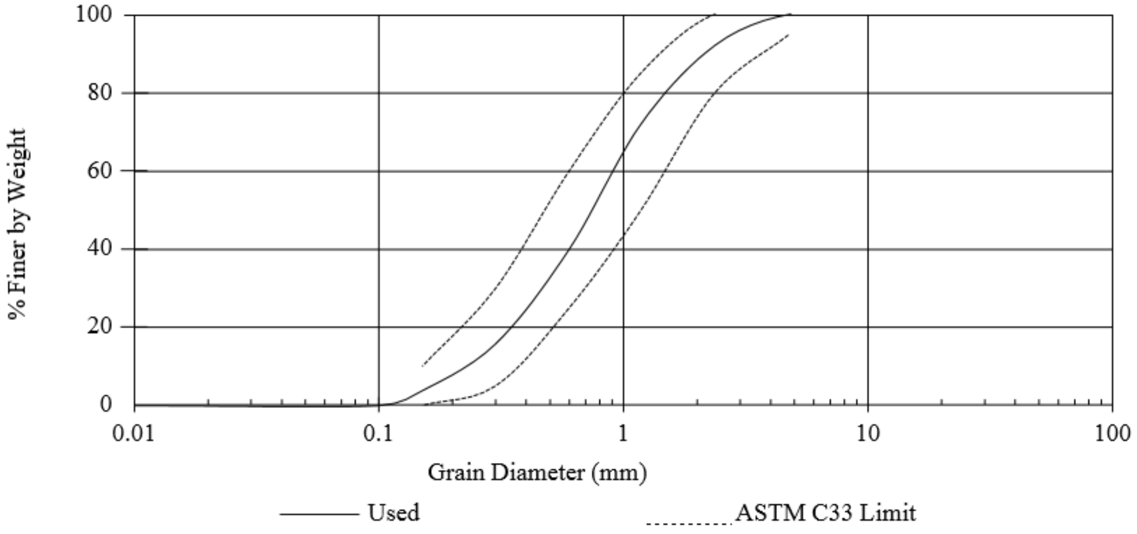

Fig.1 Fine aggregate diameter size based on the sieve analysis

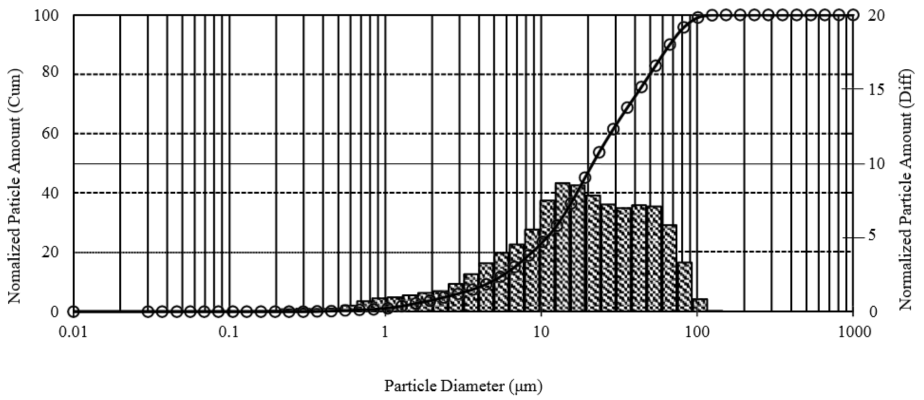

Fig.2 Glass powder particle size distribution

2.1.5 Superplasticizer

A polycarboxylate type super plasticizer (SP) with trademark of Vand Super Plast PCE according to ASTM C494 [18] type F with specific gravity of 1.03 g/cm3 was utilized to achieve the desired workability in all mortar mixtures

2.1.6 Fiber

Polypropylene fibers (PPF) were added to the mixture to determine whether improved mechanical properties and durability could be achieved. Table 4 shows the properties of these fibers.

Table 4 Properties of polypropylene fibers

Property	**Content**
Molecular formula	$(C_3H_6)_n$
Specific weight, g/cm^3	0.90-0.91
Tensile strength, MPa	300-400
Elongation at break, %	100-600
Melting point, °C	175
Thermal conductivity, W/m/K	0.12
Length, mm	6
Diameter, μm	20

2.2 Mixture proportions

Laboratory trails used to verify properties of the initial mix composition with respect to the specified characteristics. A control mix (named CO) was proportioned with reference to EFNARC [19] and modified with various glass and Nano-silica particle contents as listed in table 5. A total of eleven mixtures were designed to have constant water/binder ratio of 0.4, a total binder content of 700 kg/m3 and 0.3% polypropylene fibers by mix volume. The purpose was to determine the following effects on mixed mortar:

- The effect of glass powder as a cement replacement material at 10, 15, and 20% dosage rates.

- Combined effect of glass and Nano-silica powder as cement replacement material.

Table 5 Mix design and basic properties of mortars

Mixture ID.	Sand, kg/m^3	Cement, kg/m^3	Glass, kg/m^3	Nano-silica, kg/m^3	Water, kg/m^3	PP fiber, %
CO	1200	700	0	0	280	0.3
10G	1200	630	105	0	280	0.3
15G	1200	595	105	0	280	0.3
20G	1200	560	140	0	280	0.3
2N10G	1200	616	70	14	280	0.3
2N15G	1200	581	105	14	280	0.3
2N20G	1200	546	140	14	280	0.3

2.3 Specimens

Fresh mortar was cast into 50×50×50 mm cubes for compressive strength and water absorption tests and in briquet gang mold for tensile strength tests. The specimens were demolded 24 hours after casting and cured in water at a constant temperature of 23 ± 3 °C until they were tested.

2.4 Test Methods

Each mixture was tested for fresh and hardened concrete properties. The fresh concrete properties were measured to judge the flow and self-compactibility behavior of the concrete.

2.4.1 Slump flow test

The slump flow test is a common procedure used to determine the horizontal free-flow characteristics of each mixture. In performing this test, the standard Abrams cone is filled in a single lift without rodding. Once filled, the cone is raised and the diameter of resulting concrete paddy is measured as described by ENFARC [19].

2.4.2 V-funnel flow time test

The V-funnel test was used to access the viscosity and filling ability of each mixture. A V shaped funnel was filled with fresh concrete and the time taken for the concrete to flow out of the funnel is measured and recorded as the V-funnel flow time as described by ENFARC [19].

2.4.3 Compressive strength test

Compressive strength test was conducted in accordance with ASTM C109 [20] to evaluate the strength development of mortars containing various glass and Nano-silica content at the age of 7, 14 and 28 days, respectively.

2.4.4 Tensile *strength test*

Tensile strength test was performed with reference to ASTM C307 [21] at the age of 28 days.

2.4.5 Water absorption test

The water absorption test was carried out at 28 days of age in accordance with ASTM C642 [22]. Saturated surface dry specimens were kept in an oven at 110 °C for 48 hours. After the determination of initial weight, the specimens were immersed in water for 48 hours. The final weight was then determined, and the absorption was calculated to assess the permeability of the mortar specimens.

2.4.6 Chemical resistance test

The chemical resistance was studied by immersing the specimens in a sulfuric and hydrochloric acid solutions. After 28 days of curing, the specimens were removed from water tank and the compressive strength and mass were measured. After the initial weight was recorded, the specimen was immersed in a 3%, and 5% H2SO4 solution for 56 days. After 56 days of immersion, the specimens were removed from the solutions, rinsed with tap water and brushed before the testing of compressive strength and mass changes were measured.

2.4.7 Microstructure analysis

The microstructure of the concrete mixes was analyzed using Scanning Electron Microscope (SEM) which helps to visualize the microstructure of hydrated cement paste.

3. Results and Discussion

3.1 Fresh properties of SCM

The test results from slump flow diameter and V-funnel flow time are presented in table 5. All of mixtures were designed to give a slump flow diameter of 25 ± 1 cm with reference to EFNARC [19] by adjusting the amount of SP content. As shown in Table 5, the incorporation of Nano-silica made the mortars less flowable and more viscose, causing a significant decrease in workability. The workability of mortars was slightly decreased with an increase in glass powder content.

Table 6 Fresh properties of SCMs

Mixture ID	**Slump flow Dia. (cm)**	**V-funnel flow time (s)**	**SP%**
CO	26	9	0.5
10G	26	10	1
15G	25	11	1.5
20G	25	11	1.5
2N10G	25	12	2
2N15G	24	12	2
2N20G	24	13	2

3.2 Mechanical properties of hardened SCM

3.2.1 Compressive strength

The average compressive strength of specimens at different curing ages are shown in figure 3. The addition of glass powder shows a decrease in compressive strength of samples for early ages of curing. However, after 28 days the compressive strength evidently develops in comparison with control sample. It's due the fact that both hydration and pozzolanic reaction affect mortar strength development at late ages.

It can also be observed that the incorporation of Nano-silica has a beneficial effect on the improvement of compressive strength of cement mortars at early ages. The Nano-silica exhibits a high pozzolanic activity resulting in the production of additional strength giving C-S-H phase. In addition, Nano-silica exhibits a pore- filling effect and compacts the microstructure which contributes to the strength improvement.

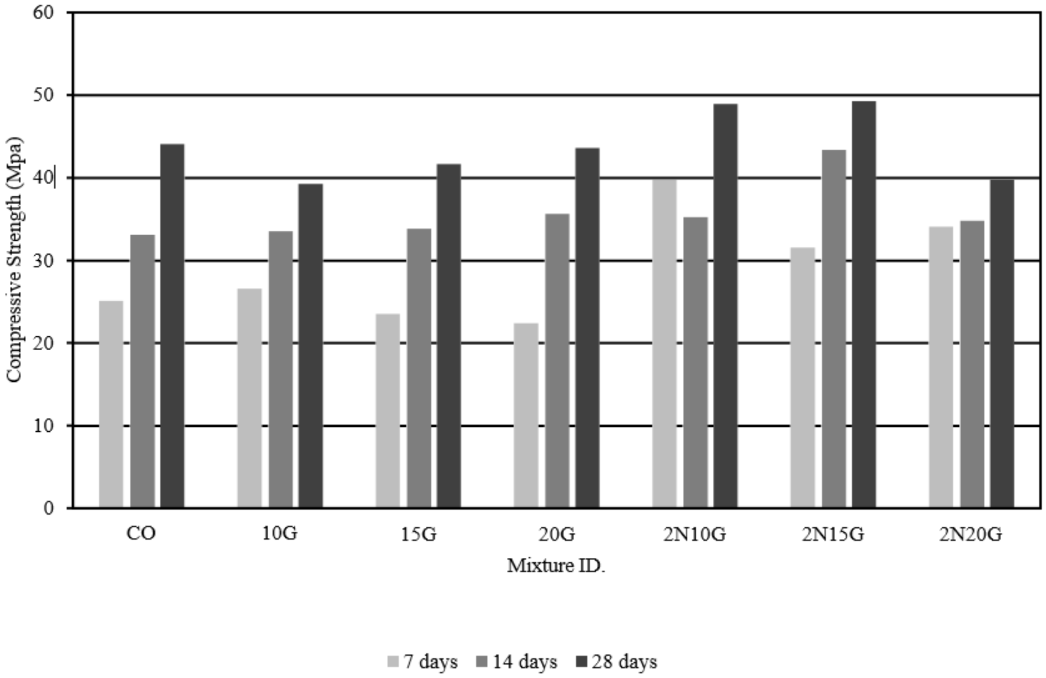

Fig.3 Compressive strength values of samples at 7, 14, and 28 days of curing

3.2.2 Tensile strength

The average tensile strength of specimens at 28 days of curing are shown in figure 4. It can be seen that the mixes with glass powder alone and in combination with Nano-silica showed higher values in comparison with that of the control sample. These particles strengthen the weak regions that is between cement paste and polypropylene fibers. Also, tensile strength of specimens incorporating Nano-silica in most cases was higher than that of the glass powder samples. The nanoparticles fill the pores especially porous Portland crystals which array in the interfacial transition zone between the cement matrix and polypropylene fibers.

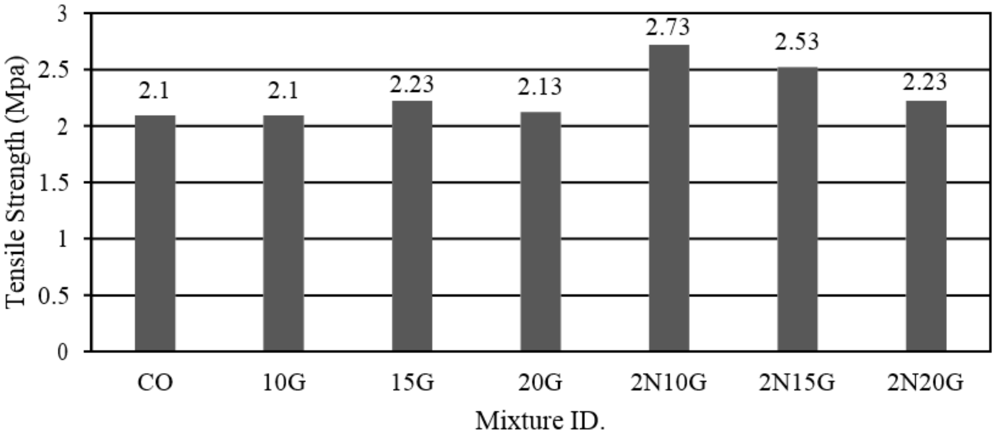

Fig.4 Tensile strength values of samples at 28 days of curing

3.2.3 Water absorption

The experimentally obtained results are presented in figure 5. In general, the results showed increased values of water absorption when glass powder was added. However, incorporation of Nano-silica, due to high specific surface area, reduced the water absorption content of mortar. The Nano-silica contained some free water on the surface, which is resulted in continuous hydration that made the matrix more compacted.

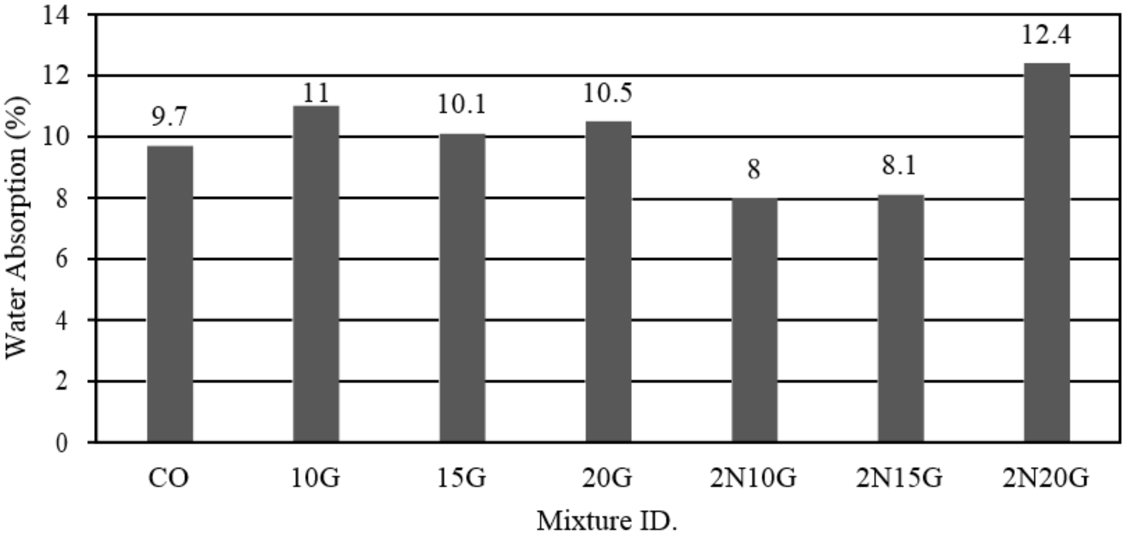

Fig.5 Water absorption values of samples at 28 days of curing

3.2.4 Resistance to sulfuric acid attack

The loss of mass and compressive strength of the specimens upon immersing in a 3%, and 5% H_2SO_4 solution after 56 days are shown in Tables 7, and 8.

Table 7 Results of compressive strength and mass change of specimen immersed in 3% H_2SO_4 solution

Mixture ID.	**Initial mass, gr**	**Mass after 56 days of immersion, gr**	**Initial compressive strength, MPa**	**Compressive strength after 56 days of immersion, MPa**
CO	294.2	288.2	44	60.2
10G	286.9	280.1	39.1	69.1
15G	273	266.8	41.5	67.4
20G	278.8	272.4	43.5	65.2

Table 8 Results of compressive strength and mass change of specimen immersed in 5% H_2SO_4 solution

Mixture ID.	**Initial mass, gr**	**Mass after 56 days of immersion, gr**	**Initial compressive strength, MPa**	**Compressive strength after 56 days of immersion, MPa**
CO	294	282.1	44	52
10G	288.1	277.9	39.1	41.7
15G	278.1	269.9	41.5	43.3
20G	282.6	274.5	43.5	14

3.2.5 Microstructural observations

The microstructures of cement paste at the interfacial transition zone (ITZ) were captured by SEM, as seen in Figure 6. The porous paste structures at ITZ in CO mixture, are shown in Figure 6, where CH, ettringite, and amorphous calcium-silicate-hydrates (C-S-H) can be recognized. Among the solids, pores of varying sizes are also noticeable. In contrast, the pozzolanic reaction densified the microstructures by turning CH into secondary C-S-H, and produced a more homogeneous microstructure, as shown in Figure 7 and 8 for 10G and 15G samples, respectively. Therefore, it is expected that the mechanical and durable properties of concrete could be improved due to this densified ITZ, which is normally the weakest phase in concrete composites.

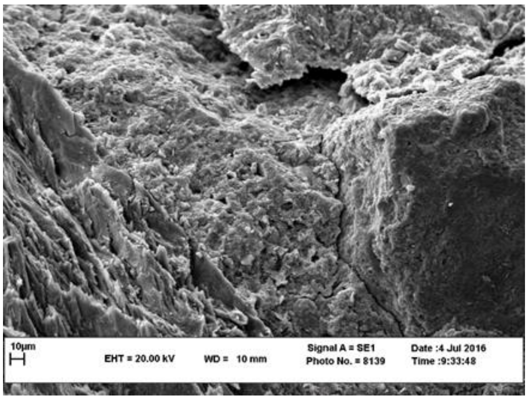

Fig.6.a SEM micrograph of CO sample – 20 µm

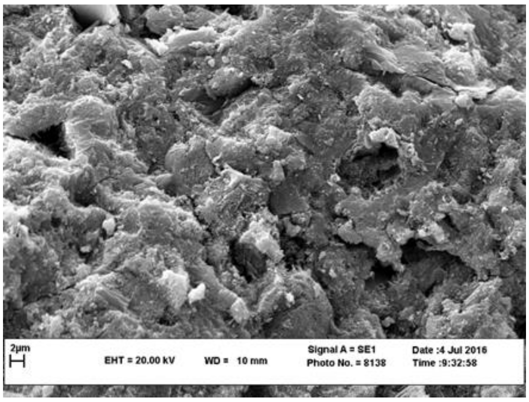

Fig.6.b SEM micrograph of CO sample – 2 µm

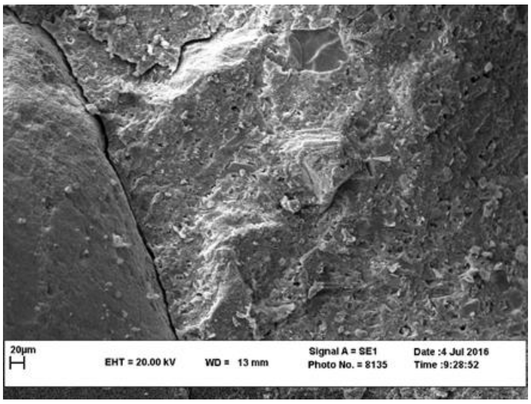

Fig.7.a SEM micrograph of 10G sample – 20 µm

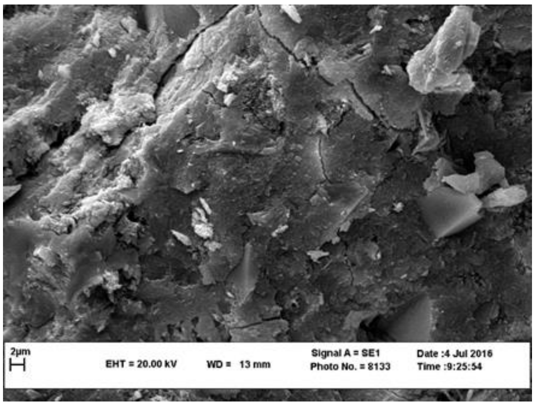

Fig.7.b SEM micrograph of 10G sample – 2 µm

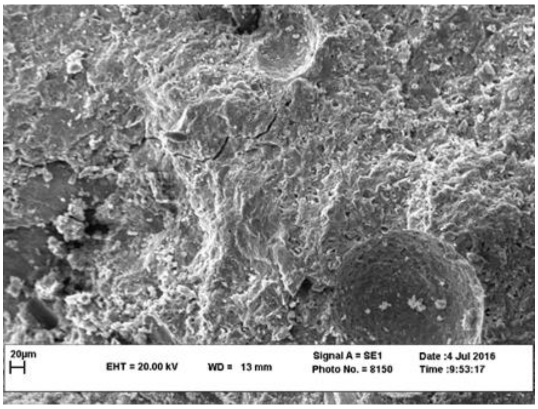

Fig.8.a SEM micrograph of 15G sample – 20 µm

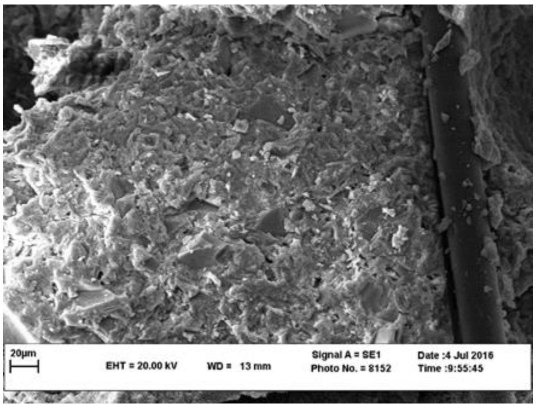

Fig.8.b SEM micrograph of 15G sample – 20 µm

4. Conclusions

This study was conducted to assess the effect of combined waste glass and Nano-silica powder on the properties of fiber-reinforced self-compacting mortar. The following results can be obtained from the present study:

1. Incorporating Nano-silica powder in mortar mixtures decreased the fluidity, and hence increased the superplasticizer dosage to maintain workability.
2. The workability of mortars was slightly decreased with an increase in glass powder content, and it can be compensated by increased dosage of superplasticizer.
3. The addition of waste glass powder up to 20%, slightly increased the compressive strength of specimens, however combined waste glass and Nano-silica powder would significantly increase the mechanical properties of mortar mixtures.
4. According to the SEM micrographs, smaller pores achieved by addition of waste glass powder, which can improve the mechanical, durability, and microstructural properties of mortar mixtures.

5. References

[1] Y. Jani and W. Hogland, "Waste glass in the production of cement and concrete - A review," Journal of Environmental and Chemical Egineering, vol. 2, no. 3, pp. 1767-1775, September

2014.

[2] Y. Shao, T. Lefort, S. Moras and D. Rodriguez, "Studies on Concrete Containing Ground Waste Glass," Cement and Concrete Research, vol. 30, no. 1, pp. 91-100, January 2000.

[3] C. Shi, Y. Wu, C. Riefler and H. Wang, "Characteristics and pozzolanic reactivity of glass powders," Cement and Concrete Research, vol. 35, no. 5, pp. 987-993, May 2005.

[4] N. Schwarz, H. Cam and N. Neithalath, "Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash," Cement and Concrete Composites, vol. 30, no. 6, pp. 486-496, July 2008.

[5] R. Nassar and P. Soroushian, "Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement," Construction and Building Materials, vol. 29, pp. 368-377, April 2012.

[6] A. Khmiri, B. Samet and M. Chaabouni, "A cross mixture design to optimise the formulation of a ground waste glass blended cement," Construction and Building Materials, vol. 28, no. 1, pp. 680-686, March 2012.

[7] A. Khmiri, M. Chaabouni and B. Samet, "Chemical behaviour of ground waste glass when used as partial cement replacement in mortars," Construction and Building Materials, vol. 44, pp. 74-80, July 2013.

[8] A. M. Matos and J. Sousa-Coutinho, "Durability of mortar using waste glass powder as cement replacement," Construction and Building Materials, vol. 36, pp. 205-215, November 2012.

[9] ACI Committee 237, "Self-Consolidating Concrete ACI 237R-07," American Concrete Institute, Detroit, MI, USA, April 2007.

[10] G. D. Schutter, P. J. Bartos, P. Domone and J. Gibbs, "Self-Compacting Concrete", Scotland, UK: Whittles Publishing, 2008.

[11] J. A. Daczko, "Self-Consolidating Concrete - Applying What We Know", New York, USA: Spon Press, 2012.

[12] K. H. Khayat and G. D. Schutter, "Mechanical Properties of Self-Compacting Concrete - State-of-the-Art Report of the RILEM Technical Committee 228-MPS on Mechanical Properties of Self-Compacting Concrete", London: Springer, 2014.

[13] American Society for Testing and Materials, "Standard Specification for Portland Cement ASTM C150-07," ASTM International, PA, USA, 2009.

[14] American Society for Testing and Materials, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate ASTM C128-07a," ASTM International, PA, USA, 2009.

[15] American Society for Testing and Materials, "Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying ASTM C566-97 (Reapproved 2004)," ASTM International, PA, USA, 2009.

[16] American Society for Testing and Materials, "Standard Test Method for Seive Analysis of Fine and Coarse Aggregates ASTM C136- 06," ASTM International, PA, USA, 2009.

[17] American Society for Testing and Materials, "Standard Specification for Concrete Aggregates ASTM C33-08," ASTM International, PA, USA, 2009.

[18] American Society of Testing and Materials, "Standard Specification for Chemical Admixtures for Concrete ASTM C494-08a," ASTM International, PA, USA, 2009.

[19] European Federation of National Associations Representing for Cocrete, "Specification and Guidelines for Self-Compacting Concrete," ENFARC, Farnham, UK, 2002.

[20] American Society for Testing and Materials, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in or [50-mm] Specimens) ASTM C109-08," ASTM International, PA, USA, 2009.

[21] American Society for Testing and Materials, "Standard Test Method for Tensile Strength

of Chemical-Resistant Mortar, Grouts, and Monolithic Surfacings ASTM C307-03 (Reapproved 2008)," ASTM International, PA, USA, 2009.

[22] American Society for Testing and Materials, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete ASTM C642-06," ASTM International, PA, USA, 2009.