

Mechanical and durability properties of self-compacting mortars incorporating glass powder

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Suggested Citation:

Gunes, M., Oz, H. O. & Yucel, H. E. (2017). Mechanical and durability properties of self-compacting mortars incorporating glass powder. *World Journal on Environmental Research*. 7(2), 61-71.

Received June 17, 2017; revised September 28, 2017; accepted December 28, 2017

Selection and peer review under responsibility of Prof. Dr. Haluk Soran, Near East University.

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Abstract

The current study experimentally investigated the effect of glass powder on the mechanical and durability properties of self-compacting mortars (SCMs). SCMs were designed with a low water/binder ratio as well as the high binder content. In this study, fly ash and glass powder can be used instead of cement to obtain the sustainable concrete and waste management control. At first, control mixture was produced with cement and fly ash without glass powder. Then, glass powder was used on the proportions 5%, 10%, 15% and 20% instead of fly ash in SCM. Compressive strength and flexural strength tests were conducted at 28 and 56 days, respectively. To determine durability properties, water sorptivity and rapid chloride permeability were tested at 28 and 56 days, respectively. Test results indicate that glass dust added to SCMs instead of fly ash improved partially the mechanical and durability properties of the mortars.

Keywords: Fly ash, glass powder, mechanical and durability properties, self-compacting mortars.

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1. Introduction

It is very important to obtain the high strength and durable as well as the high workable concrete for developing construction technology. Self-compacting concrete (SCC) which is a very special concrete type that meets the high workability characteristics thanks to settling ability under its own weight without the need for vibration (Pineaud, Pimienta, Remond & Carre, 2016; Guneyisi & Gesoglu 2008). SCCs are produced with low water/binder ratio as a result of containing the large proportion of very fine structured minerals such as fly ash, silica fume and blast furnace slag (Soliman & Tagnit-Hamou, 2017; Kurt, Gul, Gul, Aydin & Kotan, 2016). These materials are very important for the sustainable development in the terms of the environmental waste and reducing the use of natural resources thanks to using instead of cement in concrete or mortar as well as improving the mechanical and durability properties of concrete incorporating such minerals (Kalla, Rana, Chad, Misra & Csetenyi, 2015; Sabet, Libre & Shekarchi, 2016).

Cement production involved the mining of raw materials such as sand, limestone and clay needs large amounts of raw materials and energy. Firstly, those raw materials are ground, mixed and fired at 1450 °C, respectively. The result material occurred is the clinker that is the basic material of the cement. The production of the clinker requires the high temperature of the cement kilns. For this purpose, it is available many fuels such as fuel oil, mineral coal, petroleum coke, natural gas and diesel, and utilized fuels as waste or biomass (Stafford, Raupp-Pereira, Labrincha & Hotza, 2016). Because of the important amounts of cement produced and extensive resource consumption, the cement industry becomes a reason of environmental concerns (Song, Yang, Chen, Hayat & Alsaedi, 2016). This situation is particularly due to high emissions of carbon dioxide (CO₂) consisted of the burned of fossil fuels, alongside the decarbonation of limestone in the clinker production (Stafford, Raupp-Pereira, Labrincha & Hotza, 2016; Song, Yang, Chen, Hayat & Alsaedi, 2016). Additionally, the climate change and global warming caused by raised concentrations of anthropogenic CO₂ emissions to the atmosphere is the largest environmental threat of the 21st century (Ruan & Unluer, 2016; Song, & Chen, 2016). Actually, 1 ton of ordinary Portland cement can consume more than 1.5 ton of raw materials and 2.93-6.28 GJ of thermal energy, in addition to 65 to 141 kWh of electrical energy (Stafford, Raupp-Pereira, Labrincha & Hotza, 2016).

Another mineral that can be used instead of cement to reduce environmental damages caused by the cement production process is glass powder (GP). Furthermore, in recently, approaches have been performed to use waste glass as an alternative supplementary cementitious material or ultra-fine filler in concrete or mortar, depending on its particle-size distribution and chemical composition (Soliman, & Tagnit-Hamou, 2016). Glass has an amorphous structure and the high silica (SiO₂) content (Vijayakumar, Vishaliny & Govindarajulu, 2013). When particle size of GP is less than 0.075 mm and/or 0.038 mm, it can be stated that GP shows potentially pozzolanic property and contributes to concrete or mortar to the obtain the strength and durability (Soliman, & Tagnit-Hamou, 2016; Vijayakumar, Vishaliny & Govindarajulu, 2013). Additionally, according to previous studies, finely ground glass does not contribute alkali-silica reaction (Vijayakumar, Vishaliny & Govindarajulu, 2013). In study done by Orhan and Sahin (2016) found that compressive strength of concrete ground waste glass powder additive showed an increase according to control concrete at 600°C and 900°C temperatures at the later ages. According to Leadership in Energy and Environmental Design (LEED) certification, using glass in concrete can duplicate the points gained from using other pozzolanic mineral such as silica

fume, fly ash and blast furnace slag. While the others are considered post-production materials, glass powder is regarded as a post-consumption material (Soliman & Tagnit-Hamou, 2016).

Therefore, in this study, it has been investigated the mechanical and durability properties of self-compacting mortars (SCMs) by using the glass powder instead of fly ash. For this purpose, self-compacting mortars incorporating glass powder (SCMGPs) in the proportions of 5%, 10%, 15% and 20% were designed with water/binder (w/b) ratio 0.4, respectively. Moreover, control mixture containing the cement and fly ash was produced without glass powder to observe the effect of GP on the mechanical and durability properties.

2. Materials and Methods

2.1. Materials

In this study, CEM I 42.5 R type cement, class F type of fly ash and glass powder were used as binders. Physical and chemical properties of these materials are listed in Table 1. Crushed sand and natural sand used together in the production of SCMs had the specific gravities of 2.63 and 2.67 and grain sizes 0-2 mm and 0-4 mm, respectively. High-Range-Water-Reducing-Admixture (HRWRA) with a specific gravity of 1.07 was used to reach the desired workability of SCMs.

Table 1. Physical and chemical properties of Portland cement, fly ash and glass powder

Chemical Analysis (%)	Cement	Fly Ash	Glass Powder
CaO	62.58	2.24	9.89
SiO ₂	20.25	57.2	71.79
Al ₂ O ₃	5.31	24.4	1.04
Fe ₂ O ₃	4.04	7.1	0.11
MgO	2.82	2.4	4.10
SO ₃	2.73	0.29	0.23
K ₂ O	0.92	3.37	0.20
Na ₂ O	0.22	0.38	12.41
Loss of Ignition	2.96	1.52	-
Specific Gravity	3.15	2.04	2.60
Blaine Fineness (m ² /kg)	326	379	-

2.2. Preparation of the mortar mixtures

A total of 5 SCMGF mixtures were designed with a constant w/b ratio of 0.32 and a total cementitious material content of 550 kg/m³. SCMGPs were produced incorporating 80% Portland cement and the binary cementitious blends of 20% (fly ash+glass powder). In the SCMGF0 (control mixture), it was used fly ash without glass powder in the replacement ratio of 20 % of total binder content (110 kg/m³). In the other mixtures, glass powder was replaced with fly ash in the rates of 5% 10% 15% and 20%, respectively. The mixes were all the same except the fly ash being replaced by glass powder at different proportions as shown in Table 2. In the production stage of SCMGPs, the mixing process was kept constant to provide the same uniformity and homogeneity in all mixtures according to ASTM C109/C 109M-99(1999). According to EFNARC (2002), SCMGPs were designed to give a mini-slump flow diameter of 24–26 mm which was achieved by using the different amounts of HRWR.

Table 2. Mixing ratios of SCMGP for 1 kg/m³

Code Number	Water/Binder	Cement	Fly Ash	Glass Powder	Natural Sand	Crushed Sand	HRWRA
SCMGP0	0,4	440	110	0	1077,28	454,78	4,3
SCMGP5	0,4	440	82,5	27,5	1082,72	457,07	4,4
SCMGP10	0,4	440	55	55	1088,14	459,36	5,2
SCMGP15	0,4	440	27,5	82,5	1093,56	461,65	6,0
SCMGP20	0,4	440	0	110	1098,99	463,94	6,8

2.3. Test procedures

2.3.1. Compressive and flexural strength

Compressive and flexural test devices are shown in Figure 1. Compressive strength and flexural strengths of SCMGP according to ASTM C109/C 109M-99 (1999) and ASTM C348-14 (2004) were identified at 28 and 56 days, respectively. For this purpose, 3 prismatic specimens in dimensions of 40x40x160 mm were used. Firstly, flexural strength of SCMGP was determined by taking the average of the results obtained from 3 prismatic specimens. Then, compressive strength of mixtures was identified by using the 6 pieces remained after the flexural test. It was applied the load to the samples by placing a square piece in size of 4 mm on these pieces and compressive strength of mixtures was determined by taking the average of the results obtained from 6 samples.

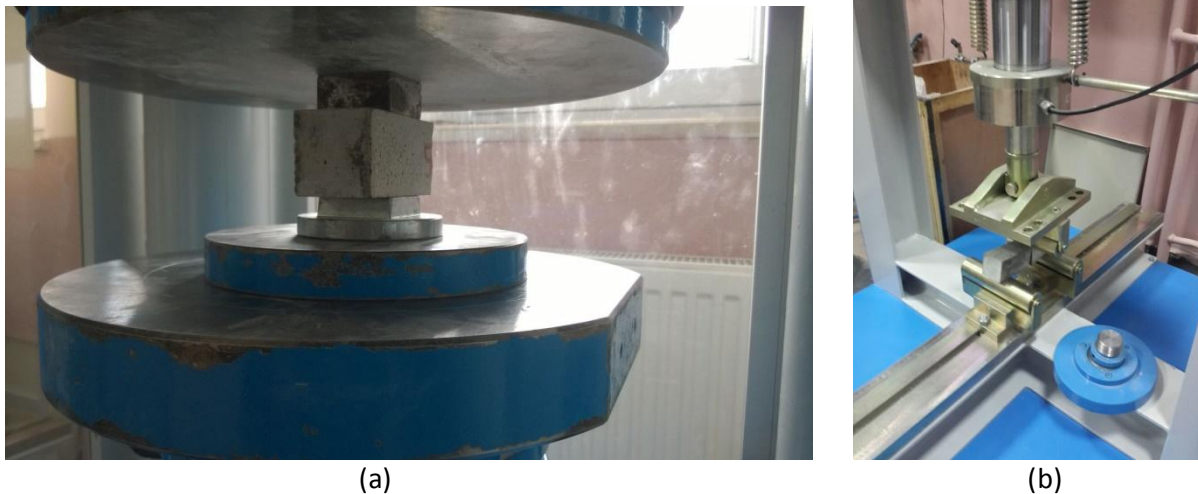


Figure 1. (a) Compressive test device, (b) Flexural test device

2.3.2. Water Sorptivity

Figure 2 shows water sorptivity test device. Water sorptivity was determined on three specimens of 50 mm in length and 100 mm in diameter cut from the of Ø100x200 mm cylinders. Firstly, the specimens were dried in an oven at 100±5°C till they achieved the constant mass. The experiment was performed on the surface of mortar which is in contact with a thin water layer while the sides of the specimens were covered by paraffin, so that capillary suction was considered the dominant invasion

mechanism. The measurement experiment was conducted on the specimens located on glass rods in a tray such that their underside as much as a height of 5 mm is got in touch water (Ozbay, 2007). Water sorptivity evaluated by the water uptake from the mortar per unit cross-sectional area with time. The experiment was applied in 28 and 56 days, respectively.

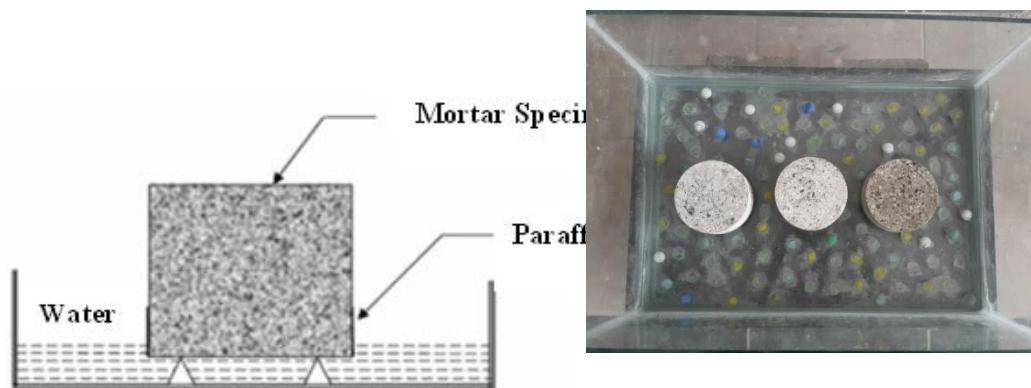


Figure 2. Water sorptivity test device.

2.3.4. Rapid Chloride Permeability Test

Figure 3 shows rapid chloride permeability test device. An experimental setup meeting the ASTM C 1202 (2012) was followed to measure the resistance of SCMGP against chloride ion penetration. Three specimens of $\text{Ø}100 \times 200$ mm were tried out at the same time for each SCMGP at 28 and 56 days. For this aim, two 50 mm thick disc samples were cut from the mid-section of each cylinder. Then, the discs were allowed to surface dry in air. To prevent evaporation of water from the saturated specimen, a rapid setting coating was applied onto the lateral surface of the specimens prior to a vacuum-saturation procedure for 2 hrs. Finally, the specimens were immersed in water in the curing room at 20°C and 50% relative humidity for 18 ± 2 hrs. Following this conditioning procedure, the disc specimens, whose one side got in touch with 0.30 N NaOH solution and the other side was in contact with 3% NaCl solution, were relocated in a test cell. A direct voltage of 60.0 ± 0.1 V was enforced between the faces by the power supply. Due to this applied voltage the chloride ions in the NaCl solution, being negatively charged, were attracted by the opposite positive electrode (+) and they penetrate through the pores of saturated mortar. The data was measured at every 30 minutes to record the current passing through the specimens over a 6 hour period. After being completed the test, current (in amperes) versus time (in seconds) were drawn for each specimen. And the area under the curve was computed to acquire the charge passed (in coulombs). Five classes from 'High' to 'Negligible' were categorized according to ASTM C 1202 (2012) depending on total coulomb (C) value.

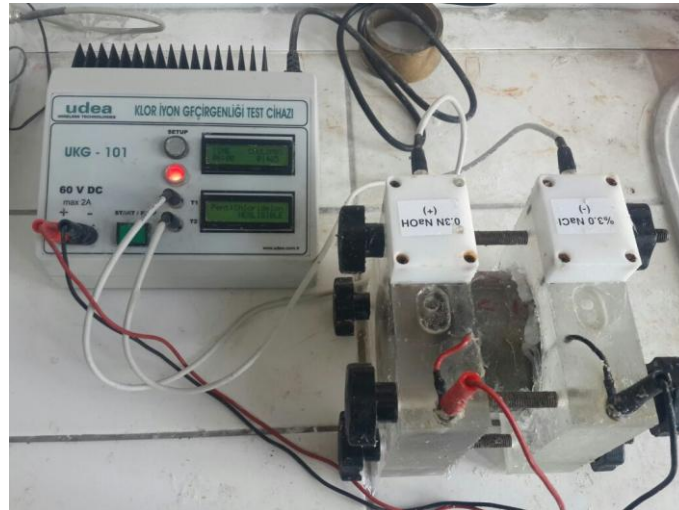


Figure 3. Rapid chloride permeability test device

3. Results and Discussion

3.1. Compressive strength

Figure 4 presents the compressive strengths of the mixtures at different ages of SCMGP. Compressive strength increased with the increase of the curing time and the glass powder ratio used instead of fly ash. The replacement of fly ash with 20% glass powder yielded the best results for both 28 and 56 days. Considering 28 and 56 day test results, the compressive strength of the mixture containing 20% glass powder with respect to control mortar increased by 26.50% and 28.87%, respectively. The main reason for the increase in compressive strength with increasing glass powder ratio in mixtures is that the pozzolanic reaction of the glass powder with the hydrated cement product is more than that of fly ash. So, the active silica content of glass powder being higher than that of the fly ash is responsible for the better mechanical properties (Oz, Yucel & Gunes, 2017).

Generated C-S-H gel can cause to densify the microstructure of the mortar or concrete. The newly generated C-S-H fills the pore structure in the mortar or concrete. Therefore, the mechanical and durability properties of the mortar or concrete are especially improved (Soliman, & Tagnit-Hamou, 2016). In study performed by Batayneh, Marie and Asi (2007), use the use of finely divided glass powder as a cement replacement material has yielded positive results in the terms of compressive strength. Similarly, F.A. Sabet et al. (2016) indicated that the mineral admixtures having pozzolanic effect added to self-compacting high performance concrete instead of cement improved the mechanical and durability properties of the concrete.

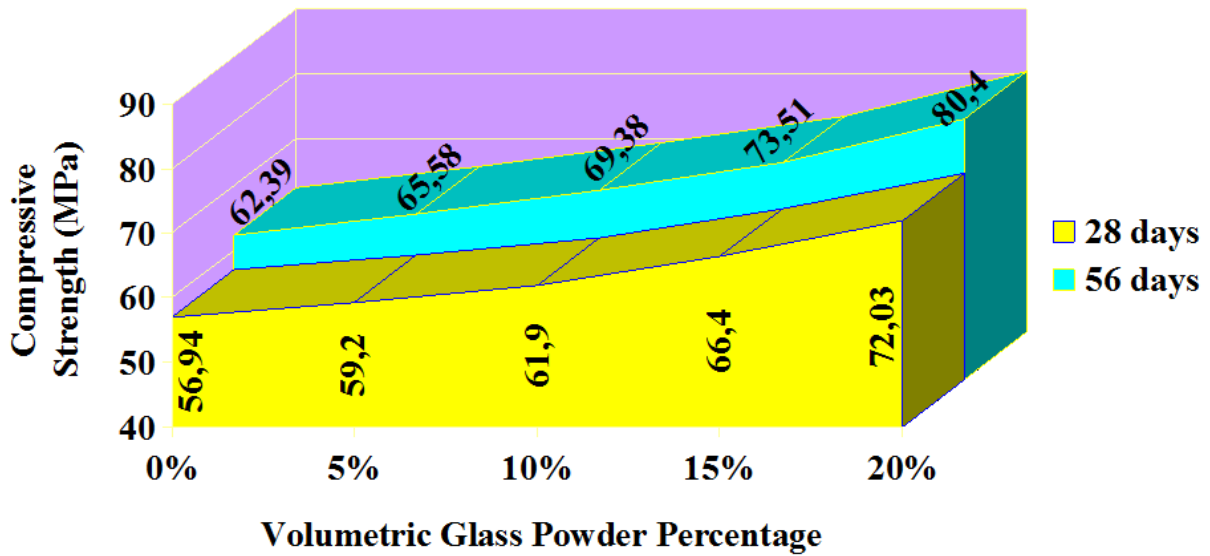


Figure 4. Compressive strength of SCMGP at 28 and 56 days

3.2. Flexural strength

The graphical representation of flexural strengths of SCMGP is shown in Figure 5. Test results of SCMGP0 and SCMGP20 for 28 days were identified as 5.7 MPa and 8.3 MPa, respectively. Nevertheless, the experiment results for SCMGP0 and SCMGP20 for 56 days were determined as 6.7 MPa and 10.2 MPa, respectively. As it can be seen from the graphic, flexural strength increased with the increase of the curing time and the glass powder ratio used instead of fly ash. These results were supported by the study of Yu, Spiesz & Brouwers (2014) in which it can be concluded that the silica content and the filler effect having due to contained a finer structure than cement of the pozzolanic material affects directly the mechanical and durability properties of mortar or concrete. In addition, with respect to the results of study performed by Vijayakumar, Vishaliny & Govindarajulu (2013) as utilization rate of glass dust increased, compressive and flexural strengths of concrete has increased.

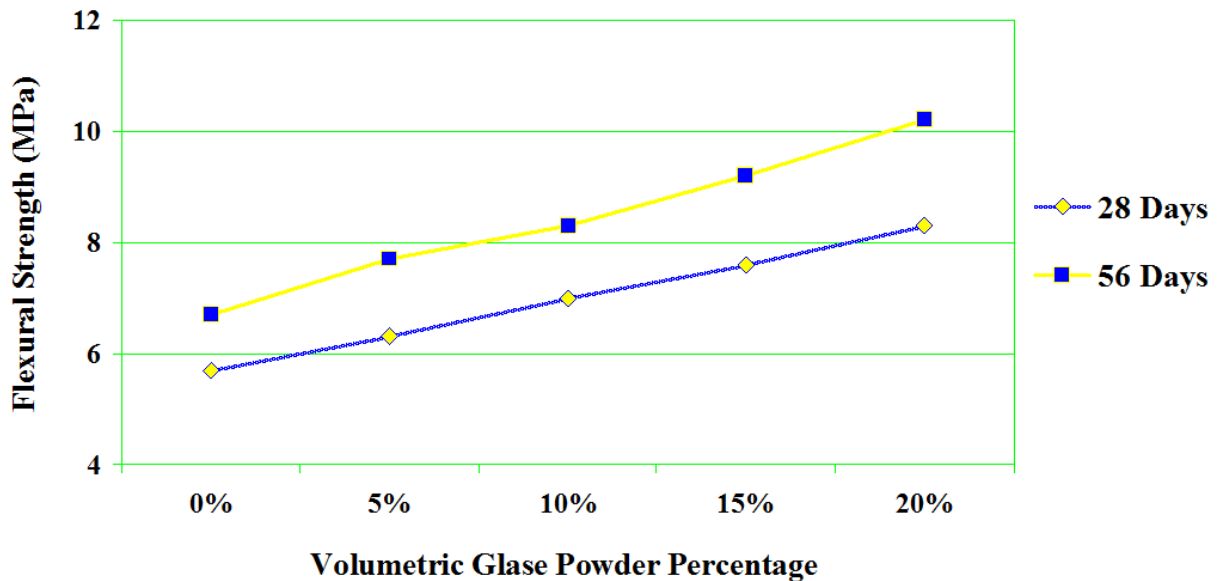


Figure 5. Flexural strength of SCMGP at 28 and 56 days

3.3. Water Sorptivity

Figure 6 shows the water sorptivity results of the SCMGP's for 28 and 56 days. Main purpose of realization of water sorptivity experiment based on water-flow into unsaturated concrete through large connected pores is check how much water gets of the mortar or concrete specimen. Thus, it is considered as a relative measure of the permeability (Ozbay, 2007). Test results for SCMGP0 and SCMGP20 for 28 days were determined as 0.055 cm/s and 0.039 cm/s, respectively. In addition, test results for SCMGP0 and SCMGP20 for 56 days were identified as 0.0382 cm/s and 0.0274 cm/s, respectively. To be understood from these results, water sorptivity values reduced with the increase of the curing time and the glass powder ratio used instead of fly ash. Due to the active silica content of the glass powder is higher than that of fly ash, water sorptivity values decreased with increased of glass powder ratio. According to study of Sabet, Libre & Shekarchi (2016), it was determined as an increase in strength and reduction in the capillary absorption of concrete, the beneficial roles in concrete of silica fume that a pozzolanic material similarly glass powder.

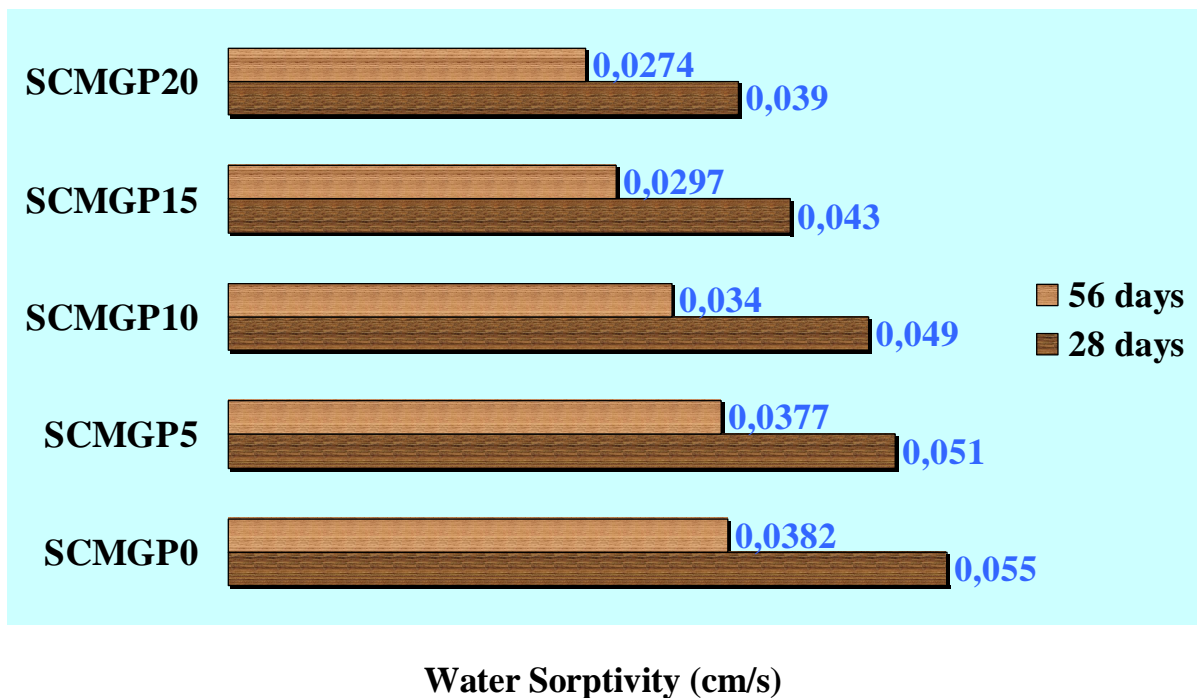


Figure 6. Water sorptivity of SCMGP's at 28 and 56 days

3.5. Rapid Chloride Permeability

The penetration of water into concrete with chloride and other effective ions is one of the most important points impressing durability performance of concrete. The microstructure of concrete which mostly determines will be how much effective of this process is related with the transport of ions and water passing in concrete (Oh, Cha, Jang & Jang, 2002).

The graphical representation of rapid chloride permeability is given in Figure 7. Considering 28 and 56 days test results, rapid chloride permeability values of the mixture containing 20% glass powder according to control mortar reduced by 31.83% and 34.14%, respectively. According to ASTM C 1202 (Talah, Kharchi & Chaid, 2015). Chlorine ion permeability is very low in the range of 0-1000 °C, low in

the range of 1000-2000 C, moderate in the range of 2000-4000 °C and high in the range of 4000-6000 °C. At 28 days, all of the SCMGP have moderate chlorine ion permeability. At 56 days, all of the SCMGP have low chlorine ion permeability. The main reason for reduction of rapid chloride permeability with increasing glass powder ratio used in the production SCMGP is filler effect having due to contained finer particles than cement and high active silica content of glass powder. These results are in good agreement with the findings of the studies reported in the literature in that incorporating supplementary cementitious materials can improve the resistance of the concretes penetration of the chloride ions. It was also reported that the concretes produced with supplementary cementitious materials are equal to or superior than the control concrete in the terms of the resistance to chloride ion permeability (Ozbay, 2007; Guneyisi & Gesoglu, 2008).

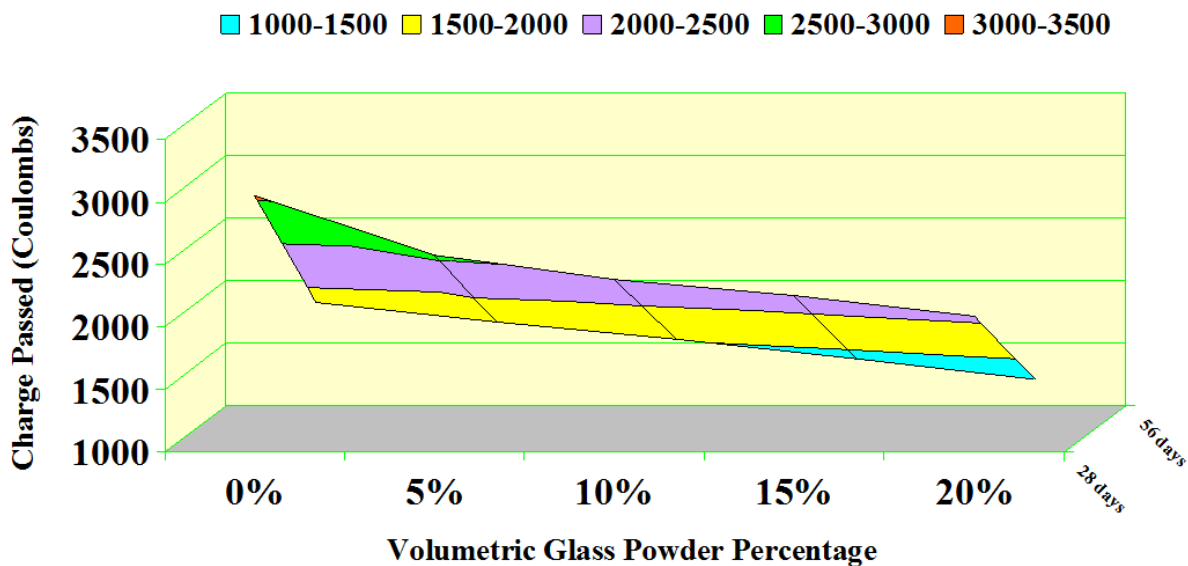


Figure 7. Rapid chloride permeability of SCMGP at 28 and 56 days

4. Conclusions

The following statements can be drawn from this study investigated of the effect on mechanical and durability properties of SCMs of glass powder and fly ash.

- The compressive and flexural strengths increased with the increased proportion of glass powder used in the production of SCMGP at 28 and 56 days. The main reason of this situation is that glass dust contains more active silica than fly ash. In this way, glass powder forms new C-S-H gels by binding with high silica content Ca(OH)_2 resulted hydration of cement and water produces.
- The water sorptivity and rapid chloride permeability that basic durability properties yielded positive results as the use rate of glass dust increased. Because, glass powder increases the mechanical and durability properties due to high silica content and filler effect, when compared with fly ash.

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