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Assessment of flowing ability of self-compacting mortars containing recycled glass powder

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Abstract. This paper investigates the effect of recycled glass powder (RGP) on flowing properties of self-compacting mortars (SCMs) containing different ratios of fillers and superplasticizer dosages. Fly ash (FA), nano-silica (NS), micro-silica (MS), metakaolin (MK) and rice husk ash (RHA) are used as fillers and their synergistic effect with RFP is studied. The effects of fillers and high-range water reducer (HRWR) on flowing ability of mortars are primarily determined by slump flow and V-funnel flow time tests. The results showed that for composites with a higher RGP content, the mortar flowing ability increased but tended to decrease when the composites containing 10% MK or 5% RHA. However, the flowing ability of samples incorporating 5% RGP and 10% SF or 25% FA showed an opposite result that their slump flow spread decreased and then increased with increasing RGP content. For specimens with 3% NS, the influence of RGP content on flowing properties was not significant. Except RHA and MS, the fillers studied in this paper could reduce the dosage of HRWR required for achieving the same followability. Also, the mixture parameters were determined and indicated that the flowability of mixtures was also affected by the content of sand and specific surface area of cement materials. It is believed that excess fine particles provided ball-bearing effect, which could facilitate the movement of coarse particles and alleviate the interlocking action among particles. Also, it can be concluded that using fillers in conjunction with RGP as cementitious materials can reduce the material costs of SCM significantly.

Keywords: recycled glass powder; Rheological properties; self-compacting mortar; cementitious materials

1. Introduction

In the recent decades, utilizing self-compacting concrete (SCC) in construction projects has gained significant importance. Having unique abilities such as high workability, filling ability of difficult accessible areas in formwork without bleeding or segregation, and compatibility with its own weight without external vibration made this type of concrete to be a groundbreaking material (Madandoust *et al*. 2011, Oltulu and Şahin 2013, Ali Sadrmomtazi *et al*. 2017, Safiuddin *et al*. 2011). Self-compacting mortar (SCM) serves as a basis for the development and design of SCC, so the understanding of SCM characteristics is essential (Madandoust *et al*. 2015, Ehsan Mohseni *et al*. 2015, Sadrmomtazi and Tahmouresi 2017). Nevertheless, there are many concerns about the high material costs of SCC and SCM compared to ordinary concrete/mortar of similar strength (Khotbehsara *et al*. 2015, Ranjbar *et al*. 2013). It is well known that an increase in cement content leads to a significant rise in material cost and often has other negative effects on concrete properties (Güneyisi and Gesoğlu 2008, Yang *et al*. 2015). It's generally believed that the stability and economic efficiency (cost-effectiveness) of SCC/SCM can be increased by incorporating fillers, such as limestone powder (LP), fly ash (FA), silica fume (SF), metakaolin (MK) and ground granulated blast furnace slag (GGBFS) (Lenka and Panda 2017, Madandoust *et al*. 2015, Madandoust and Mousavi 2012, Mohseni *et al*. 2016, Mohseni and Tsavdaridis 2016, Shadmani *et al*. 2018). The use of fillers could also improve the grain-size distribution and particle packing, resulting in a greater unity (Felekoğlu *et al*. 2007, Momtazi *et al*. 2016). High-range water reducer (HRWR) or superplasticizer (SP) are commonly used to improve the flowing ability of SCC. However, the amounts of HRWR required for SCC are usually close to maximum recommended dosages, which may lead to segregation problems associated with very high fluidity (Felekoğlu *et al*. 2007, Madandoust and Mousavi 2012, Ali Sadrmomtazi *et al*. 2018). In addition, the use of chemical additives may increase the material cost of SCC and offset the savings in labor cost. Previous studies show that the use of mineral additives not only can reduce the material cost but also improve the fresh and hardened properties of SCCs (Felekoğlu *et al*. 2007, Mohseni *et al*. 2015).

The concept of utilizing waste mineral materials for construction applications has enjoyed a long and successful history, which includes fly ash, slag, and silica fume etc. (Mohseni *et al*. 2019, Mohseni *et al*. 2017). Initially considered problematic, land filled waste materials are now

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considered valuable materials for use in improving and developing the sustainable concrete (Federico and Chidiac 2009, Mohseni *et al*. 2017, Mohseni *et al*. 2017, Ali Sadrmomtazi *et al*. 2017). The benefits of developing alternative or supplementary cementitious materials as partial replacements for ordinary Portland cement (OPC) are described by Malhotra and Mehta (Malhotra and Mehta 2004). Bottle glass is one of the waste materials which can be extensively used as a constituent of concrete. As of 2005, the total global waste glass production estimation was 130 Mt, among which the European nations, China and USA produced approximately 33 Mt, 32 Mt and 20 Mt, respectively (Belouadah *et al*. 2018, Rashad 2014). The amount of waste glass increased significantly over the recent years due to an ever-growing use of glass products. However, not all used glass can be recycled into new glass because of impurities, cost, or mixed colors (Shi *et al*. 2015, Zaidi *et al*. 2017). Most waste glasses are disposed in landfill or roadway sites. Landfills however are not the most environmentally responsible solution to waste, better alternatives for recycling waste glass are required. One promising alternative is to use recycled glass powder (RGP) in cement-based composites. There are some studies investigating the effects of RGP as cementitious substitutes or aggregates on fresh and hardened properties of self-compacting concrete/mortar. The typical benefits include increased slump of concrete with an increase of glass powder due to its angular shape in concrete mixtures, and positive effects on the mechanical properties of concrete mixtures (Du Plessis 2007, Imbabi *et al*. 2012, Silva and de Brito 2013, Imbabi *et al*. 2012, Silva and de Brito 2013). Parghi and Alam (2016) reported that the flow ability decreased when the content of RGP increased from 0% to 25%. Kou and Poon (2009) studied the influence of using recycled glass cullet (RGC) on fresh and hardened properties of SCC. Their results showed that the slump, blocking ratio and air content of RGC–SCC mixtures enhanced with increasing RGC content, while the mechanical properties of RGC-SCC mixtures decreased with an increase in RGC content. However, Cassar and Camilleri (2012) reported that the effect of RGP on slump and concrete density of mortar mixtures containing up to 50% RGP was not significant. Liu (2011) studied the effect of RGP on workability of SCC mixtures. Two different types of ground waste glass were crushed and used to partially replace the cement and fine aggregate. Due to the angular and scaly particle shape of glass, it was reported that the SCC mixtures require a relatively high water to powder ratio and low SP dosage with increasing glass content. Also, the SCC mixtures containing glass showed an improvement in segregation resistance.

Furthermore, there have been many studies about the effect of different cementitious additives or fillers on concrete and mortar engineering properties (Khotbehsara *et al*. 2017, Koushkbaghi *et al*. 2019, Koushkbaghi *et al*. 2019). Li *et al*. (2017) studied the combined effects of micro-silica (MS) and nano-silica (NS) on durability of mortar. Their results showed that the SP dosages required to maintain the same flow ability increased from 0.3% to 1.2% when the MS content increased from 0% to 10%, whereas an increase from 0.3% to 1.7% was required when the NS content increased from 0% to 2%. In similar research, Jalal *et al*. (2015) reported that addition of 15% FA led to increase in slump flow by 17% and decrease in V-funnel flow time by 33%, whereas the presence of 2% NS or 10% SF reduced the slump flow up to 13.5% and increased the V-funnel flow time up to 33%. Guneyisi and Gesoglu (2008) assessed the properties of self-compacting mortars with binary and ternary cementitious blends of FA and MK. It was indicated that FA can increase the mixtures flow diameter, however MK tended to decrease the flow diameter. Similar trend was also observed for V-funnel flow time results. They explained the presence of FA would cause a reduction in the viscosity of mortar, and the reduction became significant with increasing FA content. On the other hand, the incorporation of MK significantly enhanced the viscosity of concrete.

Use of supplementary cementitious materials or mineral admixtures as additives in concrete has a great tendency to meet the expectations in providing greater sustainability in the construction and building industry. However, there are very few studies to date that investigate the influence of RGP on rheological behavior of self-compacting mortar. Also, there is very limited or even no research currently available to reveal any synergic effect of RGP and different fillers on flowability of self-compacting mortar. The study in this paper seeks to address these research gaps by investigating the workability of self-compacting mortar incorporating recycled glass powder (RGP) and other fillers including fly ash (FA), metakaolin (MK), rice husk ash (RHA), nano-silica (NS), and micro-silica (MS). Furthermore, the amounts of high-range water reducer (HRWR) required to achieve the optimum flowability according to the EFNARC standard were determined. The mini slump flow and mini V-funnel flow tests were conducted to evaluate the flowing and passing ability of SCM mixtures. Moreover, the effective parameters on the flowability of mortars were analyzed based on the mix design of the mortars.

2. Experimental program

2.1 Materials and mix proportions

Table 1 Physical and chemical characteristic of fillers

Chemical compositions (% by weight)	OPC	MS	RHA	RGP	MK	NS	FA
SiO_2	21.54	90.7	91.62	72.5	54	99.9	56.95
Al_2O_3	4.95	1	0.49	1.06	43.2	0	25.76
Fe_2O_3	3.82	0.9	0.73	0.36	0.5	0	6.5
CaO	63.24	1.68	2.51	8	0.4	0	4
MgO	1.55	1.8	0.8	4.18	0.2	0	2.5
SO3	2.43	0.78	0	0.18	0	0	0.35>
Na_2O+K_2O	1.23	0.1	0	13.36	0.2	0	0.28
LOI	2.15	2	0	0	1	0.1	1.28
Specific gravity (gr/cm^3)	3.15	2.12	2.09	2.5	2.56	1.3	2.2
Specific surface area (m^2/kg)	319	2100	1130	650	1200	200000	315

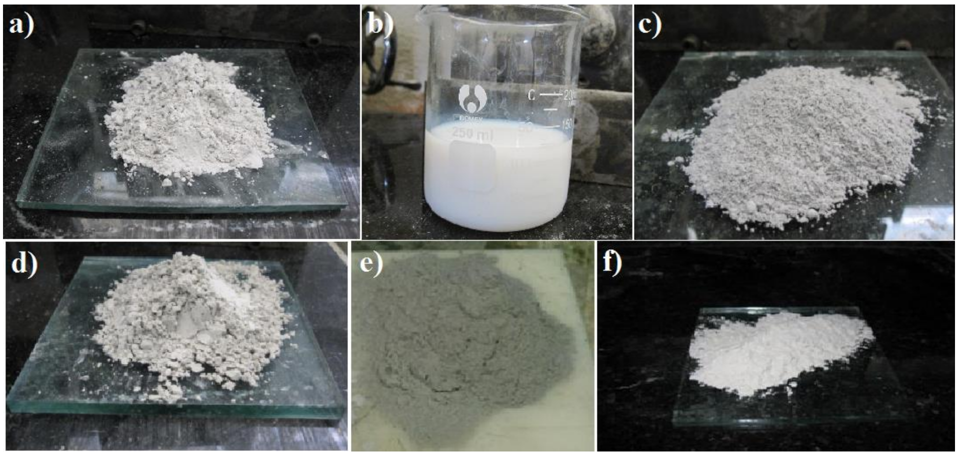


Fig. 1 The used materials: (a) fly ash, (b) nano-silica, (c) micro-silica, (d) metakaolin, (e) rice husk ash and (f) recycled glass powder

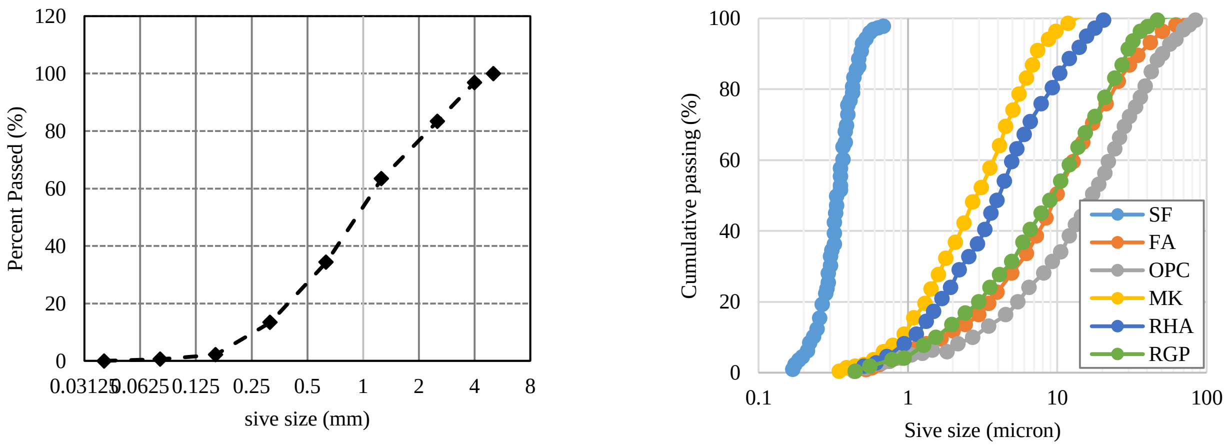


Fig. 2. Particle size distribution of a) sand and b) fillers

Type I 42.5 ordinary Portland cement was used for all mixtures according to ASTM C150. Class F- fly ash, liquid nano-silica (nano- cembinder 50), micro-silica, class N-metakaolin in dehydroxylated form of the clay mineral kaolinite, and rice husk ash fillers were used as pozzolanic materials confirming to the requirements of ASTM C618. Table 1 shows the chemical compositions and physical properties of the fillers and Portland cement, whereas Fig. 1 shows the cementitious materials used in this study. Polycarboxilate acid PCE supplied by Vand Shimi with a density of 1.03 g/cm^3 was utilized as HRWR in according to ASTM C494. The natural river sand with dry apparent density of 2.65 g/cm^3 and water absorption of 1.1% was used as fine aggregate. The sieve analysis results are plotted in Fig. 2(a).

Recycled glass powder (RGP) samples were derived by crushing waste glass bottles which were obtained from the Saravan landfill site in the city of Rasht, Guilan, Iran. To prepare RGP, the waste glass bottles were ground for about 24 h in a Los Angeles machine in the laboratory. After grinding, the particle size of RGP passing from 75 μm to 25 μm and (45 μm) sieve were 97% and 77%, respectively indicating that RGP is a fine particle. RGP was used to replace cement at ratios corresponding to 0%, 5%, 10% and 15% by weight. Fig. 2(b) shows particle size distribution of fillers.

The percentage of cement replacement by fillers and the water to binder (*w/b*) ratio were determined through trial workability tests. In this regard, 25% FA, 3% NS, 10% MS, 10% MK, 5% RHA were used to replace the cement. Moreover, the water to binder ratio of 0.4 was kept constant for all mixtures. The amounts of HRWR varied from 0.2% to 1.5% by weight of cement were used to achieve the slump flow requirements as specified by EFNARC committee (EFNARC 2002). Due to the difference in specific gravity of pozzolans and with respect to the volumetric mix designs, the amounts of sand in mixtures were slightly different. The mixture proportions are given in Table 2. The mixtures were identified by a name that represents the type of pozzolanic material, and their percentage used in that mixture. Specimens labeled Ctrl indicate that it is a plain cementitious mixture and, hence, it has no fillers and RGP. The specific surface area of fillers measured by Blaine air permeability in according to ASTM C204.

2.2 Mortar specimen preparation and testing methods

The mortars were prepared using an epicycles revolving type small mechanical mixer conforming to ASTM C305.

Table 2 Mixture proportions of fillers and RGP containing mortars (kg/m^3)

Mix ID	Water	OPC	RGP	MK	FA	RHA	MS	NS	Sand
RGP0 (Ctrl)	280	700	0						1260
RGP5	280	665	35						1252
RGP10	280	630	70						1247
RGP15	280	595	105						1237
MK10RGP0	280	630	0	70					1246
MK10RGP5	280	595	35	70					1240
MK10RGP10	280	560	70	70					1232
MK10RGP15	280	525	105	70					1225
FA25RGP0	280	525	0		175				1197
FA25RGP5	280	490	35		175				1189
FA25RGP10	280	455	70		175				1181
FA25RGP15	280	420	105		175				1173
RHA5RGP0	280	665	0			35			1243
RHA5RGP5	280	630	35			35			1236
RHA5RGP10	280	595	70			35			1228
RHA5RGP15	280	560	105			35			1220
MS10RGP0	280	630	0				70		1231
MS10RGP5	280	595	35				70		1224
MS10RGP10	280	560	70				70		1216
MS10RGP15	280	525	105				70		1209
NS3RGP0	280	679	0					21	1235
NS3RGP5	280	644	35					21	1227
NS3RGP10	280	609	70					21	1220
NS3RGP15	280	574	105					21	1212

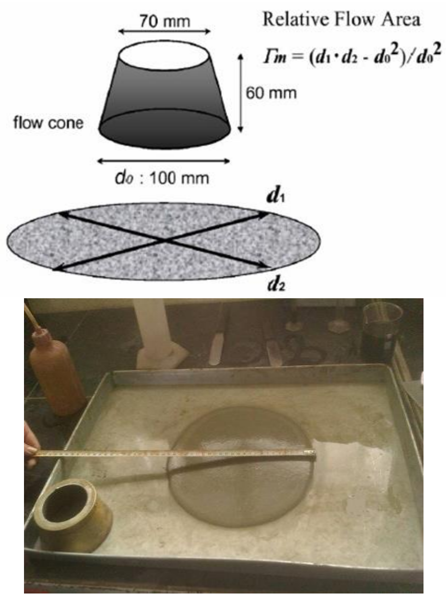


Fig. 3 Mini-slump test setup for fresh mortar (EFNARC 2002)

First, the sand, cementitious binder (containing cement, and recycled glass powder) and fillers were mixed for 30 seconds with ordinary speed (80 rpm). Then, half of water and HRWR were added and mixing was continued for an additional minute with high speed (120 rpm). Then the machine was switched off to allow the mixture to rest for about 90 seconds, Eventually, the remaining water and HRWR were added and mixed for 2 minutes.

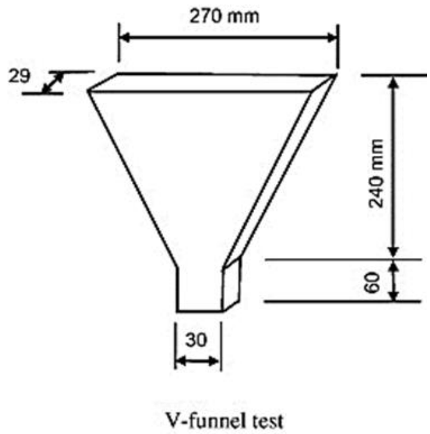
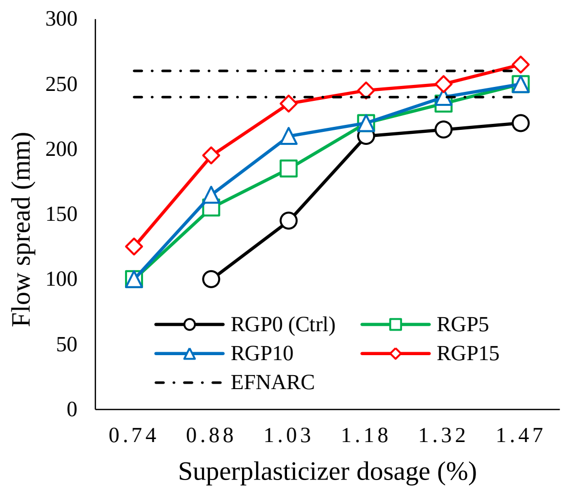
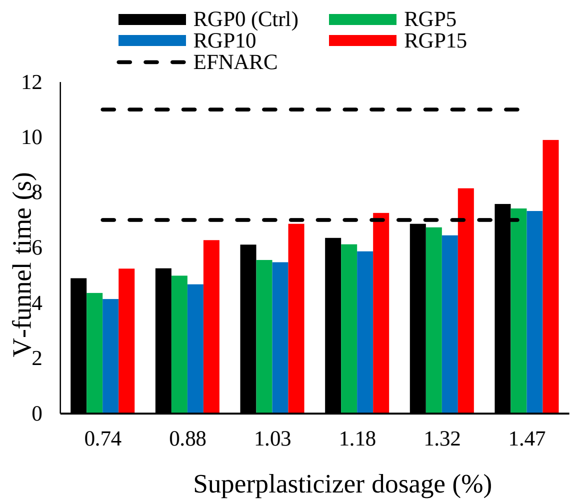


Fig. 4 Mini V- funnel flow test setup for fresh mortar (EFNARC 2002)



(a) Flow spread



(b) Mini V-funnel time

Fig. 5 (a) The flow spread and (b) mini v-funnel time results of mortars containing various RGP and HRWR dosages

After the mixing process was completed, the flowing properties of fresh mortar with different HRWR dosages were assessed using mini-slump flow in accordance with the procedures recommended by EFNARC (EFNARC 2002). The slump flow diameter (in mm) were then recorded. V-funnel test was also used to measure the flowing time (in sec) for mixtures with optimum HRWR dosages. It should be noted that the acceptance ranges suggested by the EFNARC for mini slump flow time and mini V-funnel flow time are 240-260 mm and 7-11 sec, respectively. Figs. 3 and 4 show the mini-slump flow and mini V-funnel flow tests, respectively. Segregation and bleeding were visually checked during the slump flow test.

3. Results and discussion

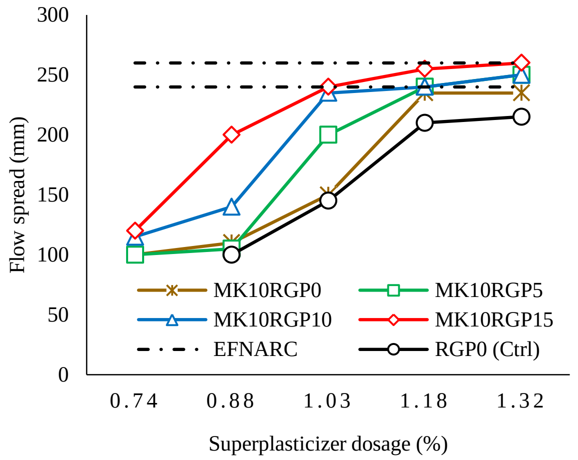
3.1 Effects of recycle glass powder (RGP)

The flow diameter and V-funnel results for self-compacting mortars containing RGP are illustrated in Fig. 5. This figure exhibits the flowing ability of SCMs with respect to the flow spread at various dosages of HRWR. The flow spread varied in the range of 100-265 mm for the Ctrl mixture and mixtures with RGP. According to the results, the flow spread of mixtures increased with increasing HRWR dosage.

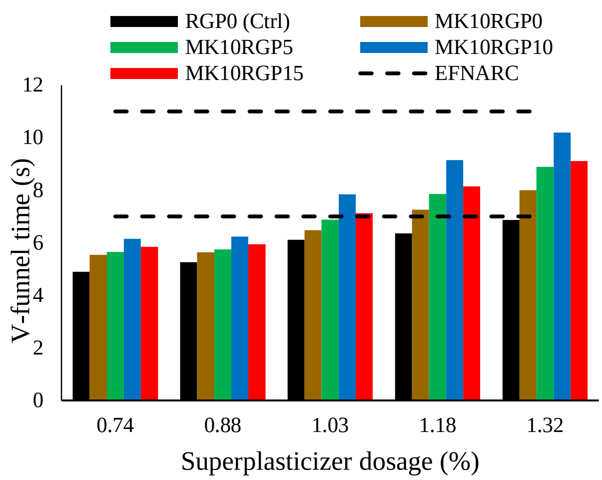
Though the control mixture with a high HRWR dosage of 1.47%, its flow spread did not meet the EFNARC's minimum slump flow requirements of 240 mm. This is due to the fact that, high cement content in control mixture caused most of the mixing water to be assigned to hydration. As a result, free water reduced and the mixture became more viscous. Moreover, the sand volume of control mixture is higher than other mixtures containing RGP. Consequently, more water accumulated in around aggregate and the free water (flowability) decreased (Mehdipour and Khayat 2018, Vanjare and Mahure 2012). When 15% of cement was replaced by RGP, the slump flow increased and was enough to fulfil the standard requirements.

According to Fig. 5(a) it can be seen that the flow spread curves shifted upward with increasing RGP content. This implies the positive effect of RGP on flow spread. At similar HRWR dosages, adding RGP led to increase in flow spread up to 95%, compared to the control mixture. The results substantiate the key role of RGP in flow spread improvement of mixtures. It can be stated that RGP could enhance flowability of cementitious matrixes as reported in the previous study (Topcu and Canbaz 2004). The minimum HRWR dosages required to meet the standard requirements were 1.18% and 1.32%, for RGP15 and RGP10 specimens, respectively. It can be concluded that using RGP not only can benefit our environments, but also can lead to the considerable saving of HRWR which is a significant contribution from the economic point of view.

The mini V- funnel time results are shown in Fig. 5(b). Although the slump flow results for control and RGP mixtures at low HRWR dosages did not meet the requirement, their flow times were in the range specified by EFNARC. The mixtures showed similar flow times when RGP in the mixtures was up to 10%, but a significant improvement can be seen when 15% RGP was used. In other words, the flowability and V-funnel flow time of



(a) Flow spread



(b) Mini v-funnel time

Fig. 6 (a) The flow spread and (b) mini v-funnel time results of mortars containing various RGP or HRWR dosages and 10% MK

cementitious mixtures increased with increasing RGP content which is in agreement with the results of other studies (Shi *et al*. 2015, Vanjare and Mahure 2012). The mixture containing 10% RGP showed the lowest V-funnel flow time, as demonstrated in Fig. 5(b). According to Fig. 5(b), the EFNARC minimum flow time required for RGP15 occurred at 1.03% of HRWR, while for other mixtures it was 1.47%. This represents about 43% of HRWR saving.

3.2 Effects of metakaolin (MK)

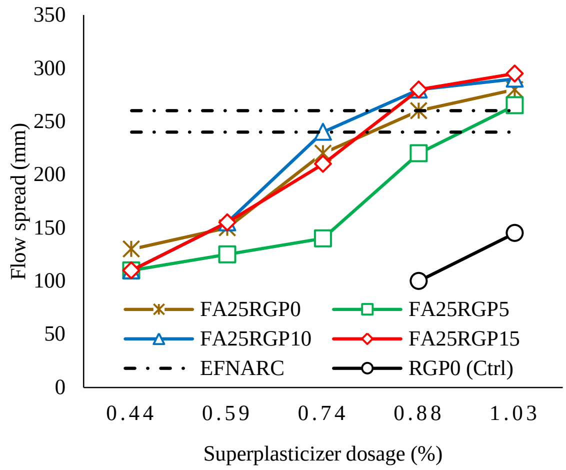
Fig. 6 shows the effects of MK on the slump flow and mini V-funnel time of RGP mixtures containing with different HRWR contents.

The results from Fig. 6(a) shows adding 10% MK had no considerable effect on flow ability, when comparing the results between MK10RGP0 and RGP0 (Ctrl). However, in mixtures with HRWR dosages less than 1% the results are almost similar. Due to the high specific surface of MK, water demand increased and self-drying emerged in the mixture (Xincheng 2012). Therefore, the actual water-cement ratio reduced and resulted in a decrease of workability. Also, considering the irregular structure and angular shape of MK particles, the inter-particles friction was high, especially in low dosages of HRWR and thus causing a lower workability. The slump flow diameter of control mixture increased up to 11% when 10% MK was added.

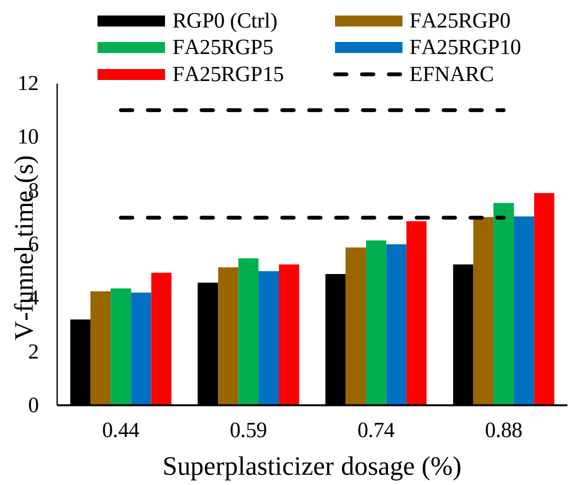
It can be seen from Fig. 6(a) that the minimum HRWR dosage required for MK10RGP15 and MK10RGP0 to meet the EFNARC requirement are 1.03% and 1.18%, respectively. The results further substantiate that RGP can decrease the required amount of HRWR. Increased HRWR dosage causes paste to reach liquefying process quickly through falling yielding stress and plastic viscosity (Wallevik and Wallevik 2011). In mixtures with 0.88% HRWR dosages, adding 15% RGP indicated an increase of 82% when compared to MK10RGP0. Noteworthy to mention that it experienced almost 60% increase to reach the EFNARC-defined range.

When comparing the results between Figs. 5(a) and 6(a), it can be inferred that MK mixtures required less HRWR dosage to meet the standard requirement. The minimum HRWR dosage for mixtures with MK and without RGP to satisfy self-compacting requirements is 1.18%. This amount is lower when compared with the control mixture which needs 1.47% of HRWR to satisfy the required slump flow diameter. It can be attributed to the micro-filling feature of MK.

As shown in Fig. 6(b), increasing the RGP replacement have a slight influence on V-funnel flow time. The flow time of all SCMs is within the standard requirements range by the addition of HRWR with the dosage more than 1.18%. It seems that the paste with RGP and MK becomes more viscous due to the higher surface area and fineness of RGP and MK compared to Portland cement, so the negative effect on flow time of mortars is exacerbated (Madandoust and Mousavi 2012). In general, it can be stated that the addition of RGP and MK together resulted in having better flowability test results.



(a) Flow spread



(b) Mini V-funnel time

Fig. 7 (a) The flow spread and (b) mini v-funnel time results of mortars containing various RGP or HRWR dosages and 25% FA

3.3 Effects of fly ash (FA)

Fig. 7 shows the effects of using FA on the slump flow and mini V-funnel time of RGP mixtures containing different HRWR dosages.

As shown in Fig. 7(a), it can be found that, adding 25% FA to RGP0 (Ctrl) mixture with HRWR amounts of 0.88 and 1.03, increased the flow spread up to 93 and 160%, respectively when compared to the control mixture. Due to the spherical shape of FA particles, as well as the ball bearing effect, adding FA increased the workability and improved mortar slump, which leads to reduced water demand.

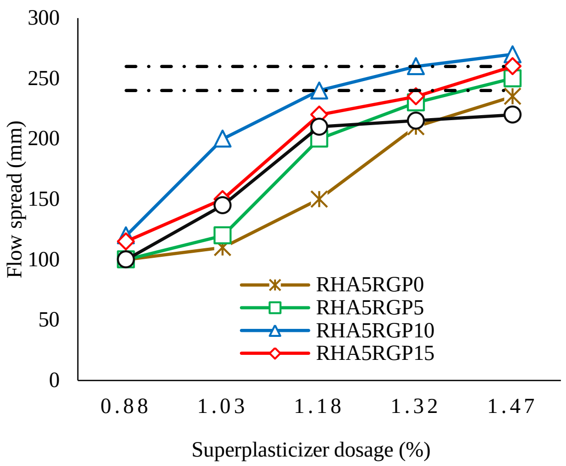
Adding 5% RGP to FA-containing mixtures reduced the flow spread, however the flow spread increased when 10% or 15% RGP were added. Increasing RGP in mixtures reduces HRWR demand. In this regard, comparisons of 5% and 15% glass shows 22% reduction in HRWR demand.

Comparing the results of mixtures with and without 25% FA, it can be seen that the minimum HRWR dosage required for mixtures without FA to reach standard requirements is approximately 1%; however, it is 0.7% for FA-containing mixtures (Fig. 7(a) and 5(a)). This corresponds to a 30% saving in HRWR. It is also clear to show that the flow diameter of mixture with 5% RGP (FA25RGP5) is less than that of mixture without RGP (FA25RGP0) at all HRWR dosages.

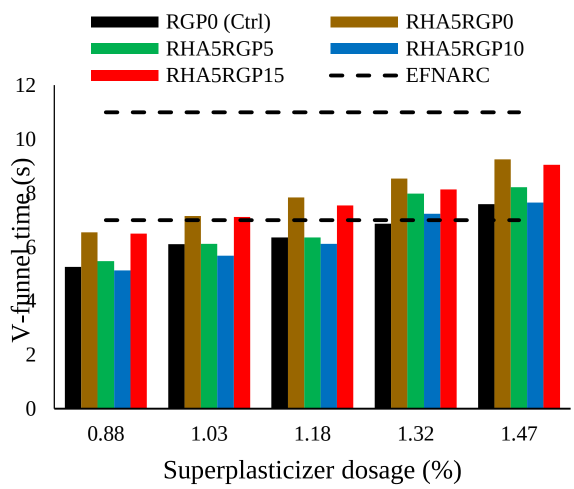
The V-funnel flow time of all mixtures containing FA was below 8 seconds, as shown in Fig. 7(b). The results meet the minimum requirement of EFNARC and indicate the positive effect of FA. Comparison of the results of adding MK, FA, RHA, MS and NS shows that FA had the highest tendency for increasing the flowability in RGP-containing mixtures.

3.4 Effects of rice husk ash (RHA)

Fig. 8 shows the effect of RHA on flow spread and mini V-funnel time results for mortar mixtures containing different RGP and HRWR dosages.

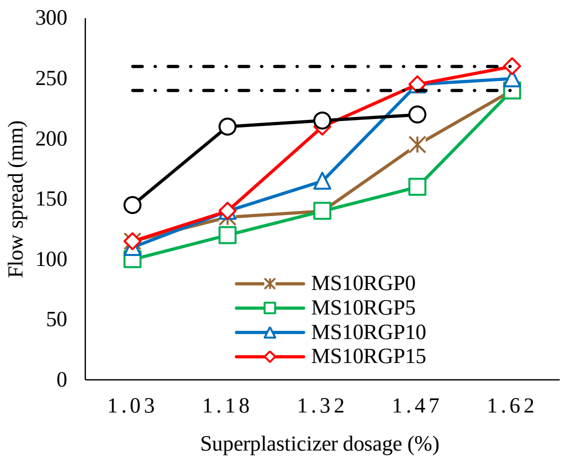


(a) Flow spread

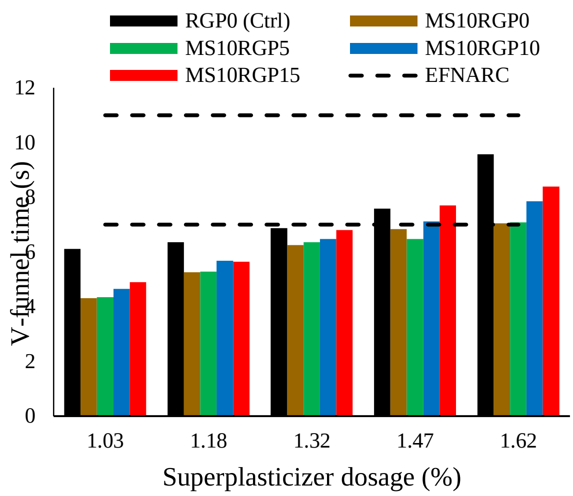


(b) Mini V-funnel time

Fig. 8 (a) The flow spread and (b) mini v-funnel time results of mortars containing various RGP or HRWR dosages and 5% RHA



(a) Flow spread



(b) Mini V-funnel time

Fig. 9 (a) The flow spread and (b) mini v-funnel time results of mortars containing various RGP or HRWR dosages and 10% MS

According to Fig. 8(a), RHA5RGP0 shows lower slump flow spreads when compared to RGP0 at all HRWR dosages up to 1.32%. It seems the presence of 5% RHA could negatively affect the slump flow of mixture. This is mainly because of the increased volume fraction and surface area of the binder in the presence of RHA. Particularly, the increase in the surface area of binder caused by RHA was very significant, as evidenced by Table 3. The increased surface area adsorbs a greater amount of water, thus decreasing the quantity of free water in mortar. Hence, greater HRWR dosages were required for RHA mixtures to satisfy the requirements for flow spread. However, the flow spread of RHA5RGP0 increased by 7% compared to the RGP0 mixture with the same amount of HRWR, i.e., 1.47%, which shows the moderate capability of RHA for increasing the flowability of SCM. It was clearly observed from Fig. 8(a) that in 1.03% and 1.18% dosages, the flowability of SCM varied significantly and the variation reduced when 1.32 and 1.47% HRWR were added to the mixtures. It is worth mentioning that 10% RGP influenced the flow spread more than other ratios.

As shown in Fig. 8(b), the flow time of all mortar mixtures is within the required standard range when 1.03% of HRWR dosage was added. Adding 5% RHA to the control mixture (RGP0) increased the flow time up to 22% which is similar to the trend seen for slump flow reduction. The addition of 5 and 10% RGP reduced the flow time compared to RHA5RGP0 mixture. Although, the flow time of mixtures containing 15% RGP increased compared to mixture with 5 and 10% RGP, a slight reduction can be seen compared to the mixture with the same amount of RHA without RGP. This is due to the fact that the surface area in the mixture with 5% RHA and 15% RGP increased considerably, so the water demand was higher at a given water to cement ratio (Ling *et al.* 2012, Liu 2011). While the minimum flow time belongs to mixtures containing 5 and 10% of RGP, it seems that the packing volume of the mixture are close to ideal value.

3.5 Effects of micro silica (MS)

Fig. 9 shows the effect of adding MS on flow spread and mini V-funnel time results for mortar mixtures containing different RGP and HRWR dosages.

According to the results shown in Fig. 9(a) , it was found that flow ability of MS-containing mixtures reduced significantly, compared to the control mixture. When the HRWR dosage is less than 1.47%, the flow spread for all mixtures is lower than the minimum standard requirement. It can be seen that adding 10% MS to a mixture without RGP has led to a drop in slump flow from 11% to 38%.

The presence of micro silica additive increased the demand of HRWR to satisfy standard requirement, especially for MS10RGP0 and MS10RGP5 mortars. Due to the high specific area of micro silica, the mixture containing MS absorbed more water and resulted in drying. Also, MS can increase viscosity and accelerate hardening (or sitting time) process (Bauchkar and Chore 2017, Gesoğlu *et al*. 2009, Jalal *et al*. 2015). As shown in Fig. 9(a), MS mixtures containing 10 and 15% of RGP exhibit better flowability, so that they get higher flow spread at the same HRWR dosages. This further shows the positive effect of RGP in mixtures with micro silica.

Fig. 9(a) also indicates the mortars without micro silica (containing different RGP contents) satisfied the minimum standard requirement at lower HRWR dosages compared to MS-containing mortars. Approximately, a minimum of 30% HRWR dosage can be saved when comparing Fig. 9(a) and Fig. 5(a).

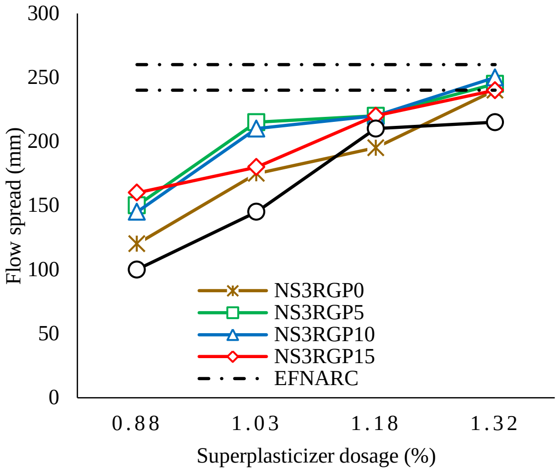
Fig. 9(b) shows the results of V-funnel flow time of MS mixtures are in the range of 7.05-8.39 sec, when 1.47% of HRWR was added. Mixture MS10RGP5 showed the lowest flow time while the mixture with 15% RGP had the highest flow time of 8.39 sec. According to previous researches (Bauchkar and Chore 2017, Mosavinejad *et al*. 2018, Koushkbaghi *et al*. 2019), the incorporation of silica fume or nano silica in cementitious mixtures generally made the concrete more viscous. As can be seen, adding RGP to mixtures containing less than 1.62% HRWR had a slight effect on flow time, so that the flow time of all mixtures is less than the control.

3.6 Effects of nano silica (NS)

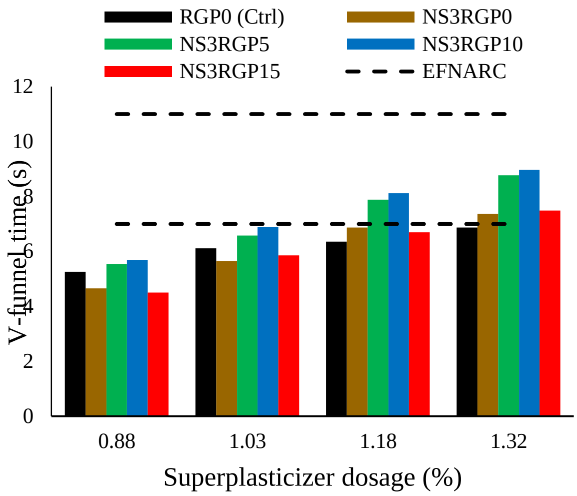
Fig. 10 shows the effects of NS on the slump flow and mini V-funnel time of RGP mixtures containing with different HRWR dosages.

According to Fig. 10(a), it can be seen that the flow spread results of NS-containing mixtures are generally higher when compared to those of control (RGP0) at all HRWR dosages. When HRWR dosage is less than 1.32%, the flow spreads of all NS mixtures do not meet the minimum standard requirement; however, in mixtures without RGP, adding NS increased slump spread up to 11%.

By comparing Figs. 9(a) and 10(a), it can be inferred that in lower HRWR dosages, MS-containing mixtures exhibited lower flow spread, while NS-containing mixtures exhibited higher flow slump. It is also understood that, at HRWR dosages higher than 1.18%, the flow spread curves tend to be convergent (close to each other), which



(a) Flow spread



(b) Mini V-funnel time

Fig. 10 (a) The flow spread results and (b) mini v-funnel time of mortars containing various RGP or HRWR dosages and 3% NS

indicating a drop in the performance of the RGP on the flowability of the mixtures. Perhaps this is because of the increased viscosity due to the combination of nanoparticles with high RGP content and HRWR dosages.

Fig. 10(b) shows the results of flow time for NS-containing mixtures. As can be seen, the V-funnel time was in the range of 7.37-9 sec and satisfied the EFNARC standard requirements. Initially, the addition of NS reduces the flow time at HRWR dosages of 0.88 and 1.03%, but that increases at higher dosages of HRWR. It can be attributed to the tiny size of NS, which could not be well dispersed in mixtures with lower dosages of HRWR. MS10RGP10 showed the greatest flow time, however the flow time decreased when the mixture contained 15% RGP.

3.7 Overall discussion

By reviewing the slump flow test results (Figs. 5-10), it can be inferred that in non-pozzolanic mixtures, increasing

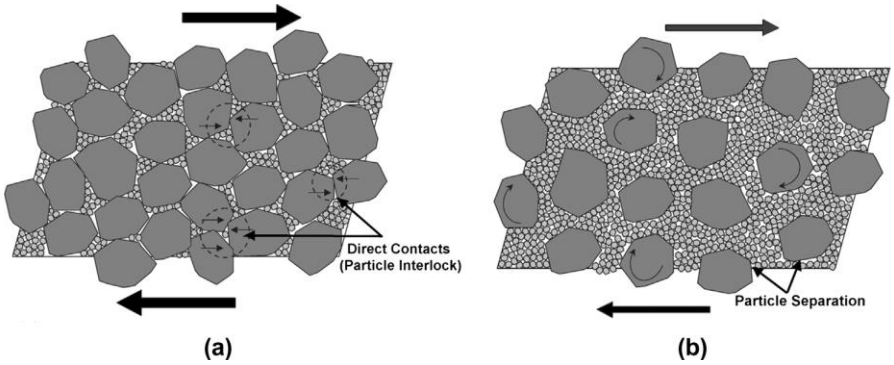


Fig. 11 Schematic illustration of aggregate structures for: (a) the state of maximum packing density and (b) the state of maximum flow rate (Mehdipour and Khayat 2018)

Table 3 Various mixture parameters of mortars

Mix ID	v^{1}_{sand} ($\times 10^{-3}$ m^3/m^3)	v^{2}_{binder} ($\times 10^{-3}$ m^3/m^3)	v^{3}_{paste} ($\times 10^{-3}$ m^3/m^3)	A^{4}_{binder} ($\times 10^{-3}$ m^2/m^3)
RGP0 (Ctrl)	497.8	222.2	512.19	223.3
RGP5	494.9	225.1	515.02	234.8
RGP10	492	228	517.85	246.4
RGP15	489.1	230.9	520.68	258
MK10RGP0	492.7	227.3	517.21	284.9
MK10RGP5	489.8	230.2	520.04	296.5
MK10RGP10	486.9	233.1	522.87	308.1
MK10RGP15	484	236	525.7	319.7
FA25RGP0	473.8	246.2	535.7	222.6
FA25RGP5	470.9	249.1	538.53	234.1
FA25RGP10	468	252	541.36	245.7
FA25RGP15	465.1	254.9	544.19	257.3
RHA5RGP0	492.1	227.9	517.71	257.6
RHA5RGP5	489.3	230.7	520.54	269.2
RHA5RGP10	486.4	233.6	523.37	280.8
RHA5RGP15	483.5	236.5	526.2	292.3
MS10RGP0	487	233	522.77	347.9
MS10RGP5	484.1	235.9	525.6	359.5
MS10RGP10	481.2	238.8	528.43	371.1
MS10RGP15	478.3	241.7	531.26	382.7
NS3RGP0	488.3	231.7	521.49	4416
NS3RGP5	485.4	234.6	524.32	4428
NS3RGP10	482.5	237.5	527.15	4439.7
NS3RGP15	479.6	240.4	529.98	4451

[1]Volume fraction of sand, [2] Volume fraction of binder, [3] Volume fraction of paste, [4] specific surface area of binder.

the amount of RGP used causes the flow spread to enhance. While the presence of supplementary materials used in this study, i.e., MK, FA, RHA MS and NS had different influences on flow spread results. In fact, the addition of MK, FA and NS increased the slump flow spread; however, the addition of RHA and MS resulted in reduction. Generally, the increase in the RGP content up to 15% has a positive effect on the followability of mixtures containing supplementary materials. Noteworthy to mention that the mixtures with MK, exhibit a relatively better performance in which the addition of 1 to 1.18% of HRWR resulted in meeting the EFNARC requirement, while in the case of other additives it occurs at higher dosages of HRWR. The weakest performance of the slump flow diameter belongs to the mixture with MS, which has consumed at least 10% more HRWR compared to other mixtures. In binary mixtures for slump test, the lowest dose of HRWR was 0.74%, for FA and then belonged to RGP, MK, NS, RHA and MS, respectively, at doses of 1.03, 1.18, 1.32, 1.47 and 1.62 % (minimum amount to satisfy self-confidence).

The V-funnel flow time of most mixtures is consistent with the range determined by EFNARC (7 to 11 sec). Among mortars without RGP, mixtures containing FA, MS and NS obtained similar results, while they experienced less time to egress the V-funnel, compared to other mixtures (7.02, 7.05 and 7.37 sec). Among all the mortars, with same content of HRWR, mixtures containing FA had the best performance with a flow time ranged from 7.02 to 7.92 secs. The flow time satisfied the requirement of EFNARC with 0.88% HRWR, while this amount was 1.18, 1.32, 1.62 and 1.32 for MK, RHA, MS and NS-containing mixtures. The mixtures containing MK showed the greatest flow time ranged from 8 to 10.2 seconds.

After replacing 5% RG, the results were turned out and metakaolin obtained the highest flow time compared to the other samples with the similar substances (see Fig. 7). But, the lowest flow time was seen in mixtures with SF. By replacing 10% RG, metakaolin again had the largest rate of V-funnel time. As the *w/b* ratio and the volume of binders were considered constant, the replacement of cement with metakaolin and 10% RG having particles with porous structure and large specific surface area reduced the free water and increased the viscosity of paste and hence boosted the V-funnel time of mortar. Finally, replacing 15% RG reduced the flow time of mixtures with metakaolin, whereas soared the V-funnel flow time of samples incorporating just RG. Taha and Nounu (2008) utilized waste recycled glass as cement and sand replacement. Based on the results, the presence of glass in mixture decreased the flow time and increased the segregation.

The various aggregate blends flow rate when discharging from V-funnel to assess the packing density impact of particle interlocking has been discussed by previous researchers (Fung and Kwan 2014). It was reported that the optimum fine content for flow rate is higher than the optimum fine content required to achieve maximum possible packing density. This is due to the fact that the coarse particles are tightly packed against each other at the state of maximum packing density, thus introducing relatively large interlocking action and friction among coarse particles. The difference between the state of maximum packing density and the state of maximum flow rate is schematically depicted in Fig. 11. At the state of maximum flow rate, the fine content is more than enough to fill the voids among coarse particles so that excess fine particles act to provide ball-bearing effect (i.e., lubricant) which can facilitate the movement of coarse particles and alleviate the interlocking action among coarse particles. This has an important implication for the design of flowable concrete to secure adequate resistance of suspension to deformation with optimized particle interlocking effect (Mehdipour and Khayat 2018).

4. Various mixture parameters of mortars

The results of mini slump flow curves and mini V-funnel time are given in Figs. 5 to 10. In addition, the mixture parameters that can affect the flowability of mortars are indicated in Table 3. These parameters were assessed based on the mix designs of the mortars (refer to Table 2). The decrease in flow spread of mortar occurred depending on the net effect of volume fraction of sand (*v* sand), binder volume (*v* binder), volume fraction of paste (*v* paste), and specific surface area of binder (Ą binder) (Güneyisi and Gesoğlu 2008). The volume fractions are determined based on the weight used in mix design divided by its specific gravity.

The flow curves illustrated in Fig. 5 exhibit that RG5, RG10, RG15 provided a higher flow spread than RG0 (Ctrl) regardless the superplasticizer dosages. In accordance to Table 3, the increase in flow spread of RG5, RG10, RG15 is due to the combined effect of greater paste volume and reduced sand content, which decrease the resistance to mortar flow. Also, most RGP-containing mixtures and mixtures with cementitious fillers showed higher flow spread compared to control mixture. Moreover, the fine aggregate (sand) content affects the amount of free water in mortar. In one hand, the sand particles entrapped some of the mixing water in mortar, and on the other hand, the amount of entrapped water is approximately proportional to the sand volume content (Okamura and Ouchi 1998). To wrap up, the lower the sand content, the higher the amount of free water would be available and thus increasing the flowing ability of mortars.

The mixture design principles applied in SCM involve partially replacing OPC by cementitious additives/fillers in conjunction with minimizing the total powder content by optimizing the solid skeleton to achieve enhanced packing density (Mehdipour and Khayat 2018).

5. Conclusions

In this research the fresh characteristics (flow spread and V-funnel time) of self-compacting mortars produced with ordinary Portland cement (OPC), recycled glass powder (RGP), Fly ash (FA), metakaolin (MK), rice husk ash (RHA), nano-silica (NS), and micro-silica (MS) were evaluated. The following conclusions can be drawn based on the obtained results:

- The workability and slump of SCM samples improve as the dosage of superplasticizer increases in the mixtures. Also the flowability of samples improves without segregating and bleeding. In the present case, bleeding mostly occurred in specimens in which HRWR was more than desired amount.
- The flowability of mixtures has been affected by their mixture proportions, namely the content of sand and specific surface area of cement materials which have been influenced significantly.
- The flowability of mixtures due to more amount of sand and less volume of cement paste deters sand particles from being segregated and also makes the resistance of samples different against segregation.
- Among all the mortars, with same content of HRWR, mixtures containing FA had the best performance with a flow time ranged from 7.02 to 7.92 secs. The flow time satisfied the requirement of EFNARC with 0.88% HRWR, while this amount was 1.18, 1.32, 1.62 and 1.32 for MK, RHA, MS and NS-containing mixtures. The mixtures containing MK showed the greatest flow time ranged from 8 to 10.2 seconds.
- The use of recycled glass influenced the flowability of mixtures dramatically. In fact, the flowability increased by the enhancement of RGP. This is due to the decreased volume of sand and increased surface area and volume of cement materials. Increasing specific area will enhance the flowability based on excess ratio of water in mixture.
- According to the obtained results, the dosage of superplasticizer should be lower than the saturated one (between 70-80% of saturation point) to prevent specimens from being segregated and bled. In addition, replacement of 10% RGP can be considered as the optimal proportion.
- In binary mixtures for slump test, the lowest dose of HRWR was 0.74%, for FA and then belonged to RGP, MK, NS, RHA and MS, respectively, at doses of 1.03, 1.18, 1.32, 1.47 and 1.62 %.
- Samples with more than 10% RGP affected the slump flow slightly and even some of them experienced segregation and bleeding.
- Using MK, FA, NS and RGP as fillers could reduce the dosage of HRWR required for achieving the same followability.
- The presence of excess fine particles (more than that needed to fill voids) acts to provide ball-bearing effect which can facilitate the movement of coarse particles and alleviate the interlocking action among particles. This has an important implication for the design of flowable concrete to secure adequate resistance of suspension to deformation with optimized particle interlocking effect.
- The packing density of colloidal particles is substantially associated with the degree of dispersion of the particles in the binder system. In order to elicit the full benefit of the higher specific surface area for particle packing improvement in binder systems, incorporation of dispersing admixtures at optimum dosage rates plays a vital rule. This is more obvious for

binders incorporating fine cementitious materials such as Micro - Nano silica.

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