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IMPROVEMENT OF PROPERTIES OF HIGH VOLUME FLY ASH BASED SELF-COMPACTING MORTAR WITH DOLOMITE AND GROUND GRANULATED BLAST FURNACE SLAG

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Abstract

Usage of filler with inert or pozzolanic property has been crucially required for fabricating the practical self-compacting mortar or self-compacting concrete. The current study investigates the influence of using the dolomite powder on the enhanced properties of the high volume Class F fly ash self-compacting mortar with/without addition of ground granulated blast furnace slag (GGBFS/slag). Experimental results showed that partial replacement of low calcium Class F fly ash with the dolomite powder not only increased the workability of the fresh modified self-compacting mortars but also enhanced the ordinary Portland cement hydration process at early. The adjustment of dolomite powder addition as partial replacement of fly ash resulted in the modified self-compacting mortars with the compressive strength increased after 7 days of curing. 30 mass percent of dolomite powder partially replacing fly ash was considered as the optimum value to induce the hardened modified self-compacting mortars with the compressive strengths increased at 4.2, 10.4, and 10.5% at 3, 7, and 28 days, respectively. With the content of dolomite powder being fixed at 30 and 50 mass percent, partial replacement of fly ash with slag at 50 mass percent induced the modified self-compacting mortars with significant enhancement of the engineering properties.

Keywords: dolomite powder; slag; high volume fly ash; self-compacting mortar; engineering property.

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1. Introduction

High volume low calcium fly ash (HVFA) concrete has been considered as one of the most potential construction materials for establishing the sustainability development due to significant reduction on CO_2 emission in a comparison with the traditionally plain ordinary Portland cement (OPC) concrete. Typically, the HVFA concretes are produced with very high dosage of low calcium Class F fly ash (up to at least 50% by mass) partially replacing OPC. Therefore, they have been preferably applied for construction sectors without serious requirements for high strengths, particularly emphasized on roller compacted concrete of dam construction and base material of highway project [1, 2].

By using low water to binder ratio (W/B) coinciding with high amount of superplasticizer (SP), the Canada Centre for Mineral and Energy Technology (CANMET) proposed manufacturing high-performance HVFA cementitious binder based concretes with excellent performance in terms of good workability, satisfactory mechanical strengths, and superior resistances to chemical aggressive environment and high temperature [1–10]. However, the existing disadvantages of applying the HVFA cementitious concretes have been the postponed initial and final setting times and reduced compressive strengths at early and even later ages [2, 7, 11, 12]. Such the negative effects crucially impact the

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applicability of HVFA concrete for structural construction due to the delayed constructing time. To overcome the problem, pretreated fly ash by adapting mechanical grinding, applying high-temperature curing, or addition of mineral or chemical activator. In jobsite application, the chemical activation with calcium sulfate [13] and sodium sulfate (Na_2SO_4) or commercial strong alkaline [13–17] has been preferably used, possibly induced extra cost. Therefore, applying industrial by-products serving as mineral modifier for HVFA cementitious concrete/mortar seems to be interesting to persuade sustainability development. Self-compacting mortar/concrete (SCM/SCC) with superior rheological properties has gradually become the dominant consideration for the jobsite constructions. Normally, SCM/SCC is applied for assuring the construction quality independent to the craftsmanship [18, 19]. Different from the conventional mortar/concrete, the SCM/SCC is normally comprised of higher volume of paste and well-graded aggregates [20]. For the practical SCM/SCC, the filling powder with the mean size of particle smaller than 0.125 mm has typically used as partial substitution of the ordinary Portland cement (OPC) [21]. The addition of filling powder significantly modified the flowing and filling abilities and viscosity of the fresh SCM/SCC [22]. Conventionally, the pozzolanic industrial by-products including fly ash from coal combustion and ground granulated blast furnace slag (GGBFS/slag) have been commonly used as the filling materials for the SCM/SCC manufacture. On the other hand, the inert filling powders sourced from limestone powder [23–25], quarry dust [26], binary mixture of limestone and quarry waste [27], mixture of limestone and chalk powder [28], and the industrial by-products of marbles and tiles [29–32] were successfully applied for producing high quality SCM/SCC. Moreover, the utilization of the dolomite powder (DP) commonly known as an impure limestone powder with high content of magnesium oxide (MgO) for producing the SCC with excellent performance has been also reported [33]. However, it is quite difficult to find out the further studies concerning on using the DP as the filling powder for the SCM manufacture, particularly for the SCM with HVFA binder.

The current study investigates the influences of using DP on the engineering properties of the modified SCM with the HVFA based supplementary cementitious binder. Particularly, the effect of slag with higher pozzolanic reactivity partially substituting fly ash on the properties of the modified SCM was preliminarily estimated, which has not been previously explored. Obviously, the achievement of this study is not only confirming the high potential utilization of the DP for fabricating the SCM/SCC but also proposing a promising way for efficiently enhancing the performance of the SCC/SCC with mixture of fly ash and DP as filling fraction.

2. Experimental program

2.1. Materials

The powder of the mortars were comprised of Type I ordinary Portland cement (OPC) complying with ASTM C150, ground granulated blast furnace slag (GGBFS/slag), low calcium Class F fly ash (FA) in accordance with ASTM C618 [34], and commercial dolomite powder (DP) supplied from China. The physicochemical properties, the mineralization, and particle sizes distributions of these raw materials are shown in Table 1, Figs. 1 and 2, respectively.

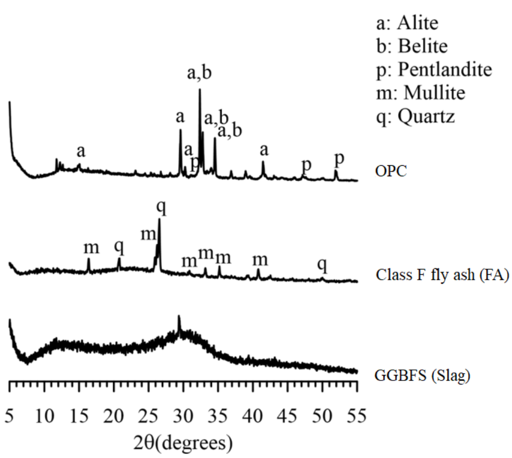

Figure 1. XRD patterns of raw materials

Accordingly, the OPC mostly contained four CaO-rich compounds of alite, belite, tricalcium

Table 1. Physicochemical properties of the powders

	Portland cement	Slag	Fly ash	Dolomite
Specific gravity	3.15	2.90	2.17	2.90
SiO_2, wt.%	20.42	34.90	58.33	-
Al_2O_3, wt.%	4.95	13.53	26.23	-
Fe_2O_3, wt.%	3.09	0.52	3.49	-
CaO, wt.%	61.96	41.47	5.72	43.91
MgO, wt.%	3.29	7.18	1.26	6.04
SO_3, wt.%	2.40	1.74	-	-
Na_2O, wt.%	-	-	0.27	-
K_2O, wt.%	-	-	0.48	-
TiO_2, wt.%	-	-	1.46	-
L.O.I, wt.%	1.75	-	2.76	-
C_3S	49	-	-	-
C_2S	21	-	-	-
C_3A	7.9	-	-	-
C_4AF	9.4	-	-	-

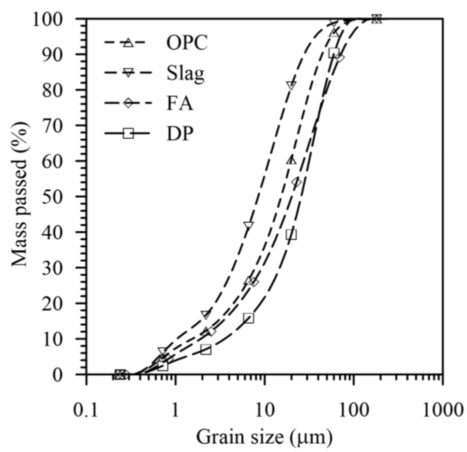

Figure 2. Particle size distributions of the powders

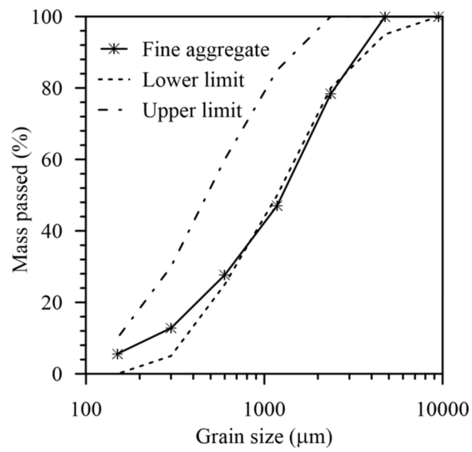

Figure 3. Particle size distributions of fine aggregate

aluminate, and tetracalcium aluminoferrite. The fly ash mainly contained silica and alumina-rich mullite and quartz. Different from fly ash, slag mostly contained calcium oxide and amorphous silica and alumina, implying the higher pozzolanic reactivity for slag particles. As expected, the DP contained calcium oxide coinciding with magnesium oxide as impure fraction. Obviously, Fig. 2 showed that the mean size of the DP was fairly closed to that of OPC, slag, or FA, which confirms that the DP could belong to powder fraction. In this study, the river sand with specific gravity of 2.65 was used as fine aggregate of the SCM. The water absorption and finesse modulus (FM) of the sand were 1.0 mass percent and 2.72, respectively. The particle sizes distribution of the sand is shown in Fig. 3, which shows that the sand essentially complied with ASTM C33. In order to achieve the workability of the SCM, the commercial Type G superplasticizer (SP) was used.

2.2. Mix proportions

The mixture design principle for the SCMs was in accordance with the previous report [20]. The control SCM was comprised of the fly ash-cement mixture produced by replacing 50 mass percent of OPC with addition of Class F fly ash. On the other hand, the modified SCMs were produced with sole addition of DP or addition of mixture of DP and slag as partial replacement of fly ash. In this study, to estimate the effect of DP on performance of the SCM, five levels of fly ash replacement with DP at 10, 30, 50, 70, and 100 mass percent were used. By fixing amount of DP at 30 and 50 mass percent, the mortar mixtures with further replacement of fly ash with slag at 50 mass percent were also prepared. Based on preliminarily experimental conduction, for producing the SCM mixture proportions with satisfactory workability, the water to powder ratio was fixed at 0.32, and the volume ratio of sand to paste was fixed at 0.4. The superplasticizer (SP) addition was varied based on the desired properties of the fresh SCMs. The mixture proportions of the SCMs are shown in Table 2.

Table 2. Mix proportions and fresh properties of SCMs

Mix designations	OPC (kg/m^3)	Slag (kg/m^3)	FA (kg/m^3)	DP (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	SP (kg/m^3)	SF (mm)	VF (s)
DP-0	413	-	413	-	264	1060	4.0	300	6
DP-10	417	-	376	42	267	1060	4.2	310	6
DP-30	426	-	298	128	273	1060	3.8	315	6
DP-50	436	-	218	218	279	1060	3.7	315	6
DP-70	445	-	134	312	285	1060	3.6	335	6
DP-100	461	-	-	461	295	1060	2.8	250	6
S-DP-30	443	155	155	133	283	1060	2.8	245	5
S- DP-50	448	112	112	224	287	1060	2.7	260	5

Note: SP = Superplasticizer; SF = Slump flow (mm); VF = V-funnel flowing time (s).

2.3. Mixing procedure, sample preparation, and test methods

The mixing procedure for all the SCMs was based on the suggestion from ASTM C305. The mini slump flow and mini V-funnel tests were applied for the estimation on the fresh properties of the SCMs in accordance with the previous studies [20, 35, 36]. In this study, the desired flowing time detected from the mini V-funnel test was controlled at 5 or 6 seconds by adjusting the SP dosage as previously reported by Brouwers and Radix [37]. The mortar cubes with dimensions of 50×50×50 mm were cast for the compressive strength test complying with ASTM C109. After 24 hours being cured in molds at 25 ± 2 °C and 65% relative humidity (RH), all the hardened specimens were removed from the molds and cured in air at temperature of 25 ± 2 °C and 65% RH until ages of testing. For each test, three SCM samples were used. Moreover, hydration heat evolution of the HVFA pastes was conducted using isothermal calorimetry test. In the test, the ambient temperature around the specimens was recorded with precision sensors and was computer-controlled by Calmetrix's software interface. Especially, with the I-Cal 2000 HPC Isothermal Calorimeter, sensitivity to outside conditions was minimized to reach the condition of so-called non-air conditioned environment.

3. Results and discussions

3.1. Hydration heat evolution

Estimation on hydration mechanism of a new or a modified cementing binder has been a crucial requirement for cement industry. In this study, the influences of the DP and slag additions on the hydration heat liberation of the HVFA pastes are shown in Figs. 4 and 5, respectively. According to the figures, the curves of hydration heat flow of all the HVFA pastes consisted of the full stages of initiation, induction, acceleration, and deceleration of heat released, which obviously implied that the OPC hydration mainly contributed to the hydration heat evolution of the HVFA pastes. Therefore, the effects of the additives on the early hydration of the modified HVFA pastes were primarily induced by the change of the hydration rate of the OPC fraction. Fig. 4 showed that addition of DP partially substituting fly ash accelerated the early hydration process of the modified HVFA pastes due to the shortened periods of induction, acceleration after period of 2 - 4 hours, and deceleration after 16 - 20 hours during age of 1 day. In addition, the cumulative hydration heat of the modified HVFA pastes increased with the increase of the DP amount. Therefore, the DP addition not only uninfluenced the setting property but also enhanced the early hydration of the modified HVFA pastes. As reported in the previous study [38], although the addition of either limestone powder or fly ash led to the accelerated early hydration of the OPC fraction in supplementary cementitious binder due to the dilution and nucleation effects, the utilization of limestone powder illustrated the superior efficiency.

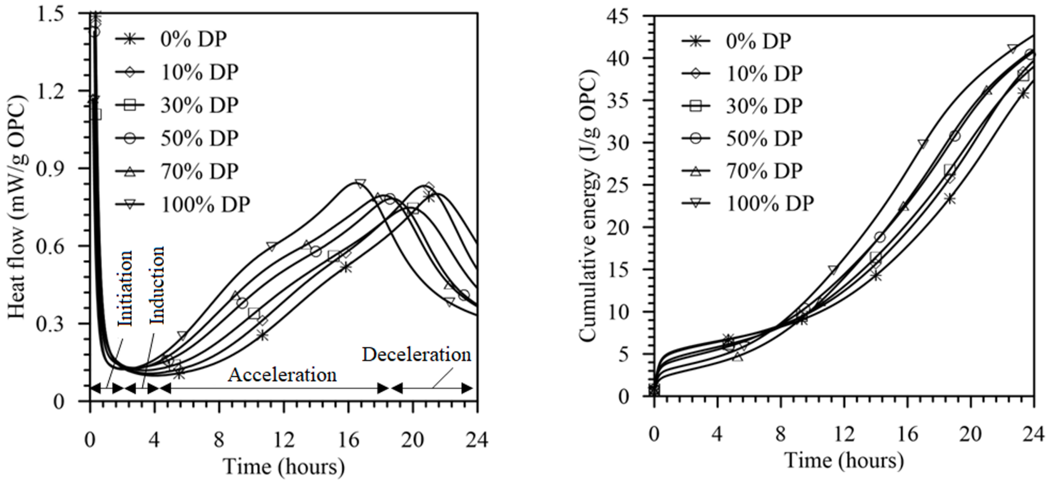

Figure 4. Effect of dolomite powder (DP) on hydration heat evolution of HVFA paste

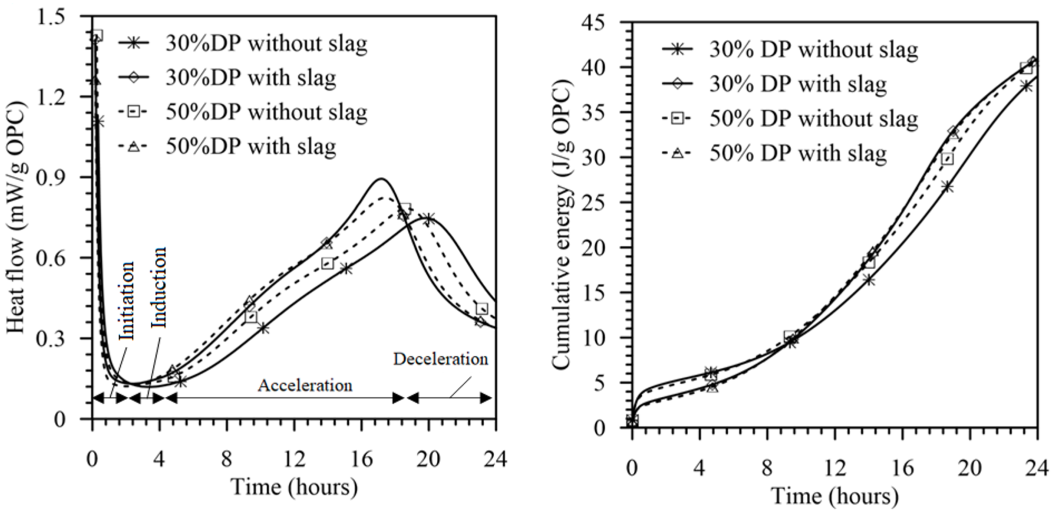

Figure 5. Effect of slag on hydration heat evolution of paste

On the other hand, according to Fig. 5, with the DP amount fixed at certain level, slag addition as partial replacement of fly ash further accelerated the hydration process of the DP modified HVFA pastes during 1 day. Fig. 5 showed that the curves of hydration heat flow of the modified HVFA pastes were shifted into the side of shortened hydration time with addition of slag irrespective of the DP amount. The result could be explained due to the increased amount of slag induced the filling mixture with the increased fineness, which significantly increased the nucleation effect [38].

3.2. Fresh properties and compressive strength of the SCMs

a. Fresh properties and compressive strength of the SCMs

For the practical SCMs/SCCs, the desired fresh performance has been the most crucial consideration. With the absence of the vibrating compaction, the excellent fresh properties of the SCMs/SCCs assured the quality of the structural construction. In this study, the fresh properties of the SCMs with/without additives are illustrated in Table 2. As being desired, all of the fresh SCMs had the mini V-funnel flowing time varied in a range of 5 to 6 seconds, implying that the SCMs had sufficient potential for being applied for practical SCC manufacture [37]. The mini slump flow values of the fresh SCMs were in a range of 245 to 335 mm, which referred to the fresh SCMs with satisfactory flowing and filling capacity as suggested in the previous report [37]. As shown in Table 2, with equivalent fresh performance, the DP addition significantly reduced the superplasticizer (SP) dosages used. Such result implied that the DP could be suitably applied for enhancing the performance of the fresh SCMs with the HVFA pastes. In addition, as shown in Table 2, with fixed amount of DP, replacement of fly ash with slag at 50 mass percent also improved the fresh properties of the modified HVFA based SCMs due to the reduction of the SP amount added. In this study, the enhanced fresh performance of the modified SCMs was possibly due to the improved particle sizes distributions of the mortar samples, which was properly discussed at later section.

b. Compressive strength

The influences of DP and slag additions on the compressive strengths of the hardened modified SCMs are shown in Fig. 6 and Fig. 7, respectively.

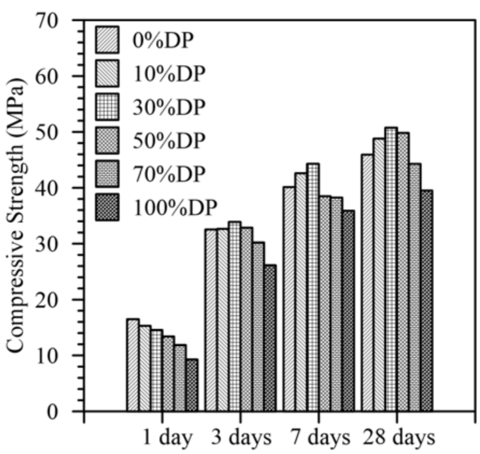

Figure 6. Effect of dolomite powder (DP) on compressive strength of SCMs

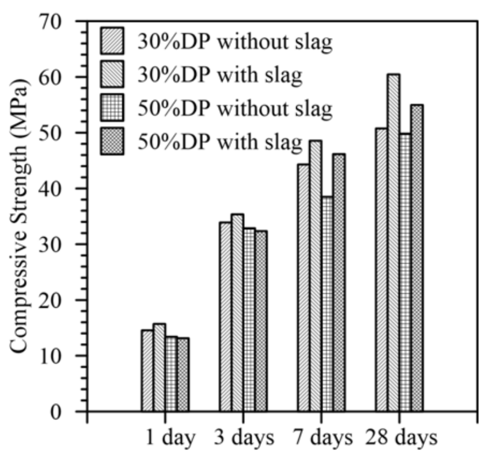

Figure 7. Effect of slag on compressive strength of SCMs

Generally, the compressive strengths of all the hardened SCMs increased with ages of curing, due to the enhanced hydration process of cementitious material. As shown in Fig. 6, the addition of DP partially substituting fly ash reduced the compressive strengths of the hardened modified SCMs with irrespective of the DP amount at early ages (i.e., earlier than 3 days) of curing. The reason could be due to the increased content of DP led to the increased ratio of water to supplementary cementitious powder (i.e., mixture of OPC and FA) as shown in Table 2. From 3 days of curing, the increased amount of DP up to 30 mass percent substituting fly ash resulted in the hardened modified SCMs with enhancement of the compressive strengths, which could be due to the changed particle sizes distribution of the modified SCMs as subsequently discussed. In this study, when compared with the reference SCM without DP addition, the modified SCMs with DP as partial replacement of fly ash at 10 mass percent had the compressive strengths increased at 0.3, 6.1, and 6.3% at ages of 3, 7, and 28 days of curing, respectively. With the increase of the DP addition at 30% substituting fly ash, the compressive strength increment increased at 4.2, 10.4, and 10.5% at 3, 7, and 28 days, respectively. In addition, as shown in Fig. 6, the amount of DP replacing for fly ash at 50 mass percent could be suitable to produce the modified SCMs with the compressive strengths equivalent to the reference SCMs without DP addition. Indeed, as can be seen in Fig. 6, the modified SCM with DP replacing for fly ash at 50 mass percent had the compressive strengths comparable or slightly higher than those of the reference SCM specimens from 3 days of curing. Excessive addition of the DP, i.e., beyond 70 mass percent as replacement of fly ash, induced the hardened SCMs with significant reduction of compressive strengths at all days. Such result implied that the DP primarily acted as the filling material, which differed from the fly ash acting as both filling and pozzolanic materials.

On the other hand, with fixed amount of DP at certain level, the addition of slag positively influenced the strength development of the modified SCMs. In this study, by fixing DP amount at 30 mass percent as fly ash substitution, replacement of the fly ash with slag at 50 mass percent increased the compressive strengths of the modified SCMs at all ages of curing. When compared with the SCM modified with sole addition of DP at 30 mass percent substituting fly ash, the modified SCM with slag addition had the compressive strengths increased at 7.8, 4.3, 9.6, and 19.1% at 1, 3, 7, and 28 days of curing, respectively. With the DP amount increased at 50 mass percent replacing for fly ash, replacement of fly ash with slag at 50 mass percent insignificantly affected the compressive strength of the modified SCM at early ages (earlier than 3 days) of curing. However, the compressive strengths of the modified SCM with addition of slag were higher than those of the SCM without slag up to 19.9 and 10.3% at later ages of 7 and 28 days, respectively. Such result indicated that the beneficial effect of using slag to enhance the strengths of the HVFA SCMs with DP addition was remarkable after 7 days of curing. In this study, in order to maximize the strength enhancement of the modified HVFA SCM with binary mixture of slag and DP, the DP dosage could be limited at 30% of total amount of filling powder.

3.3. Grain size distribution

The grain sizes distributions of the SCMs, which were extracted from the data shown in Table 2, are shown in Fig. 8. Accordingly, the DP addition as partial replacement of fly ash up to 50 mass percent increased the fraction of the fine particles of the modified SCMs due to the increased mass ratio of OPC to fly ash (Table 2). With the DP amount fixed at 30 mass percent substituting fly ash, the addition of slag partially replacing for fly ash at 50 mass percent resulted in the proportion of the modified SCM with the highest fraction of fine particles due to the increased amount of binary mixture of slag and OPC (Table 2 and Fig. 2). However, the fine fraction of the mixture of the modified SCMs with ternary mixture of slag, fly ash, and DP decreased with the increase of DP amount at 50 mass percent substituting fly ash. Such results were possibly due to the SCM with higher amount of fine fraction would have the more condensed microstructure. In this study, the modified SCM with the mixture of 30 mass percent of DP and 50 mass percent of slag partially substituting fly ash had the highest fraction of fine particles, which induced the mortar specimens with the most condensed microstructure. Therefore, the benefit of using the DP and slag replacing for fly ash for improvement of mechanical property of the modified SCMs was maximized with the DP addition being limited at 30 mass percent as aforementioned.

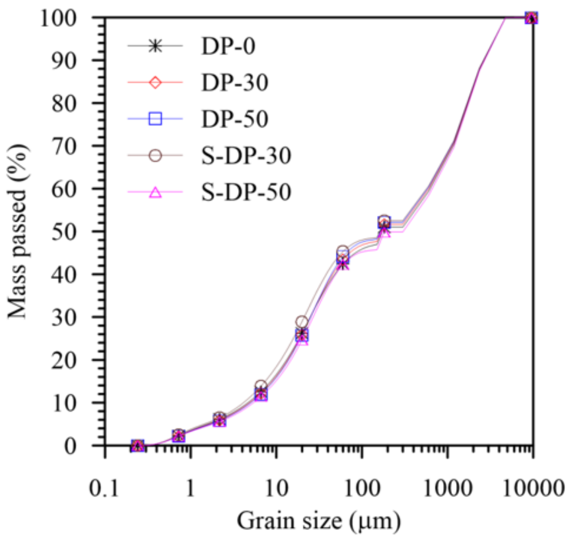

Figure 8. Effect of slag and/or DP on grain size distribution of SCMs

4. Conclusions and recommendations

Effects of utilizations of dolomite powder (DP) and ground granulated blast furnace slag (GGBFS/slag) to enhance the performance of the self-compacting mortar (SCM) with high volume fly ash (HVFA) cementitious binder were conducted. According to the experimental results, addition of either the sole amount of DP or the mixture of DP and slag not only improved the fresh properties of the modified SCMs due to the reduction of the superplasticizer (SP) dosage used but also accelerated the early hydration of the ordinary Portland cement (OPC). Adding DP as partial substitution of fly ash at 30 mass percent induced the hardened modified SCMs with the compressive strengths increased at 4.2, 10.4, and 10.5% at 3, 7, and 28 days, respectively. By fixing the amount of DP at 30 mass percent as partial replacement of fly ash, further substitution of fly ash with slag at 50 mass percent significantly improved the compressive strengths of the modified SCMs at all ages of curing. Analysis on particle sizes distribution clarified that the SCMs modified with optimized amount of DP accompanying with further slag addition as partial substitution of fly ash had the highest amount of fine particles, possibly resulting in the most condensed microstructure of the resultant samples. Due to certain limit of the current study findings, advanced study on durability of the HVFA based SCM modified with DP and slag could be considerably investigated.

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