Dry-Mix Concrete Incorporating Ultrafine Slag and Medium-Grade Metakaolin for Potential Application in Concrete Block Masonry Unit Production

Saeid Ghasemalizadeh[i] **and Rahil Khoshnazar** [ii]

ABSTRACT

Concrete block masonry units (CMUs) are widely used around the world in construction practices. CMUs mainly rely on Portland cement (PC) to develop compressive strength. Production of PC, however, is a significant source of greenhouse gas (GHG) emissions, emphasizing the need for methods to reduce the carbon footprint of CMUs. A practical and effective approach to reduce the carbon footprint of concrete products is partially substituting PC with supplementary cementitious materials (SCMs). However, the extent of PC substitution with SCMs in CMUs has remained limited as it adversely affects the strength development of the CMUs, where achieving a high early-strength is crucial. It is therefore necessary to develop methods to benefit from higher quantities of SCMs in CMUs without compromising their strength development. This study focuses on the utilization of ultrafine slag (UFS), instead of ordinary slag, in combination with a locally available medium-grade metakaolin (MK) to replace up to 40 wt% of PC in cementitious mixtures. Combinations of MK-UFS, and MK-slag were used to substitute 40 wt% of type GU and HE cement in mortar samples. The superplasticizer demand of the mortars and their compressive strength for up to 7 d were recorded. The results were then compared with those obtained for mortars prepared with only GU or HE cement. Selected blends were then used in preparing dry concrete mixtures which were tested for the compressive strength at the ages of 3 and 7 d. The results of mortar samples showed that replacing 40 wt% of GU cement with MK-UFS blend resulted in mortar samples with a higher compressive strength compared to that made with 100 wt% GU cement starting from 1 d, however, such an enhancing effect was not observed when the UFS-MK blend was used to replace the same content of HE cement. The dry concrete mixture made with 60 wt% GU cement and 40 wt% UFS-MK blend achieved a 7-d compressive strength of higher than 50 MPa, showing promising results for application in high-strength CMU production.

Keywords: Supplementary cementitious materials, Slag, Metakaolin, Compressive strength, Concrete block masonry Unit.

[i] Postdoctoral Researcher, University of Calgary, Calgary, Canada, saeid.ghasemalizadeh@ucalgary.ca
[ii] Associate Professor, University of Calgary, Calgary, Canada, rahil.khoshnazar@ucalgary.ca

INTRODUCTION

Concrete block masonry units (CMUs) are among popular construction materials worldwide due to their good durability, thermal and acoustic insulation properties, fire-resistance, and ease of construction [1]. As construction demands grow globally, there is an increasing need to produce lower carbon construction materials, including CMUs. However, the reliance of CMU manufacturing on the consumption of Portland cement (PC) as the primary cementitious materials, raises concerns about CMU carbon footprint. The production of PC is a main source of greenhouse gas (GHG) emissions, which accounts for the majority of the GHG emissions associated with the CMU production [2,3]. Hence, reducing the PC content in CMU manufacturing is one of the key steps towards reducing their carbon footprint. This is even more important in manufacturing high-strength CMUs as they may require a higher cement content compared to normal-strength ones.

One practical approach to reducing the PC content in CMUs is partially substituting the PC with supplementary cementitious materials (SCMs). The incorporation of SCMs such as fly ash and granulated blast furnace slag (slag) in CMU manufacturing has been practiced for several years. However, the current level of SCMs utilization in CMUs is mainly limited to 10-20 wt% [4], which may not be sufficient to make significant carbon footprint reductions. Therefore, there is a need to incorporate higher SCMs content in the CMU mixture designs. Increasing the replacement level of PC with SCMs, however, usually reduces the compressive strength of the mixtures, especially at early ages. This strength reduction may not be desirable in CMU manufacturing, as it can lead to practical issues such as extended production times and delays in block handling and curing processes. In addition to the compressive strength reduction, using high SCMs contents as PC replacement in CMUs may also compromise other performance parameters such as durability of the blocks.

The low early-age strength in CMU with high SCMs content is due to the low reactivity of SCMs in the early ages along with the dilution effect of PC replacement [5]. Consequently, increasing the reactivity of SCMs to achieve higher PC replacement levels without compromising the early-age strength development of CMU could be one of the potential methods to advance production of CMUs with lower carbon footprints.

The reactivity of SCMs can be increased by reducing their particle size through fine or ultrafine grinding [5,6]. Ultrafine SCMs (USCMs) such as ultrafine fly ash and ultrafine slag (UFS) have been shown to possess higher surface area, higher amorphous content, and enhanced reactivity compared to ordinary-size SCMs, which make them more effective in the strength development of cementitious mixtures [7–9]. UFS, with a median particle size predominantly lower than 5 μm, has demonstrated promising results in enhancing the mechanical performance of cementitious mixtures [9–11]. For example, it was reported that substitution of 15 wt% of PC with UFS in standard mortar samples increased the 1-d compressive strength of samples by ~ 45%[10]. However, UFS utilization in dry-mix concrete has not been reported in the open literature.

Increasing the replacement level of PC with UFS, however, may not be practical mainly due to the high-energy demands and costs for ultrafine grinding of slag, and also its adverse effect on the workability of the resulting concrete mixture [12,13]. In order to benefit from the beneficial effect of UFS, few studies suggested using a relatively small amount of UFS in combination with other SCMs such as commercial slag or SCMs with low reactivity such as steel slag. For example, Gowda and Ranganath [14] used ~ 4 wt% UFS with a mean particle size of 3.9 μm in combination with 33 wt% ordinary slag to replace a total of 37 wt% of PC high-performance concrete. They observed that the 1-d compressive strength of concretes prepared with UFS-slag was ~75% higher than that measured for the concrete with slag alone. Despite the potential of such combinations in increasing the replacement level of PC in cementitious mixtures, there are limited studies exploring the combination of UFS with other SCMs.

Metakaolin (MK), which is a natural pozzolan obtained by the calcination of kaolinite clay, is one of the SCMs that can be combined with UFS for reducing the PC content of cementitious mixtures. Pure metakaolin, however, is an expensive SCM due to its application in other industries. Low- and medium-grade MK have shown to be effective in replacing high PC contents (up to 40 wt%) and still achieve a similar compressive strength at 28 d compared to samples containing 100 wt% PC [15]. Combined utilization of MK and commercial slag (before grinding) has also been proven effective in further enhancing the compressive strength of cementitious mixtures compared to that of samples with MK only as PC replacement [16]. However, combination of MK with UFS has not been investigated in previous studies.

The current study aimed to investigate the use of UFS combined with MK to develop low-PC content dry concrete mixtures with enhanced early-age strength development for potential application in CMU production. The focus is on concrete mixtures with compressive strengths of higher than 50 MPa for potential applications in manufacturing high-strength CMU. In this regard, first the enhancing effect of UFS on the strength development of standard mortar samples was monitored for up to 7 d. A combination of UFS and a medium-grade MK was then used to replace 40 wt% of general use (GU) and high-early (HE) strength PC in mortar samples. The strength development and superplasticizer (SP) demand of these mortar samples were compared to those prepared with the same content of MK-ordinary slag blend, and also with the reference samples prepared with 100 wt% GU or HE PC. Selected binders were then utilized in preparing high-strength and zero-slump concrete mixtures that can potentially be used in manufacturing CMUs.

MATERIALS AND METHODS

Cementitious Materials

Type general use (GU) and high-early strength (HE) Portland cement (Lafarge, Canada), complying with the Canadian Standard Association specification, CSA A3001.23, were used in this study. A commercial medium-grade MK was procured from a locally available source (EnviroPozz^{TM}, Canada). A commercially available slag was also used both in its as-received form and as UFS. The UFS was prepared from ultrafine grinding of slag using a lab-scale planetary ball mill. The particle size distribution of the cementitious materials as obtained by the laser diffraction technique is provided in Figure 1. GU and HE cement had a median particle size of 8.7 and 6.5 μm, respectively. The median particle size of MK was obtained as 8.5 μm. The median particle size of slag was 8.6 μm which reduced to ~ 0.9 μm in the UFS.

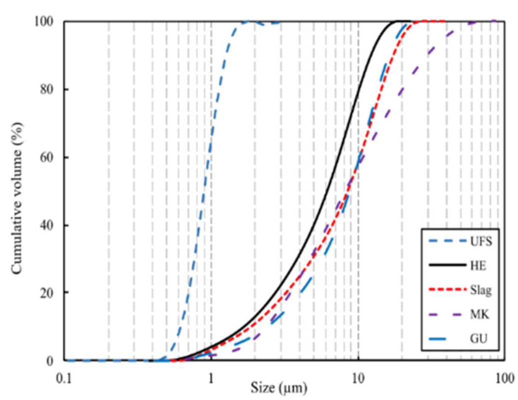

Figure 1. Particle size distribution of the cementitious materials

The main oxide compositions, as obtained by the X-ray fluorescence (XRF) spectroscopy, and loss on ignition (LOI) for the cementitious materials used in the study are provided in Table 1.

Table 1. Main oxide compositions and loss on ignition of the cementitious materials

Cementitious materials	Main oxides (wt%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
Portland cement, type GU	19.58	4.21	3.63	62.22	4.36	2.82	0.4	0.11	2.56
Portland cement, type HE	18.71	4.71	3.07	60.05	4.10	3.09	0.27	0.10	5.85
MK	63.51	29.68	1.22	0.48	0.48	0.3	1.79	0.14	1.95
Slag	31.02	12.81	1.05	42.34	5.34	2.56	0.25	0.29	3.16

Aggregates

Standard sand conforming to ASTM C778 was used in the preparation of the mortar samples. Three different aggregates, labelled as fine sand, coarse sand, and 7-mm chips, were used in the preparation of the dry concrete mixtures. These aggregates were combined with fine sand: coarse sand: 7-mm chip volume ratio of 0.1:0.67:0.23. The gradations of the individual and combined aggregates are shown in Figure **2**. The specific gravity and water absorption of the aggregates are presented in

Table 2.

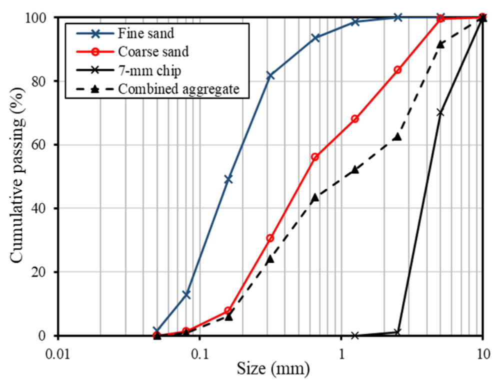

Figure 2. Gradations of the individual and combined aggregates

Table 2. Specific gravity and water absorption of the aggregates

Aggregate	Specific gravity (kg/m^3)	Water absorption (%)
Fine sand	2630	2.8
Coarse sand	2650	3.0
7-mm Chip	2620	1.2

Preparation of mortar samples

A total of seven mortar samples were prepared using cementitious materials-to-sand ratio of 1:2.75, and water-to-cementitious materials ratio of 0.485. The proportions of cementitious materials in mortar samples are listed in Table 3.

Table 3. Proportions of cementitious materials in the mortar samples

Mortar sample	GU	HE	MK	UFS	Slag
Ref_GU	100	-	-	-	-
Ref_HE	-	100	-	-	-
GU85_U15	85	15	-	-	-
GU60_M25_U15	60	-	25	15	-
GU60_ M25_S15	60	-	25	15	-
HE60_M25_U15	-	60	25	15	-
HE60_M25_S15	-	60	25	-	15

The mortar samples were mixed according to the method adopted from ASTM C305 and were cast in 50 mm × 50 mm × 50 mm cubic molds. The flow of the mortar samples was measured in accordance with ASTM C1437. The flow value of the Ref_GU was used as the reference, and all other samples were prepared with the comparable flow by adding sufficient amounts of a polycarboxylate-based superplasticizer (Glenium 3030, Master Builder Solutions, Canada). The samples were sealed with plastic wrap and left in the molds for the first 24 h. They were then demolded and cured in a fog room with a relative humidity of 95 ± 5% and temperature of 23-25 °C until the testing ages. The compressive strength tests were performed at ages of 1, 3, and 7 d following the method described in ASTM C109 [17]. Three samples were tested for each mortar mixture at each age, and the average results along with their standard deviation were reported.

Preparation of dry-mix concrete mixtures

Four dry concrete mixtures were prepared using the cementitious materials proportions labeled as Ref_HE, GU85_U15, GU60_M25_U15, and HE60_M25_S15 in the mortar series. The mixture proportion of the concrete mixtures are presented in Table 4. The total cementitious materials content for all mixtures was fixed as 380 kg/m^3 to achieve a 7-d compressive strength of 50.0 ± 5 MPa for the reference mixtures made with only HE cement (C_Ref_HE). The water content for each mixture was selected based on trials to achieve a dry mixture with minimum entrapped air content (providing the highest compressive strength). For the preparation of concrete mixtures, first, aggregates were added to the mixer and mixed for 1 min. Then, the water required for making the aggregates at a saturated surface dry (SSD) condition was added to the aggregates, and the mixing continued for an additional 1 min. Cementitious materials were first dry mixed with each other and then added to the aggregates and mixed thoroughly for ~3 min. Finally, the remaining water was added to the mixture and mixing continued for 3-4 mins. The consistency of the mixture was evaluated by squeezing the mixture in the palm and by observing whether the mixture retained its shape. The dry concrete mixture was cast in 75 mm ×150 mm cylindrical molds. The concrete was poured in three layers inside molds, and each layer was compacted by 15 uniformly distributed drops of a standard proctor hammer. A total of six cylindrical samples were prepared for each mixture design for the compressive strength tests.

Table 4. Mix design of dry concrete mixtures (kg/m^3)

Concrete label	Fine sand	Coarse sand	7-mm chip	HE	GU	UFS	Slag	MK	Total water
C_Ref_HE	178.2	1131.2	479.3	380.0	-	-	-	-	151.8
C_GU85_U15	177.9	1129.0	478.4	-	323.0	57.0	-	-	151.6

C_GU60_M25_U15	173.9	1104.2	467.9	-	228.0	57.0	-	95.0	159.5
C_HE60_M25_S15	173.9	1104.2	467.9	-	228.0	57.0	-	95.0	159.5

The prepared concrete samples were sealed with a plastic wrap for 24 h. They were then demoulded and placed in the fog room (relative humidity of 95 ± 5%, and temperature of 24±1 °C) until their testing age. At each testing age, three cylinders were end-ground and then tested using a standard compression testing machine (ELE international, load capacity of 3000 kN) with a loading rate of ~ 0.3 MPa/s, according to the method described in ASTM C39. The average compressive strength and standard deviation of the measurements were reported.

RESULTS AND DISCUSSION

Superplasticizer content

Figure 3 shows the superplasticizer (SP) content (blue lines) and the measured flow (red bars) of the fresh mortar samples. The flow of the Ref_GU sample, with no SP addition, was measured as 95 %. The SP content of the other mixtures was adjusted to achieve a flow comparable to that of Ref_GU (95 ± 5%). For the mortar samples prepared with the HE cement, 0.5 wt% SP was required to achieve the targeted flow value. This is due to the smaller particle size, and possibly higher surface area of HE cement compared to that of the GU cement. A similar flow was achieved in the mortar sample with the GU cement and 15 wt% UFS (GU85_U15) by using 0.3 wt% SP. This aligns with previous studies which reported that UFS incorporation in cementitious pastes decreased their flowability [12]. Nevertheless, the SP demand of GU85_U15 was lower than that of Ref_HE.

Replacing 40 wt% of the GU cement with the MK-UFS blend in mortar samples (GU60_M25_U15) required utilization of 0.8 wt% SP to achieve a comparable flow to that of Ref_GU. As expected, a lower SP content (0.5 wt%) was needed in GU60_M25_S15 mortar compared to that used for GU60_M25_U15 mortar to achieve the targeted flow, which is attributed to the larger particle size and lower surface area of slag compared to those of UFS. The highest SP content (1.4 wt% of total cementitious materials) amongst all the mixtures was needed for the HE60_M25_U15 mortar, which could be due to the presence of both HE cement and MK-UFS blend in the mixture. Moreover, the SP content of HE60_S15_M25 mortar sample was 0.9 wt%. This SP content was comparable to that of GU60_M25_U15 mortar (0.8 wt%).

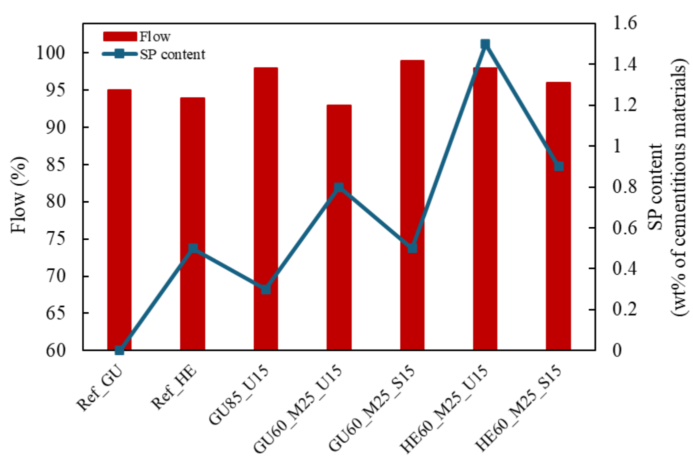

Figure 3. Flow and superplasticizer content of the mortars

Compressive strength of mortars

Figure 4 shows the compressive strength of mortar samples at 1, 3, and 7 d. The compressive strength of the Ref_GU sample at 1, 3, and 7 d was obtained as 10.1, 25.0, and 30.1 MPa, respectively, whereas the Ref_HE sample achieved higher compressive strengths of 16.2, 36.2, and 37.1 MPa at the same ages. The higher compressive strength of Ref_HE mortar compared to that of Ref_GU mortar at similar testing ages was attributed to the smaller particle size of HE cement compared to that of GU (Figure 1). This strength improvement was more pronounced at earlier ages and became less significant at 7d.

Replacing 15 wt% of the GU cement with UFS in GU85_U15 mortar increased the 1- and 3-d compressive strength of the mortar by 40% and 28%, respectively, reaching ~ 90 % of the compressive strength of Ref_HE mortar at each of these ages. This suggests that the combination of GU cement and UFS can be considered as an alternative to type HE PC in applications where high early strength is needed. The improvement in the 1- and 3-d compressive strengths of GU85_U15 mortar, compared to that of Ref_GU, is primarily attributed to the increased hydration rate of GU cement in the presence of UFS due to the nucleation and filler effects of UFS, as shown in previous studies [9,10]. Moreover, the reaction products of UFS can contribute to the strength development of the mortar sample. At 7 d, the compressive strength of GU85_U15 was 36.4 MPa, which was 17% higher than that of Ref_GU mortar (30.1 MPa), and comparable to that achieved for the Ref_HE mortar (37.1 MPa).

The 1-d compressive strength of GU60_M25_U15, containing 25 wt% MK and 15 wt% UFS as GU cement replacement, was 11.9 MPa. This was slightly higher than the compressive strength of Ref_GU mortar (10.1 MPa) with a 40 wt% reduction in PC content. The strength developed at a faster rate in the mortar containing MK-UFS blend compared to the Ref_GU mortar, such that the 3- and 7-d compressive strength of GU_M25_U15 reached 30.0 and 42.2 MPa, respectively, which were 20 and 40% higher than those measured for Ref_GU at similar ages. On the other hand, the 1-, 3- and 7-d compressive strength of GU60_M25_S15, prepared with the MK and slag, was 16, 32 and 40% lower than those of Ref_GU, respectively. The higher strength of the mortar with the MK-UFS blend compared to that with the MK-slag blend was mainly related to the increased reactivity of UFS compared to the ordinary slag. Previous findings have shown that ultrafine grinding of slag can increase its surface area and amorphous content, and also reduce the binding energy of its surface elements, therefore, increasing the reactivity of slag [9]. This resulted in the formation of more reactions products such as calcium-alumino-silicate-hydrate (C-A-S-H), hemi-carboalumiantes (Hc), and mono-carboalumiantes (Mc) in the mortars incorporating MK-UFS, which can significantly contribute to the strength development of the samples. Other contributing factors to the higher strength development in the mortar with MK-UFS compared to that with MK-slag could be a higher hydration degree of cement, a higher reaction rate of MK in the presence of UFS, and a denser microstructure in the mortar with MK-UFS, although they were not directly measured in this study.

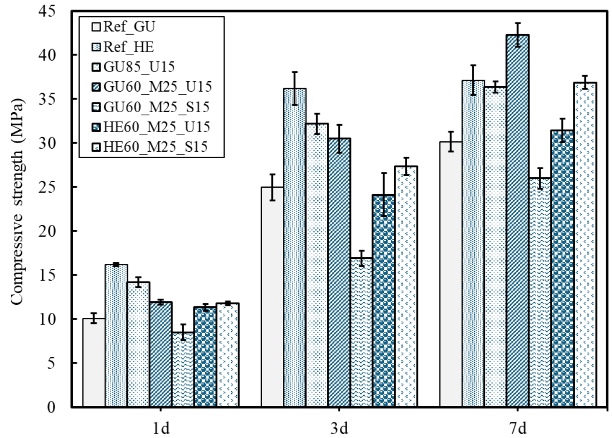

Figure 4. Compressive strength of the mortar samples

Despite the considerable enhancing effect of MK_UFS blend when partially replaced the GU cement on the compressive strength of the mortar, this blend was not effective on the strength enhancement of the mortar made with the HE cement. The compressive strengths of HE60_M25_U15 were 11.3, 24.1 and 31.4 MPa at 1, 3, and 7 d, respectively. These strengths were 30, 34, and 16% lower than those of Ref_HE at 1, 3, and 7 d, respectively. Despite such reduction, the strengths of HE60_M25_U15 mortar were still comparable to that of Ref_GU mortar at all testing ages.

Overall, the MK-slag blend showed a better performance in replacing HE cement in the mortar sample compared to the MK-UFS blend. While the 1-d compressive strength of HE60_M25_S15 mortar was comparable to that of HE60_M25_U15, at 3 and 7 d, the compressive strength of the mortar sample prepared with the MK-slag blend outperformed the one prepared with MK-UFS by 13 and 17%, respectively. Nevertheless, the compressive strength of HE60_M25_S15 mortar was 28 and 25% lower than that of Ref_HE mortar at 1 and 3 d respectively while the 7-d compressive strength of this sample was comparable to that observed in Ref_HE (~ 37 MPa). It is noteworthy to say that these strengths were comparable to those of Ref_GU at 1 and 3 d and 22% higher than that at 7 d.

The compressive strength of GU60_M25_U15 and HE60_M25_S15 mortars provides insights into the role of PC and slag fineness in the strength development of the samples. At 1 d, both GU60_M25_U15 and HE60_M25_S15 mortars developed a comparable compressive strength (~11.8 MPa). However, the strength of GU60_M25_U15 increased at a higher rate compared to HE60_ M25_S15, such that the 3- and 7-d compressive strength of the mortar with MK-UFS was almost 11% and 18% higher than that of HE60_ M25_S15. These observations highlight the importance of optimizing cementitious blends components in terms of particle size and reactivity to achieve the most efficient strength development rate for a given application.

Overall, amongst all binders tested in the mortar samples to replace 40 wt% of PC, the one containing MK-UFS blend as GU replacement (GU60_M25_U15) showed the highest strength development. It is noteworthy to say that despite the enhanced strength development in this binder, the 1- and 3-d compressive strength of GU60_U15_M25 mortar were lower than those of Ref_HE or GU85_U15 mainly due to the reduced cement content, although it reached a higher compressive strength compared to Ref_HE and GU85_U15 by 7 d.

Compressive strength of high-strength and dry concrete mixtures

Figure 5 shows the compressive strength of the four dry concrete mixtures prepared in this study. The 3- and 7-d compressive strength of concrete with HE cement (C_Ref_HE) was 40.9 and 49.8 MPa, respectively. The concrete prepared with 85 wt% GU cement and 15 wt% UFS as the cementitious materials achieved comparable compressive strengths to those of C_Ref_HE at similar ages.

The concrete prepared with MK-UFS and GU cement (C_GU60_M25_U15) had a 3-d compressive strength of 39.2 MPa, almost similar to that achieved for C_Ref_HE (40.9 MPa). Moreover, the compressive strength of this concrete reached 52.9 MPa, which was slightly higher than that of C_Ref_HE (49.8 MPa). However, for the concrete prepared with MK-slag as the HE cement replacement (C_HE60_M25_S15), the 3-d compressive strength was obtained as 34.6 MPa, which showed a 16% decrease compared to that of C_Ref_HE (40.9 MPa). At 7 d, this concrete had a compressive strength of 46.7 MPa, slightly lower than that of C_Ref_HE (49.8 MPa).

It is noteworthy to say that all the concrete mixtures were cast with a water content that resulted in minimum entrapped air content in the mixtures. In this regard, the C_GU60_M25_U15 and C_HE60_M25_S15 were prepared with a water-to-solid ratio of 7.5 % which was higher than that used for C_Ref_HE and C_GU85_U15 (7.0 %). This is consistent with the flow table results of mortar samples, where the mortars prepared with MK-UFS and MK-slag blend needed a higher SP content compared to Ref_HE and GU85_U15 mortars to achieve the desired flowability.

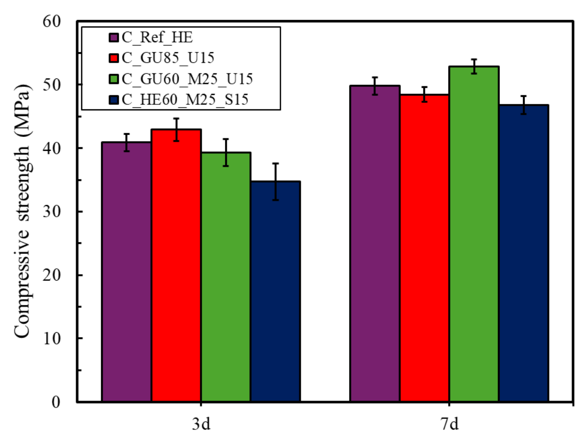

Figure 5. Compressive strength of the concrete mixtures

Overall, the combination of the GU cement, MK, and UFS showed a great potential for manufacturing low PC content dry concrete mixtures. The concrete with GU-MK-UFS blend showed comparable compressive strength development compared to that prepared with HE cement at the testing ages of 3- and 7-d, while it had 40 wt% less PC. While the extra grinding required to produce UFS from commercial slag may increase the costs of CMUs manufacturing, mass production, process optimization, and the use of advanced grinding technologies can significantly reduce these costs. Moreover, compared to the C-Ref-HE, the C-GU-MK-UFS utilizes GU cement, which requires less electrical energy for grinding, and potentially a lower cost compared to that of HE cement.

It is important to mention that the compressive strength of CMUs also depends on the compaction degree of the zero-slump concrete mixture as well as their curing regime. In this study, the concrete mixtures were compacted by 15 drops of proctor hammer, which could be different from the compaction effort applied to the concrete mixture in the CMUs manufacturing plant. Moreover, the samples in this study were cured at a temperature of 23-25 °C, which differs from the relatively higher temperatures commonly used in manufacturing plant to accelerate the strength development of the CMUs. Despite these differences in the CMUs manufacturing in the plant with the preparation of the samples in this study, the results presented can demonstrate great potentials of UFS in producing CMUs with lower carbon footprint. Furthermore, other performance parameters, such as flexural strength and drying shrinkage of the concretes, or their durability in different environmental conditions, should be further investigated to obtain more insights regarding the use of UFS in the CMUs production.

Conclusions

In this study, the effect of UFS with a median particle size of ~ 0.9 µm on the compressive strength development of cementitious mixtures with high SCMs content was investigated. UFS was used to replace 15 wt% of GU cement in preparing mortar samples, and the results compared to those of reference samples prepared with general use (GU) cement and high-early strength (HE) cement. A combination of UFS and MK was also considered to replace 40 wt% of general use (GU) and high-early strength (HE) PC in standard mortar samples. The strength development and superplasticizer demand of these samples were compared to those of mortars prepared with the same content of ordinary slag-MK blend. Selected binders were also used to prepare high-strength dry concrete mixtures. The main concluding remarks are as follows:

1- Using HE cement instead of GU, or replacing GU cement with UFS, MK-UFS or MK-slag blend reduced the flowability of fresh mortar samples. The SP demand of mortar made with 15 wt% UFS and 85 wt% GU cement was lower than that of mortar made with 100% HE cement. Moreover, the SP demand of mortar containing HE cement and MK-slag blend was almost comparable to that of mortar made with GU cement and MK-UFS blend. The SP content of these mortars was higher than that of mortar made with HE cement, which was consistent with the higher water-to-solid ratio required for preparing concretes with MK-UFS and MK-slag compared to that made with HE cement.

2- Replacing 15 wt% of GU cement with UFS resulted in mortar samples with superior compressive strength, which was almost 90 wt% of that obtained by HE cement as early as 1 d. The blend containing 15 wt% UFS and 25 wt% MK as 40 wt% GU cement replacement resulted in mortar samples with comparable 1-d compressive strength compared to that achieved with 100 wt% GU cement. Moreover, the 7-d compressive strength of mortar with this blend was 40 % higher than that made with 100 wt% GU. Nevertheless, the compressive strength of mortar sample with this blend (GU60_M25_U15) was lower than that recorded for mortar made with 100% HE cement at 1 and 3 d, but surpassed that by 7 d.

3- MK-slag blend performed better compared to UFS-MK blend when replacing HE cement in mortar samples while MK-UFS outperformed MK-slag when replacing GU cement in mortar samples. The compressive strength of mortar samples prepared with GU cement and MK-UFS (GU60_M25_U15) was higher than that prepared with HE cement and MK-slag (HE60_M25_S15) at all testing ages. These observations suggest that the particle size of UFS and cement should be carefully optimized to ensure enhanced strength development for CMUs manufacturing.

4- Low PC content concrete with a 7-d compressive strength of higher than 50 MPa could be obtained with a cementitious materials content of 380 kg/m^3 which only had 228 kg/m^3 GU cement and the remainder being a combination of MK and UFS. The concrete mixture prepared with this binder had a relatively comparable 3-d compressive strength compared to that prepared with 100% HE cement with a slightly higher 7-d compressive strength.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), Canadian Concrete Masonry Producers Association (CCMPA), and Canada Masonry Design Centre (CMDC). The authors would also thank Lafarge Canada for providing the cements and slag.

REFERENCES

[1] G. Parsekian, H.R. Roman, C.O. Silva, M.S. Faria, Concrete block, in: Long-Term Perform. Durab. Mason. Struct., Elsevier, 2019: pp. 21–57.

[2] J. Dahmen, J. Kim, C.M. Ouellet-Plamondon, Life cycle assessment of emergent masonry blocks, J. Clean. Prod. 171 (2018) 1622–1637.

[3] H. Huang, T. Wang, B. Kolosz, J. Andresen, S. Garcia, M. Fang, M.M. Maroto-Valer, Life-cycle assessment of emerging CO_2 mineral carbonation-cured concrete blocks: Comparative analysis of CO2 reduction potential and optimization of environmental impacts, J. Clean. Prod. 241 (2019) 118359.

[4] Canadian Industry-average Cradle-to-gate LCA of concrete block masonry units produced by CCMPA Members, 2022.

[5] M.C.G. Juenger, R. Snellings, S.A. Bernal, Supplementary cementitious materials: New sources, characterization, and performance insights, Cem. Concr. Res. 122 (2019) 257–273.

[6] J. Skibsted, R. Snellings, Reactivity of supplementary cementitious materials (SCMs) in cement blends, Cem. Concr. Res. 124 (2019) 105799.

[7] S.W.M. Supit, F.U.A. Shaikh, P.K. Sarker, Effect of ultrafine fly ash on mechanical properties of high volume fly ash mortar, Constr. Build. Mater. 51 (2014) 278–286.

[8] P. Sharmila, G. Dhinakaran, Compressive strength, porosity and sorptivity of ultra fine slag based high strength concrete, Constr. Build. Mater. 120 (2016) 48–53.

[9] S. Ghasemalizadeh, R. Khoshnazar, Compressive Strength and Microstructural Development of Cementitious Mixtures Incorporating Ultrafine Granulated Blast Furnace Slag, J. Mater. Civ. Eng. 36 (2024) 4023572.

[10] S. Ghasemalizadeh, R. Khoshnazar, Effect of Ultrafine Granulated Blast Furnace Slag on the Strength Development of Portland Cement Mortar, in: Can. Soc. Civ. Eng. Annu. Conf., Springer, 2022: pp. 847–858.

[11] Y. Wang, X. He, Y. Su, J. Yang, B. Strnadel, X. Wang, Efficiency of wet-grinding on the mechano-chemical activation of granulated blast furnace slag (GBFS), Constr. Build. Mater. 199 (2019) 185–193.

[12] Y. Zhou, S. Pu, F. Han, H. Zhang, Z. Zhang, Effect of ultrafine slag on hydration heat and rheology properties of Portland cement paste, Powder Technol. (2022) 117549.

[13] L. Ting, W. Qiang, Z. Shiyu, Effects of ultra-fine ground granulated blast-furnace slag on initial setting time, fluidity and rheological properties of cement pastes, Powder Technol. 345 (2019) 54–63.

[14] T.S. Gowda, R. V Ranganath, High early strength-high performance concrete produced with combination of ultra-fine slag and ultra-fine silica: Influence on fresh, mechanical, shrinkage and durability properties with microstructural investigation, Constr. Build. Mater. 385 (2023) 131462.

[15] D. Zhao, R. Khoshnazar, Microstructure of cement paste incorporating high volume of low-grade metakaolin, Cem. Concr. Compos. 106 (2020) 103453.

[16] Z. Li, Z. Ding, Property improvement of Portland cement by incorporating with metakaolin and slag, Cem. Concr. Res. 33 (2003) 579–584.

[17] ASTM, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, ASTM Int. 04 (2020) 9. https://doi.org/10.1520/C0109.