



Mechanical Performance and Thermo-Physical Properties of Cement Mortar Incorporating Hybrid Slags

Mahad Baawain

msab@squ.edu.om

Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman

Hamada Shoukry

aboshoukry2020@gmail.com

Housing and Building National Research Center (HBRC), Building Physics Institute, Cairo, Egypt

Khalifa Al-Jabri

aljabri@squ.edu.om

Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman

ABSTRACT

Owing to the growing environmental pressure to reduce waste and pollution, the effective utilization of industrial solid wastes in construction applications has gained notable attention. This study investigates the mechanical and thermal properties of cement mortars incorporating two types of waste slags. Ferrochrome (FeCr) slag aggregate was used as a replacement for sand at the ratios of 25, 50, 75 and 100 wt. %. Ground granulated blast furnace slag (GGBS) has been used as a partial replacement of cement at the ratio of 25 wt. %. Compressive strength, permeable voids content and thermal conductivity tests have been conducted after 28 days of curing. The microstructure characteristics have been investigated by scanning electron microscope (SEM) equipped with energy dispersive analytical x-ray unit (EDAX). The experimental results revealed that FeCr waste aggregates could satisfactorily replace for natural fine sand in cement mortars up to 25 wt. % without a remarkable degradation of the compressive strength. Furthermore, Increasing replacement ratios of FeCr aggregates over 25 wt. % have resulted in noticeable decrease in thermal conductivity and an increase in the permeable voids content of cement mortars. The integration of GGBS with FeCr aggregates leads to enhanced compressive strength, reduced voids content and contribute to improved microstructure. The developed mortars with comparatively improved thermal resistance can be recommended for several structural and non-structural applications especially in hot weather regions.

Keywords: Ferrochrome slag; Blast furnace slag; Compressive strength; Thermal conductivity; Microstructure

1 INTRODUCTION

The utilization of industrial solid waste materials as aggregates in concrete structures has become of great importance in terms of saving landfill space and reducing the consumption and demand for extraction of natural aggregates (Rao & Prasad, 2002; Taha & Nounu, 2008; Borhan, 2012). Various types of waste metallurgical slags like steel slag (Nadeem & Pofale, 2012), copper slag (Al-Jabri et al., 2009), ferronickel (FeNi) slag (Saha & Sarker, 2017) and recently ferrochrome (FeCr) slag (Al-Jabri et al.,

2018a) have been utilized for fine and coarse aggregates replacements in the production of cement mortar and concrete for various construction applications. Nadeem and Pofale (2012) investigated the use of granular slag as a partial replacement of natural sand in masonry and plastering applications. In this study, cement mortars in various (cement : sand) proportions of 1:3, 1:4, 1:5 and 1:6 by volume were prepared with granular slag replacing 25, 50, 75 and 100 wt.% of sand. The compressive strength increased with increasing the replacement level up to 75 wt. %. An enhancement by about 15% has been attained relative to the ordinary mortar. An experimental study conducted by Al-Jabri et al. (2011) in which various mortar and concrete mixtures were prepared with different proportions of copper slag ranging from 0% to 100% as fine aggregates replacement. The results obtained for cement mortars revealed that all mixtures with different copper slag proportions achieved comparable or higher compressive strength than that of the control mixture. The results obtained for concrete indicated that the substitution of up to 40-50% copper slag as a sand replacement yielded comparable strength to that of the control mixture. Increasing copper slag over 50% resulted in strength reduction. The mechanical performance of cement mortar incorporating 25, 50, 75 and 100 wt. % of FeNi slag as a replacement of natural sand has been studied by (Saha & Sarker, 2017). The compressive strength of the hardened mortars increased with the increase of FNS up to 50% and then declined with further increase of FNS. The study also revealed that the use of fly ash as 30% cement replacement together with FNS as replacement of sand decreased the strength of hardened mortars. Ferrochrome (FeCr) slag is a by-product from the production of ferrochrome.

The production of 1 ton of FeCr alloys yields about 1.1 to 1.6 ton of slag (Niemela & Kauppi, 2007). In Oman, there are two FeCr plants producing about 355,000 t of FeCr slag annually Al-(Jabri, 2018a). The majority of this by-product is not reused in an effective manner and is currently being dumped. Dumping of FeCr slag in the landfills induces environmental problems in terms of the risk of leaching of hazardous elements like Cr (VI) causing contamination of the soil and ground water. Panda et al. (2013) studied the properties of normal and high-strength concrete made with FeCr slag as an alternative for aggregate. The results indicated that replacement of fine aggregate with FeCr slag up to 75% has improved the strength of concrete compared with conventional concrete. The influence of elevated temperature on concrete incorporating 50 wt. % FeNi slag as sand replacement and 30% fly ash as cement replacement has been recently studied by (Saha & Sarker, 2019), the use of 30% fly ash showed significant improvement in residual compressive strengths of all the mixtures for exposure up to 600°C. Although, the use of supplementary cementitious materials (SCMs) like silica fume (SF), Fly ash (FA), Ground granulated blast-furnace slag (GGBS), metakaolin (MK), etc., was proved to be very helpful in improving physical, mechanical and microstructural properties of conventional concrete; in addition, the use of SCMs in the production of blended cement can reduce carbon dioxide emissions by approximately 22% and improve sustainability in construction (Flower & Sanjayan, 2007), few studies investigated the influence of SCMs on properties of cement mortar and concrete containing high amounts of recycled waste slag aggregates. The aim of this study is to investigate the combined effects of FeCr slag fine aggregates and GGBS (a by-product of steel making industry) as partial replacement for cement on the properties of cement mortar.

2 EXPERIMENTAL DETAILS

2.1 Materials

The cement used in this study was ordinary Portland cement, OPC (CEM I: 42.5 N). Two types of slags have been used in this study including FeCr and GGBS slags. FeCr slag granules were collected from the plants of ferrochrome industry, situated in Al Tamman Indsil Company (ATIC), Sohar city, Oman. GGBS is a byproduct of iron and steel manufacturing; it is also locally available in Oman. The chemical compositions of both FeCr and GGBS are demonstrated in table (1). The type of sand used is natural siliceous. The specific gravity of FeCr is (2.97) which is slightly higher than that of the sand (2.77). The FeCr grains are angular in shape; while, the sand grains are semi-rounded. The grain size distribution for the sand, FeCr-slag aggregate (as received) and their combinations in various proportions along with the lower and upper acceptable limits of grading according to ASTM C33 is presented in Fig. 1. It can be seen that the sand possessed the optimum gradation. The FeCr grading curve has exceeded the upper limit of ASTM C33; in addition, the grading is curve is approximately flat especially in the mid-size range, this indicates that the grains are not well-graded; i.e., they can be prone to segregation during mixing. The combination of FeCr with natural sand has relatively improved the gradation. The replacement of sand by 25% FeCr possessed a grading comparable to that of the natural fine sand.

Table 1: Chemical compositions of used slags (mass, %)

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	SO ₃	TiO ₂	Cl ⁻	L.O.I.
FeCr	37.29	22.50	1.91	1.46	31.10	0.23	0.04	4.64	0.50	0.17	0.06	0.10
GGBS	35.10	10.60	0.38	42.00	5.95	0.15	0.31	--	2.75	0.76	--	2.00

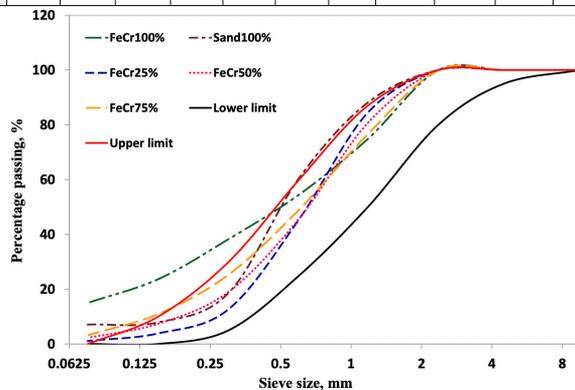


Figure 1: Gradation of sand, FeCr slag and their combinations

2.2 Samples preparation, identification and testing

The mortar samples were prepared using binder-sand ratio of 1:2.75. Fine sand was replaced with FeCr-slag aggregates at the ratios of 0, 25, 50, 75 and 100 wt. %. These mixtures were termed as (FeCr0, FeCr25, FeCr50, FeCr75 and FeCr100) respectively. Two groups of samples were prepared using different binders; a group made of OPC and the other made of 25 wt. % GGBS blended-OPC. The GGBS replacement ratio of 25 wt. % was proved to be the optimum by (Oner & Akyuz, 2007). The blended mortars were prepared using the water of standard consistency in order to attain a constant workability

degree among different samples. The compressive strength and volume of permeable voids tests were conducted on 50 mm cube samples at the age of 28 d in accordance with ASTM C109 and ASTM C642 respectively. Thermal properties analyzer (model: KD2 Pro) was used to evaluate the thermal conductivity of 50 mm cube dried samples in accordance with ASTM D 5334. The analytical scanning electron microscope, (JEOL JSM-7500F) equipped with EDAX unit for phase analysis was used to examine the microstructural characteristics of the freshly fractured samples.

3 RESULTS AND DISCUSSION

3.1 Compressive strength

Figure 2 shows the variations in compressive strength of the mortars incorporating various percentages of FeCr fine aggregates prepared with plain and GGBS-blended cements at the age of 28 day of curing. The mortar incorporating 25 wt. % of FeCr slag aggregates showed slight insignificant decrement in strength by about 5.70 %; whilst, the compressive strength considerably decreases by 23.74, 28 and 41.54 % for the use of FeCr aggregates at higher percentages 50, 75 and 100 wt., % respectively. This is attributed to the variation in grading characteristics of Fine sand and FeCr slag aggregates. Based on the grading analyses, the fine sand exhibited better grain size distribution than FeCr slag, which showed lesser proportion of finer aggregates passing 1.18mm. This is in line with previous studies reported that the use of slag with poor grading inversely affects strength (Saha et al., 2019). The grading that contains small percentages of aggregates in the mid-size range negatively affects the particle packing quality and result in the creation of permeable voids inside the structure. As it was expected, the use of GGBS as a SCM replacing 25 wt. % of OPC has satisfactorily compensated for the loss in compressive strength. The FeCr25 mortar attained a gain of strength by 10% and exceeded the compressive strength of the reference mortar made with natural sand and without GGBS. The maximum enhancement caused by GGBS incorporation is obtained for the mortar containing 50 wt. % FeCr slag aggregates; i.e., FeCr50 mixture has retrieved about 19% of the loss of strength relative to the reference ordinary mortar. The pozzolanic activity of GGBS explains the reason of enhanced strength. GGBS is classified as one of the active pozzolanic materials which consumes $\text{Ca}(\text{OH})_2$ crystals liberated during cement hydration and creates additional cementing calcium silicate phase (CSH) and results in refining the pore structure and providing compact microstructure (Oner & Akyuz, 2007).

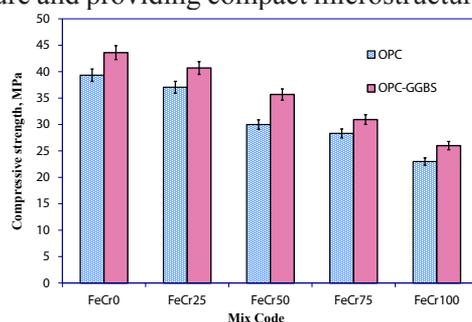


Figure 2: Compressive strengths of mortars containing various amounts of FeCr aggregates prepared with OPC and GGBS-blended OPC binders at the age of 28 day of curing

3.2 Volume of permeable voids

Figure 3 presents the permeable voids content (vol. %) for the mortars incorporating various percentages of FeCr slag aggregates prepared with plain and GGBS-blended cements at the age of 28 day of curing. The remarkable increase of volume of permeable voids (VPV) with increasing FeCr slag aggregates is consistent with the reduction in compressive strength. The VPV has been increased by about 8, 33.6, 40 and 49% relative to the reference mortar with the inclusion of 25, 50, 75 and 100 wt. % FeCr slag aggregates respectively. The increase of VPV points to the poor packing of FeCr grains inside mortar structure as compared with fine sand. Due to its ultrafine size and high pozzolanic activity, GGBS has considerably reduced VPV for all of FeCr slag-blended mortars by improving the physical packing; furthermore, the additional CSH produced by its pozzolanic reaction gets deposited in the inter-grain space and results in denser microstructure (Babu & Kumar, 2000). Although GGBS has relatively reduced VPV of the FeCr slag blended mortars, the mixtures that containing high percentages 50, 75 and 100 wt. % of FeCr recorded permeable voids contents higher than that of the reference mortar which indicates that there is still void spaces not filled with any hydration products.

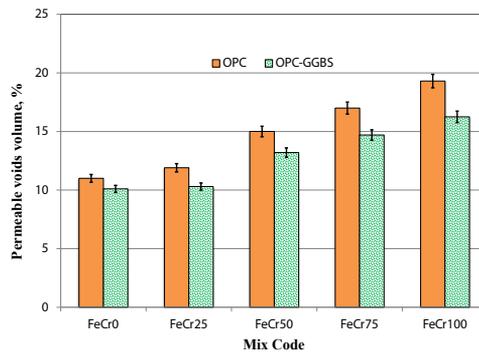


Figure 3: Volume of permeable voids of mortars containing various amounts of FeCr aggregates prepared with OPC and GGBS-blended OPC binders at the age of 28 day of curing

3.3 Thermal conductivity

Figure 4 presents the variation in thermal conductivity of the developed mortars containing FeCr and GGBS hybrid slags. It can be seen that the thermal conductivity decreases with increasing FeCr slag aggregates in the mortar. The thermal conductivity coefficients have been decreased by about 2.9, 7, 10.6 and 15.5% for the mortars incorporating 25, 50, 75 and 100 Wt. % of FeCr respectively as compared with the reference mortar. This is assigned to the increase of the voids content and the decrease of the bulk densities of the FeCr slag-blended mortars. These results are in line with findings of a previous study on the use of waste glass as sand replacement (Sikora et al., 2017). Due to its very low thermal conductivity, the static air entrapped in the voids between aggregates caused by the poor packing is responsible for the reduced conductivity coefficients (Krishnamoorthy & Zujip, 2013). The use of GGBS generally increases the thermal conductivity coefficients of the mortars with and without FeCr slag aggregates;

however, the maximum increase was found for the mortar made with fine sand (i.e., without FeCr). The increase of thermal conductivity is attributed to the improvement in the physical packing and the relative compactness of the microstructure achieved by incorporating GGBS. The compactness of solid structures facilitates the heat flow by conduction; therefore, increases thermal diffusivity and hence thermal conductivity (Al-Jabri & Shoukry, 2018b). The pozzolanic reaction induced by GGBS and the produced CSH affects the porosity of blended mortar and may alter the size, distribution, shape, and connectivity of the pores; this is the reason behind the considerable variation in the thermal conductivity attained upon the loading of GGBS (Gori & Corasaniti, 2014).

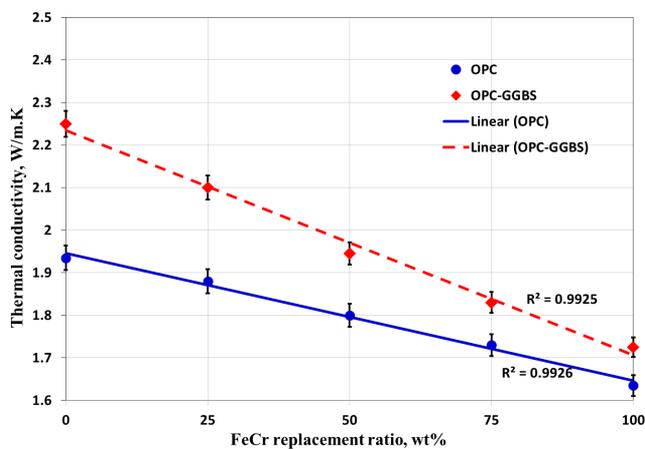
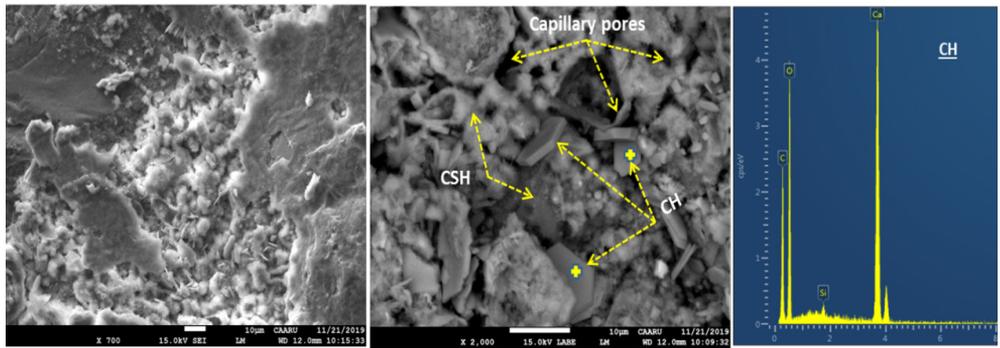


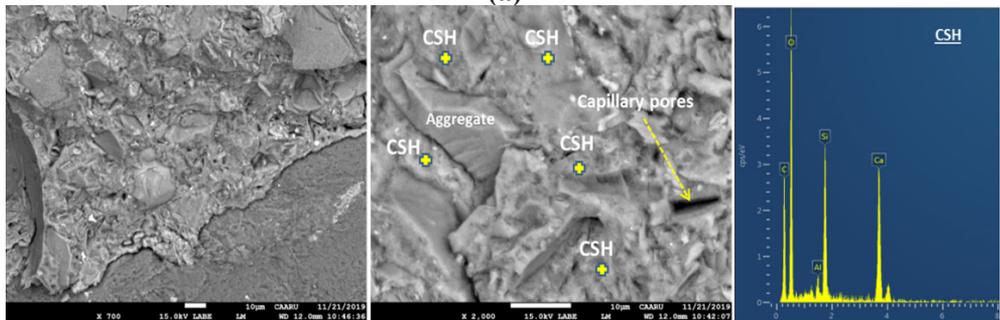
Figure 4: Variations in thermal conductivity of mortars containing various amounts of FeCr aggregates prepared with OPC and GGBS-blended OPC binders at the age of 28 day of curing.

3.4 Microstructure characteristics

SEM investigation was conducted to provide visual evidence of the change in microstructure characteristics responsible for the variation in the mechanical and thermal properties of the mortars incorporating hybrid slags. Figs. 5 and 6 Present SEM micrographs and EDAX spectra for the mortars incorporating 0 and 25 wt. % of FeCr slag aggregates made of plain and GGBS-blended cements. The SEM in Fig. 5(a) displays the most common hydration products of OPC including gel-like CSH and CH hexagonal crystals, these phases are not uniformly distributed through the hardened cement matrix; in addition, capillary micro pores are obvious. The inclusion of GGBS has remarkably improved the microstructure, denser and compact microstructure has been observed; furthermore, CH big crystals are absent; instead, gel-like CSH is predominant because of the pozzolanic reaction as shown in fig.5b. Fig.6a shows a FeCr aggregate embedded within the cement matrix the EDAX confirm the growth of CSH over FeCr aggregate surface; although, good binding is evident between aggregate and hydrated cement, big voids are present owing to the relatively less packing. The use of GGBS resulted in the production of additional honeycomb-shaped CSH networks in the inter-particle space and relatively improves the packing efficiency as depicted in fig.6b and confirmed by EDAX analysis.

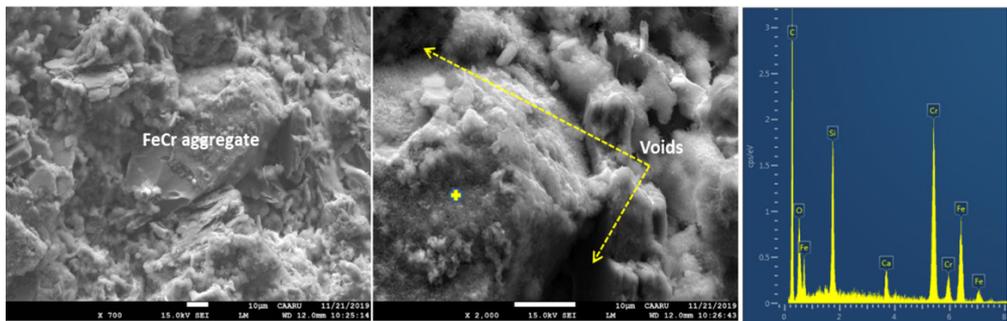


(a)

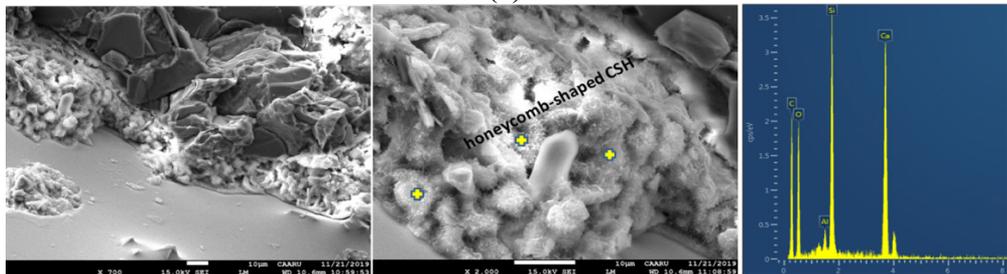


(b)

Figure 5: SEM micrographs and EDAX spectra of selected areas for mortars containing 0 wt.% FeCr made of (a) OPC and (b) GGBS-blended OPC



(a)



(b)

Figure 6: SEM micrographs and EDAX spectra of selected areas for mortars containing 25 wt.% FeCr made of (a) OPC and (b) GGBS-blended OPC

4 CONCLUSION

The combined/hybrid effects of FeCr slag together with GGBS on compressive strength, permeable voids content, thermal conductivity and microstructure of cement mortar have been investigated. The experimental results of this study warranted the following conclusions:

- The FeCr slag has a potential to be used as a substitute for fine natural sand in cement-based construction materials.
- The grading characteristics of FeCr fine aggregates affect to a great extent the mechanical strength and thermo-physical properties of mortar and play important role in determining the optimum replacement levels for natural sand. The inadequate gradation of the as received FeCr slag samples has restricted its utilization as sand replacement at higher percentages more than 25%.
- Controlling the grain size distribution of FeCr slag could help in improving the strength of the mortars incorporating high percentages of FeCr slag.
- The use of SCMs like GGBS is very helpful in enhancing strength, reducing voids content and improving microstructure of the FeCr-slag blended mortars.
- The use of FeCr slag at percentages higher than 25% reduces compressive strength and thermal conductivity, this may recommend these mortars (containing high amount of FeCr) for plastering applications where the high strength is not an important factor; however, the reduced thermal conductivity is useful for reducing heat transfer by conduction and hence improving thermal performance of exterior walls of buildings especially in hot weather regions.

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