Feasibility Using Electric Arc Furnace Dust as Cementing Material in High Performance Concrete

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Abstract. High performance concrete (HPC) is a specialized type of concrete that has been designed to be more durable and stronger than conventional concrete, thus became popular due to its superior mechanical and durability properties. Use of supplementary cementing materials such as fly ash, silica fume, and EAFD is often mandatory in the production of high-strength concrete. The effect of EAFD on the fresh and hardened properties of high performance mortar (HPM) mixtures prepared using different water-to-cementious materials (w/cm) ratios were investigated. A comparative study between EAFD and two well-known supplementary cementitious materials at different replacement levels of 0, 5, 10, 15 and 20% at w/cm ratios of 0.4 and 0.3 was carried out. The results showed that the setting times of mixtures incorporating up to 20% EAFD were in the normal range and similar to those of controls, SF and FA mixtures. At any w/cm ratio, the EAFD can be used up to 15% replacement level and at this replacement level, the compressive strength is between the FA and SF contents. Furthermore, the 20% EAFD give lower electric charge values than the control mixture, and it is better than FA mixtures. Tests on selected high-performance concrete (HPC) mixes confirmed the results from HPM mixtures. Use of 10% EAFD as a cement replacement in HPC show there are similar setting times to HPC mixes with 10% SF and 20% FA. The compressive strength of EAFD mix was slightly lower than those of SF and FA mixes but exceeded that of controls.

1. Introduction.
Steel is the most recycled and produced material worldwide [1]. It can be easily extracted from natural resources and steel wastes available all around. However, a potential quantity of electric arc furnace dust (EAFD), a by-product of the electric steelmaking industry, represents an environmental dilemma. The total steel produced is accompanied by EAFD representing approximately 2% of its weight [2]. In KSA, EAFD is also known as Bag House Dust (BHD). Different investigations were carried out on EAFD [3-5]. It was found that the most abundant heavy metals found in EAFD are zinc (Zn), lead (Pb), Chromium (Cr), and Cadmium (Cd) [6-8]. Because of the leaching potential of heavy metals in EAFD, it has been designated by the European Union (EU), and the EPA (United States Environmental Protection Agency) as a hazardous waste, which means that it cannot be disposed of at landfills without treatment [6]. EAFD can vary greatly in composition depending on the composition of the scrap charge, the furnace additives used, and the type of steel being manufactured. For example, use of galvanized steel scrap would increase the zinc content in the EAFD significantly. Zinc content in EAFD may vary between 7% to 40%, and lead content between 4 to 9% [7-9].
Recycling of EAFD in concrete has attracted the attention of many researchers [10, 11-12]. The cementitious matrix of concrete encapsulates the heavy metals and lowers their leach ability and their negative environmental impact. Several studies [13-14] reported enhanced hardened properties of concrete when EAFD is used at a replacement level of 3%. However, higher replacement levels negatively affect the fresh and early hardened concrete properties as they excessively retard the concrete setting and lower its compressive strength at an early age. De Vargas et al [15] investigated the effect of higher replacement levels of 5%, 15% and 25% EAFD on setting time of cement paste. They showed that increased replacement of EAFD will prolong setting time of concrete up to 70 hrs. Recently, De Souza et al [16] investigated compressive strength of treated EAFD by 10%, 15% and 20% replacement. They found that the compressive strength of concrete increased with the addition of EAFD. They also found that the use of 15% EAFD as a replacement of cement shows a reduction in chloride penetration of concrete. Al-Mutlaq [17] investigated the use of local EAFD in concrete and reported excessive setting times even in the presence of chemical accelerators. It is concluded that the use of EAFD was still in conventional concrete with water cement ratio of 0.45 to 0.60, respectively. Hence, this study interests to investigate the effect of EAFD in high performance mortar.

2. Experimental Program
Three variables are basic to the HPM mix design. They are water to cementitious materials ratio (w/cm), sand to cement ratio (S/C) and superplasticizer dosage. Many trials were carried out to arrive at the optimum sand-to-cement ratio (S/C) for control mixtures. The w/cm ratios used in this investigation were 0.4 and 0.3. The S/C ratios used were 2.25, 2.0, 1.75 and 1.5. Superplasticizer was added to HPM mixtures at w/cm ratio 0.4 and 0.3 to obtain the desired workability. The setting time and compressive strength at 7 days were measured for each mixture. For each w/cm ratio, the mixture which gave the highest compressive strength was selected as the optimum mixture. The S/C ratio of this mixture was then selected as the optimum ratio.

3. Results and Discussion

3.1. Chemical composition
Typical compositions of PC, SF, FA, and EAFD are given in Table 1. Each powder has its own characteristic oxides. PC is characterized with high lime and silica contents while FA is characterized with high silica and alumina. SF is composed mainly of silica while EAFD is composed of high contents of silica, ferric oxide and zinc oxide. It is evident from Table 1 that elemental oxides are distributed in various proportions in these materials with EAFD having some similarity in chemical composition with SF and FA which makes it a likely candidate as a new SCM.

| Oxide Composition | Analysis, % by weight |
|-------------------|-----------------------|
|                   | PC        | SF        | FA        | EAFD       |
| SiO₂              | 20.2      | 86.2      | 55.23     | 36.54      |
| Al₂O₃             | 5.49      | 0.49      | 25.95     | 3.9        |
| Fe₂O₃             | 4.12      | 3.79      | 10.17     | 25.6       |
| CaO               | 65.43     | 2.19      | 1.32      | 6.72       |
| MgO               | 0.71      | 1.31      | 0.31      | 3.8        |
| Na₂Oeq            | 0.06      | 2.80      | 1.59      | 0.96       |
| SO₃               | 2.61      | 0.74      | 0.18      | 0.4        |
| ZnO               | -         | -         | -         | 18.2       |
| MnO               | -         | -         | -         | -          |
| Loss on Ignition  | 1.38      | 2.48      | 5.25      | 3.88       |
3.2. Workability

Many trials were conducted to formulate HPM mixtures with low w/cm ratio and different replacement levels of EAFD, SF and FA and to determine the appropriate SP dosage needed. Based on the results of these trials, two SP dosages of 0.05% and 0.14% (as a dry extract expressed in cement weight percent), respectively, were selected for w/cm ratios of 0.4 and 0.3, respectively. The use of fixed SP dosage for each w/cm ratio has dual benefits: It shows the effect of different SCMs on workability as well as it helps keeping comparable workability.

The flow diameters for final HPM mixtures at the two w/cm ratios of 0.4 and 0.3 are summarized in Tables 2 and 3, respectively. It is observed from these tables that the addition of SF decreases workability while FA increases it, for all w/cm ratios. However, EAFD mixture improves slight workability.

Table 2. Flow diameter for mixes with w/cm ratio of 0.4, (S/C=1.5; SP=0.05%).

| Mix ID | Type of Replacement | Replacement Level (%) | Flow diameter (cm) |
|--------|---------------------|-----------------------|--------------------|
| PC     | -                   | -                     | 23.4               |
| SF5    | SF                  | 5                     | 21.2               |
| SF10   | SF                  | 10                    | 19.9               |
| SF15   | SF                  | 15                    | 18.8               |
| SF20   | SF                  | 20                    | 17.8               |
| FA5    | FA                  | 5                     | 24.2               |
| FA10   | FA                  | 10                    | 24.9               |
| FA15   | FA                  | 15                    | 25.7               |
| FA20   | FA                  | 20                    | 26.5               |
| EAFD5  | EAFD                | 5                     | 23.5               |
| EAFD10 | EAFD                | 10                    | 23.7               |
| EAFD15 | EAFD                | 15                    | 23.8               |
| EAFD20 | EAFD                | 20                    | 24.0               |

Table 3. Flow diameter for mixes with w/cm ratio of 0.3 (S/C=1.5; SP=0.14%).

| Mix ID | Type of Replacement | Replacement Level (%) | Flow diameter (cm) |
|--------|---------------------|-----------------------|--------------------|
| PC     | -                   | -                     | 23.5               |
| SF5    | SF                  | 5                     | 21.3               |
| SF10   | SF                  | 10                    | 20.0               |
| SF15   | SF                  | 15                    | 18.7               |
| SF20   | SF                  | 20                    | 17.9               |
| FA5    | FA                  | 5                     | 24.2               |
| FA10   | FA                  | 10                    | 24.8               |
| FA15   | FA                  | 15                    | 25.7               |
| FA20   | FA                  | 20                    | 26.5               |
| EAFD5  | EAFD                | 5                     | 23.6               |
| EAFD10 | EAFD                | 10                    | 23.7               |
| EAFD15 | EAFD                | 15                    | 23.8               |
| EAFD20 | EAFD                | 20                    | 24.1               |

3.3. Setting Time

Figure 1 shows setting time of EAFD, SF and FA mixtures at a w / cm ratio of 0.4. The figure shows that the setting times of ED and FA mixtures at different replacement levels to be similar and vary
only slightly in comparison with control. For SF mixtures, setting times decreased with increased replacement level. At 20% SF, the setting time of SF mixture is approximately 100 minutes less than that of control mixtures.

Figure 1. Setting time test results of EAFD, SF and FA mixtures with w/cm of 0.4.

Figure 2 shows setting times of EAFD, SF and FA mixtures at a w/cm ratio of 0.3. The figure shows that the setting times of ED, SF and FA at 5% replacement have a similar set time, which are slightly higher than that of control mixtures. At additional replacement from 5% to 20%, there is an increase in setting time for EAFD and FA mixtures of approximately 60 and 35 minutes, respectively. SF mixture showed a decrease in setting time by approximately 30 minutes. The figure also shows that at replacement level of more than 5%, the setting time of EAFD is consistently higher than both SF and FA.

The results of the comparison of the setting times of EAFD to those of SF and FA mixtures for the three w/cm ratios and varying replacement levels of up to 20% clearly show that the effect of EAFD on setting time is consistent and similar to FA. These results confirm that EAFD can be used at replacement levels of up to 20% without negatively affecting the setting times of HPM mixtures.

Figure 2. Setting time test results of ED, SF and FA mixtures with w/cm of 0.3.
3.4. Compressive Strength

Figure 3 shows compressive strength of FA, SF and EAFD mixtures with w/cm ratio of 0.4 at 1, 7, 28 and 90 days. The figure shows that there is a trend of decreased compressive strength of ED and FA with an increased replacement for up to 20%, while SF compressive strength is similar to control for replacement level up to 15% and decreased at 20% replacement level. This figure also shows that in later ages and up to 15% replacement level, the compressive strength of EAFD is close to the compressive strength of FA and lowers than the compressive strength of SF. However, the compressive strength of EAFD at 20% replacement level is lower than the compressive strength of FA and SF.

![Figure 3. Comparison of Compressive Strength of EAFD, SF and FA at w/cm of 0.4.](image)

Figure 4 shows compressive strength of FA, SF and EAFD with w/cm ratio of 0.3 at 1, 7, 28 and 90 days. The figure shows that there is a trend showing a decrease in compressive strength value of EAFD at the early days, whereas the compressive strength of FA and SF with an increase in replacement level up to 20%. At later ages, there is a trend showing a decrease in compressive strength value of EAFD and SF with an increase in replacement level up to 20%. On the other hand, the compressive strength of a FA increase from 10% to 15% replacement level, and it drops at 20% replacement. This figure also shows that in later ages and up to 15% replacement level, the compressive strength of EAFD is close to the compressive strength of SF, but lower than the
compressive strength of FA at replacement level of 10% to 15%. However, the compressive strength of EAFD at 20% replacement level is lower than the compressive strength of FA and SF.

![Graphs showing compressive strength of ED, SF, and FA at different replacement levels for 1-day, 7-days, 28-days, and 90-days.](image)

**Figure 4.** Comparison of Compressive Strength of ED, SF and FA at w/cm of 0.3.

### 4. Conclusions
- The presence of EAFD has slightly improved the flowability with limited effect on the setting time of all mixtures and w/cm ratios within the range from 4 to 6 hours;
- The comparison setting time concluded that the setting time of EAFD mixtures was higher than the setting time of SF and it’s opposite with a w/cm ratio of 0.3;
- At the optimum replacement level, there is an insignificant loss in compressive strength in comparison to the control mixture; for all w/cm ratios, the EAFD content of 15% was proven to be the optimum replacement level;
- The EAFD content of 5% was shown to provide the maximum compressive strength at w/cm of 0.3 while further incorporation of EAFD up to 15% insignificantly reduce the compressive strength which was lower than the compressive strength of SF and higher than the compressive strength of FA.
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