Influence of Steel Slag Fineness and Replacement Level on the Compressive Strength of Cement Mortars

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Abstract:

This experimental study used 50-mm cement mortar cubes to examine the effects of fineness and various substitution levels (0, 10, 20, and 30% by weight) of local electric arc furnace slag on the compressive strength of cement mortars at 3, 7, 28, 56, and 90 days. The slag was mechanically ground to achieve 250, 350, and 400 m^2/kg of Blaine surface area. The flow test on the mortar specimens and setting times were also performed.

The experimental findings demonstrated that compressive strength of cement mortars made with local electric arc furnace slag increases with time, and that the amount of slag in the mortar and its fineness affect this growth. The compressive strength of cement mortars decreases as the replacement level of steel slag increases. However, strength growth is enhanced by the slag's increasing fineness, and for optimal performance, the slag's fineness must exceed that of the cement. A 10 percent substitution of Portland cement with 400 m^2/kg EAFS fineness causes improvement in the 28, 56, and 90-days compressive strength of cement mortars by about 2.5%, 7%, and 13%, respectively.

Keywords: Electric Arc Furnace Slag, Fineness, Substitution level, Compressive Strength.

الملخص

استخدمت هذه الدراسة التجريبية مكعبات مونة اسمنتية بابعاد 50 مم لفحص تأثيرات النعومة ومستويات الإحلال المختلفة (0، 10، 20، و30٪ بالوزن) لخبث فرن القوس الكهربائي المحلي على قوة الضغط للمونة الأسمنتية عند 3، 7. و 28 و 56 و 90 يومًا. تم طحن الخبث ميكانيكيًا لتحقيق 250، 350 و400 م2/كجم من مساحة سطح بلين. كما تم ايضا إجراء اختبار الانسياب وزمنى الشك على عينات المونة والعجينة الاسمنتية.

أظهرت النتائج أن قوة ضغط مونة الاسمنت المصنوعة من خبث فرن القوس الكهربائي تزداد مع مرور الوقت، وأن كمية الخبث ونعومته تؤثر على هذا النمو. حيث تتناقص قوة الضغط للمونة الاسمنتية مع زيادة مستوى استبدال الخبث. ومع ذلك، يتم

تعزيز نمو القوة من خلال زيادة نعومه الخبث، وللحصول على الأداء الأمثل، يجب أن تتجاوز نعومة الخبث نعومة الأسمنت. يؤدي استبدال 10% من الأسمنت البورتلاندي بخبث افران ذو نعومة 400 م2/كجم إلى تحسين قوة الضغط للمونة الاسمنتية لمدة 28 و56 و90 يومًا بحوالي 2.5% و7% و13% على التوالي.

الكلمات المفتاحية: خبث فرن القوس الكهربائي،النعومة، مستوى الاستبدال، مقاومة الضغط.

1. INTRODUCTION

The role of supplementary cementitious materials (SCM) and cement replacement materials has grown in importance within the cement industry from an economic, technological, and environmental perspective. Numerous studies (Abdalkader & Elzaroug, 2010, Abubaker et al., 2018, Xu et al., 2017, Dadsetan & Bai, 2017, Pal et al., 2003, Şahin & Eker, 2024, Scrivener & Kirkpatrick, 2008*)* have been carried out to investigate the potential substitution of Portland cement (PC) in the production of concrete using by-product materials such as fly ash, silica fume, and slag.

Slag is one of the most common types of industrial waste, it is a by-product of the iron and steel industry. Slag can be used in concrete as aggregate or as a partial replacement for cement. According to its production process, slag can be classified into three different categories: blast furnace slag (BFS), basic oxygen furnace slag (BOFS), and electric arc furnace slag (EAFS) (Proctor et al., 2000). Blast furnace slag is generated from iron production, while EAFS and BOFS are generated from scrap-based steel production or refined pig iron output from blast furnaces (Brand & Fanijo, 2020). Air-cooled slag (BFS) can be used as an aggregate, but it is commonly used as SCM in the form of water-cooled GGBFS. This type is found to improve the properties of concrete when used as a cement binder (Brand & Fanijo, 2020).

Electric arc furnace slag (EAFS) is primarily utilized for low-value applications, such as fillers for foundation engineering and aggregates for asphalt concrete (Jiang et al., 2018, Li et al., 2013, Pasetto et al., 2023). Steel slag (EAFS) to employ supplementary cementitious materials (SCM) is considered low reactivity due to its low CaO/SiO2 ratio and air-cooled processing method (Bougara et al., 2009). When steel slag is substituted for Portland cement, Pal et al. (2003) found that the product's resulting fineness, glass content, calcium to silica ratio, and chemical composition all play important roles. Alsadig & Wagialla (2018) investigated the effect of electric arc furnace slag addition on the strength properties of mortars and they found that the use of

(EAFS) as a partial replacement of cement is a good pozzolan. Wang & Suraneni (2019) argue that since SFS may have variable chemistry and mineralogy, it is perhaps not surprising that the hydraulic or pozzolanic reactivity is also variable, and found that compressive strength testing defines steel slag materials as SCM. Brand & Fanijo (2020) state that because the various steelmaking processes are different from one another, the resultant SFS chemistry and mineralogy change. In general, the bulk oxide chemistry of most SFSs consists of CaO, MgO, SiO_2, and FeO, along with some Al_2O_3 and MnO. The mineralogy of the SFS is dependent on the steelmaking process and fluxing agents, but it is also dependent on the cooling process. The cooling process can influence SFS properties and composition, such as degree of crystallinity, particle size, and free CaO and MgO contents. The crystalline composition of SFS also varies. Santamaría-Vicario et al. (2015) revealed that after 90 days of testing, the cement mortar's compressive strength increased with the amount of slag in the mix. A study by Pan et al. (2019) discovered that adding steel slag to 10% of the cement substitute resulted in a 6% increase in compressive strength after 28 days. According to Jexembayeva et al. (2020), adding slag in relatively small amounts (less than 15% of cement weight) improved compressive strength for both early and late ages. Steel slag with a size less than 600 µm was observed to reduce the 7, 28, and 90-day compressive strengths of pastes containing cement and slag, according to Lizarazo-Marriaga et al. (2011). A study by Amin (2017) showed that the strength of mortar increased as EAFS fineness increased. It was observed that mortars made with slag superfine (less than 32µm) delivered the most comparable results to control mortars when it was substituted at a 10% level. But as compared to control mortars, the strength of mortars containing slag fine (less than 75µm), or 30% slag superfine, was far lower.

This experimental investigation examined the influence of partially replacing cement with local electric arc furnace slag (0, 10, 20, and 30% by weight) and its fineness on the compressive strength of cement mortar at 3, 7, 28, 56, and 90 days of curing. The slag was mechanically ground to achieve 250, 350, and 400 m^2/kg of Blaine surface area. The setting time and workability were also examined.

2. EXPERIMENTAL PROGRAM

Materials used

Cement

A commercial CEMI 42.5N obtained from Al Fataiah cement factory (local manufacturing plant), conforming to the requirements of BS EN 197-1:2000 was used. The physical, and chemical composition of the cement are given in Table 1.

Electric arc furnace slag (EAFS)

In this study, local electrical arc furnace slag (EAFS) was collected in aggregate form (Figure 1) with an average particle size between 2 cm and 5 cm, from a steel factory located in Benghazi. To turn it into a fine powder of the requisite fineness (250, 350, and 400 m^2/kg Blaine surface area), the slag was subjected to a grinding process. For this purpose, two types of mills were used in the grinding process, ball mills and ring mills, as shown in Figures 2 and 3. The slag powder (Figure 4) was included in the mixtures as a cement replacement with different levels (10, 20, and 30%). The oxide composition of the slag (Table 1) was determined using X-ray fluorescence (XRF) spectroscopy.

Table 1. Physical and chemical analysis of used cement and EAFS.

Item	OPC	EAFS
Physical properties		
L.O.I	2.52	———
Specific gravity (g/cm^2)	3.13	3.19
Fineness (m^2/kg) (Blaine)	320	250, 350, and 400
Chemical properties (Oxides, % by weight)		
SiO_2	20.86	35.8
Al_2O_3	5.6	13.5
CaO	62.39	25.2
Fe_2O_3	4	10.4
MgO	1	1.52
SO_3	2.93	-
K_2O	-	0.38

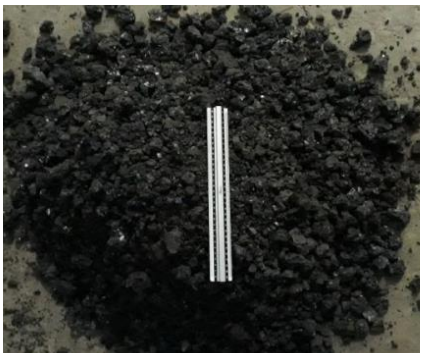
Figure1. Slag in aggregate form.


Figure 2. Ring mill used.


Figure 3. Ball mill used.

Figure 4. EAFS after grinding.

Sand

A standard silica sand obtained from the Al Fataiah cement factory was used in this study. The sand used complied with the specification given in BS EN 196-1:2005.

Water

Tap water available at the laboratory of civil engineering was used to make all mortar mixtures.

Proportions and mixing procedure

In this study, the mortar mixes were designed by replacing cement with electrical arc furnace slag (EAFS), at different replacement levels (0, 10, 20, and 30%). Detailed information on mixes is given in Table 2. As specified in ASTM C109, the water-to-cementitious materials and the sand-to-cement ratios in all mixes were kept at 0.485 and 2.75, respectively. The mortars were mechanically mixed using a Hobart mixer according to the standard method as specified by ASTM C305.

Table 2. Mortar mixtures.

Mix	EAFS Fineness (m^2/kg)	EAFS (%)	Per weight of binder			
			Cement	EAFS	Sand	Water
CM (Control)	-	0	1	0	2.75	0.485
10%CS	250	10	0.9	0.1	2.75	0.485
20%CS		20	0.8	0.2	2.75	0.485
30%CS		30	0.7	0.3	2.75	0.485
10%SF	350	10	0.9	0.1	2.75	0.485
20%SF		20	0.8	0.2	2.75	0.485
30%SF		30	0.7	0.3	2.75	0.485
10%SSF	400	10	0.9	0.1	2.75	0.485
20%SSF		20	0.8	0.2	2.75	0.485
30%SSF		30	0.7	0.3	2.75	0.485

Curing of specimens

After casting, the mortar specimens were left for 24 hours in the mould at laboratory conditions (20±2°C). Then, specimens were removed from the mould and kept at 20°C in curing water until test dates.

Testing procedure

Compressive strength tests on 50-mm mortar cubes were conducted in accordance with ASTM C 109, and the flow of freshly mixed mortars was measured according to ASTM C1437. Setting time tests were performed according to BS EN 196-3.

3. RESULTS AND DISCUSSION

Setting time

The results of the setting time of cement pastes are presented in Table 3. It is obvious from the results that the increase in slag content resulted in further delays in the initial and final setting times of cement pastes. This may be attributed to the dilution effect and the latent properties of the slag. The initial setting time for control mortar was 95 min, and mixtures containing slag with various fineness ranged from 112 to 144 min, and the final setting time was from 131 to 159 min. The 30% slag with 250 m^2/kg fineness (30% CS) resulted in retarding the initial and final setting times by about 49 min and 30 min, respectively. It can also be seen that the setting times decreases as the fineness of the slag increases. Slag with a fineness of 400 m^2/kg (SSF) resulted in a shorter setting time compared to coarse slag (CS). The initial setting time for cement specimens with (10%.SSF), (20%.SSF), and (30%.SSF) mortars was shortened by 7, 10, and 20 minutes, respectively, as compared with those of (10%.CS), (20%.CS), and (30%.CS). This effect was expected as slag with a higher specific area accelerates the cement hydration process and reduces the setting time.

Table 3. Setting times (min) of cement pastes.

Mix	Setting Time (min)	
	Initial	Final
Cp	95	129
10%.CS	119	142
20% .CS	129	148
30% .CS	144	159
10%. SF	116	133
20%. SF	124	136
30%. SF	131	152
10%.SSF	112	131
20%. SSF	119	134
30%. SSF	124	145

Workability

The results of flow are shown in Figures 5, 6, and 7. It can be observed from Figure 5 that the diameter of the flow tests decreases with increased EAFS with a fineness of 250 m^2/kg (CS) content. For the control mix (CM), the mean diameter is 84 mm. As the slag content of the CS mix increases to 30%, the mean diameter of the composite decreases to 54 mm. As Figure 6 shows, the flow displays a slight increase with the addition of EAFS with a fineness of 350 m^2/kg (SF), and thus the workability increases with increasing the slag content. The flow for the 30%SF mix is 88 mm, compared to 84 mm for the control mortar (CM). Additionally, Figure 7 demonstrates a minor increase in SSF mix flow with the addition of EAFS. The 30%SSF mix has a flow of 95 mm, whereas the control mix (CM) has a flow of 84 mm.

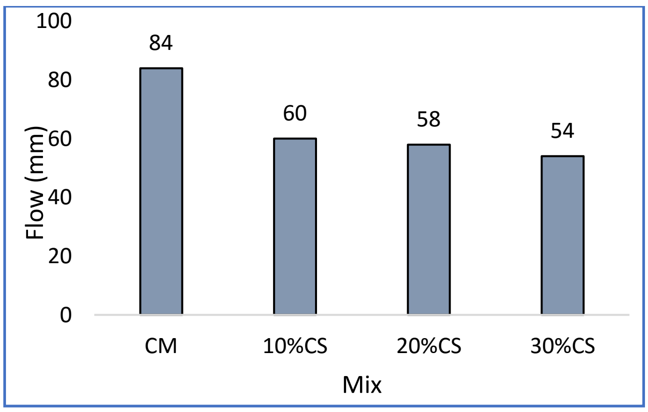

Figure 5. Flow of mixes with 250 m^2/kg slag fineness (CS).

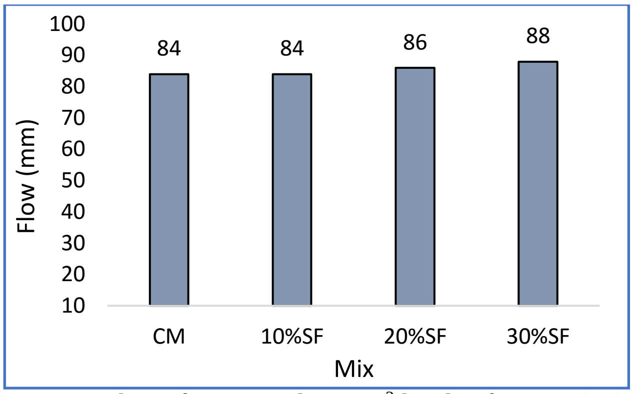

Figure 6. Flow of mixes with 350 m^2/kg slag fineness (SF).

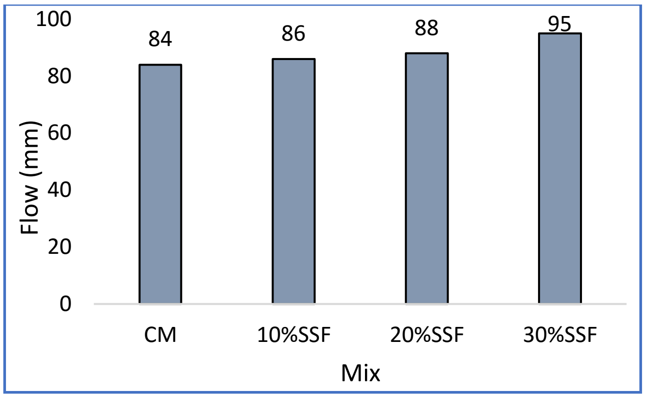

Figure 7. Flow of mixes with 400 m^2/kg slag fineness (SSF).

Compressive strength of mortar specimens

Figures 8, 9, and 10 show the results of the compressive strength of cement mortars. The results indicate that the development of compressive strength with age is dependent on the replacement level and fineness of EAFS. It can be seen from the graphs that, at early age, all slag cement mortars show lower compressive strengths in comparison to the control mix (CM). However, after 56 and 90 days of curing, SF and SSF mortar specimens made with 10 and those of SSF made with 20% substitution show greater compressive strength values compared to the control mix. The 10%SF mix shows an increase in the 56 and 90-day compressive strengths of about 5 and 11%, respectively, compared to the control mix (CM). Furthermore, a 10% substitution of cement with 400 m^2/kg EAFS fineness (SSF) causes improvements in the 28, 56, and 90-day compressive strengths by about 2.5%, 7%, and 13% compared to the control mortar (CM). This confirms previous results reported by Jexembayeva et al. (2020), where they note that adding a relatively small amount of slag (less than 15%) had positive effects in terms of compressive strength.

Even after 90 days of curing, as Figures 8-10 show, the compressive strength of all CS mortar specimens (with 250 m^2/kg EAFS fineness) remains lower compared to that of the control mortar.

Further, as Figure 10 demonstrates, all ages' mortars prepared with 30% substitution exhibit lower compressive strength values, with the strength drop decreasing with increasing slag fineness.

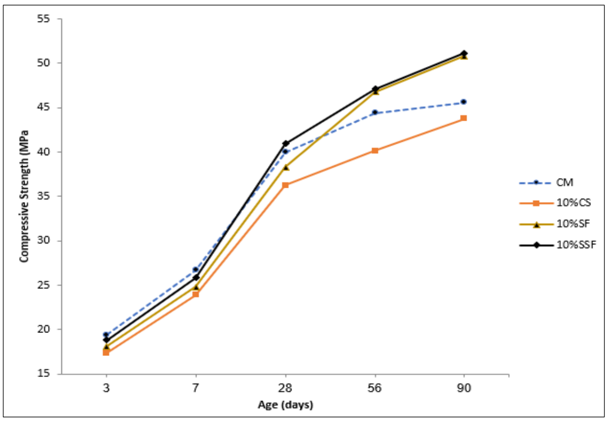

Figure 8. Compressive strength for mortars with 10% slag and different fineness.

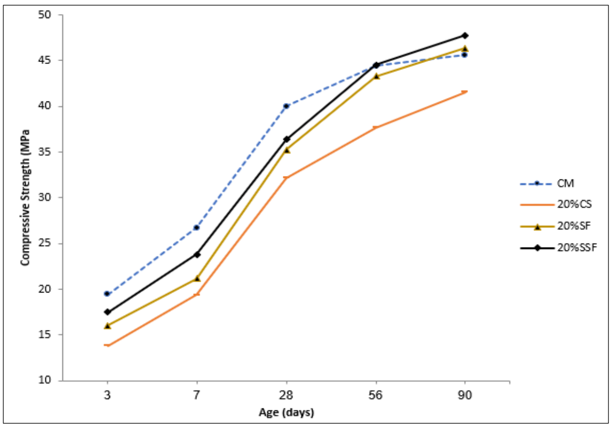

Figure 9. Compressive strength for mortars with 20% slag and different fineness.

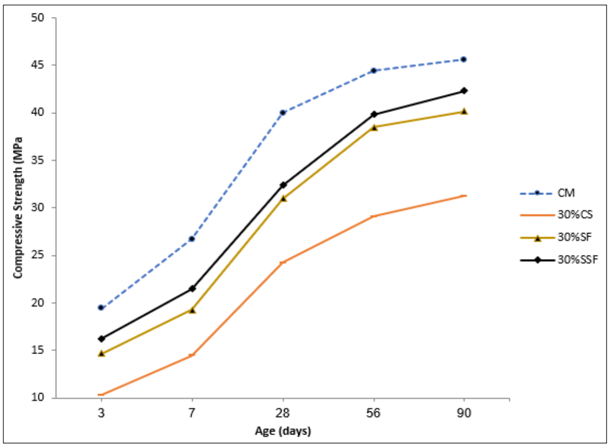

Figure 10. Compressive strength for mortars with 30% slag and different fineness.

4. CONCLUSION

According to the test results, the following main conclusions were drawn from this study:

- The initial and final setting times of cement are delayed when Portland cement is substituted with electrical arc furnace steel slag (EAFS), and the delaying time decreases as fineness decreases.
- The compressive strength of EAFS mortars increases as curing time increases.
- The compressive strength development of slag mortars depends on EAFS replacement level and slag fineness.
- The strength development of EAFS mortars decreases as the replacement level of EAFS increases.
- The compressive strength of mortar specimens increases by about 2.5%, 7%, and 13% for the 28, 56, and 90-day, respectively, periods when 10% of the cement is replaced with 400 m^2/kg EAFS fineness.

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