Effect of Partial Replacement of Cement by Steel Slag Powder Upon Mortar Properties

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ABSTRACT

Today, waste is one in all the key problems faced by the planet normally, and engineering science has been trying to handle this issue by following the principles of sustainable development. This paper describes an investigation of the various properties of cement mortars incorporating steel slag as an ordinary Portland cement (OPC) replacement material. The materials used for this study included Portland cement and a non-commercial air-cooled Electric Arc Furnace Steel Slag (EAFS) produced in Libya (Libyan Iron and Steel Company). The effects of various replacement ratios of steel slag powder to Portland cement (i.e., 10%, 20%, 30%, 40%, and 50%) on the workability, mechanical, physical and chemical properties were studied. The fineness of cement and slag was standardized by using a 90 µm sieve. According to the physical and chemical analysis of locally produced electric arc furnace slag, it was found that it has acceptable chemical and physical qualities comparing with the standard steel slag. The results showed that the preferred additional content of steel slag powder in a combined admixture was less than 20%. with the increase of content steel slag power, water requirement of normal consistency is increased, and the setting times are become shorter. The early mortar strength is lower. Additionally, this research contributes to our understanding of how to sustainably manage industrial wastes and has the potential to provide several important environmental and economic benefits.

Keywords: Steel slag power, Cement mortar, physical and mechanical properties, Sustainability**,** Cement industry, waste management.

تأثير الاستبدال الجزئي للإسمنت بمسحوق خبث الصلب على خصائص المونة الإسمنتية

الملخص

النفايات اليوم هي واحدة من المشاكل الرئيسية التي يواجهها الكوكب بشكل طبيعي ، ويحاول علم الهندسة التعامل مع هذه المشكلة من خلال اتباع مبادئ التنمية المستدامة، يصف هذا البحث دراسة الخصائص المختلفة لمونة الإسمنت التي تتضمن خبث الصلب كمادة بديلة للإسمنت البورتلاندي العادي (OPC). تضمنت المواد المستخدمة في هذه الدراسة الإسمنت البورتلاندي وخبث فرن القوس الكهربائي غير التجاري المبرد بالهواء المنتج في ليبيا (الشركة الليبية للحديد والصلب). تمت دراسة تأثير نسب الاستبدال المختلفة لمسحوق خبث الصلب إلى الإسمنت البورتلاندي (10٪، 20٪، 30٪، 40٪، 50٪) على قابلية التشغيل والخواص الميكانيكية والفيزيائية والكيميائية. تم توحيد نعومة الإسمنت والخبث باستخدام منخل 90 ميكرون. وفقًا للتحليل الفيزيائي والكيميائي لخبث أفران القوس الكهربائي المنتج محليًا، وجد أن له صفات كيميائية وفيزيائية مقبولة مقارنة بخبث الصلب القياسي. أظهرت النتائج أن المحتوى الإضافي المفضل لمسحوق خبث الصلب في خليط مركب كان أقل من 20٪. مع زيادة محتوى مسحوق خبث الصلب، ترتفع متطلبات الماء للقوام القياسي، وتصبح أوقات الإعداد أقصر. تكون قوة المونة المبكرة أقل. بالإضافة إلى ذلك، يساهم هذا البحث في فهمنا لكيفية إدارة النفايات الصناعية على نحو مستدام والقدرة على توفير العديد من الفوائد البيئية والاقتصادية الهامة.

كلمات مفتاحية: خبث فرن القوس الكهربائي، تقليل انبعاث ثاني أكسيد الكربون، استدامة، صناعة الاسمنت، إدارة النفايات.

Introduction

The construction industry constitutes around one-tenth of gross domestic product worldwide. Construction activities consume tremendous amounts of materials, including cement, aggregate, steel, nonferrous metals. During this process, a huge amount of energy is used, and greenhouse gas emission takes place. Reuse and recycle industrial and municipal coproducts and by-products can significantly save natural resources and contribute sustainability in environmental, social, and economic aspects [1,2].

The use of steel slag in clinker production may result in a significant reduction in the environmental impact of two industrial process namely cement and production at the same time the standard of the final product won't be compromised, and steel dumping is reduced the environmental impact of the use of steel slag in clinker production is the reduction of co_2 emission. [3].

Through the centuries, iron and steel slag was used for various purposes. However, the most field of application of this material was for construction purposes, and this remains the case today

All the cement replacement materials have one property in common; it's as fine as Portland cement particles, sometimes much finer. Their other features, however, are diverse. this is often applicable to their origin, their chemical composition, and their physical characteristics like surface texture or relative density [4].

When using steel slag powder as a mineral admixture could improve the fluidity of paste, which is helpful for the workability of concrete. this might be because that the activity of steel slag powder is less than that of cement, and therefore the water requirement of composite binder containing steel slag powder is a smaller amount than that of the equal cement mass within the same plastic state [5].

The influence of steel slag powder on water requirement of normal consistency of cement is in reference to its specific area, the worth of water requirement of normal consistency decreases for steel slag powder with lower-specific area while increases with higher-specific area [6].

The strength of mortar is decreased with increasing steel slag. When steel slag powder is increased, the degree of strength is decreased with the prolonging of curing age. This shows that the late strength increasing rate is great [7].

Materials and methods

Raw Materials

An ordinary Libyan Portland Cement CEM I 52.5N obtained from the Libyan cement company plant was used throughout the tests.

Libyan Steel Slag (LSS) is a non-commercial air-cooled electric-arc furnace steel slag produced in Libya as a by-product of the Iron and Steel Industry. The slag was supplied initially in the form of medium size (100mm to 400mm) rocks, then was grinding by Los Angeles machine. Finally, the slag powder was sieved to pass 90 µm, in order to remove any remaining larger particles.

Gypsum was obtained from the Libyan Cement Company. It was air dried and mixed thoroughly in dry condition. It was passed through 90 micron sieve. In order to reveal the properties of cement paste and mortar with steel slag, the Portland cement is taken as a reference in this study, as Portland cement generally contains 6 wt% gypsums, so 6 wt% gypsum is also added in steel slag, forming a composite system of steel slag and gypsum.

Air jet sieving is an efficient process that uses air flow as the only variable that sieves the material being analyzed. Finest dry bulk materials be analyzed with Air Jet Sieve by ALPINE, as shown in figure 1.

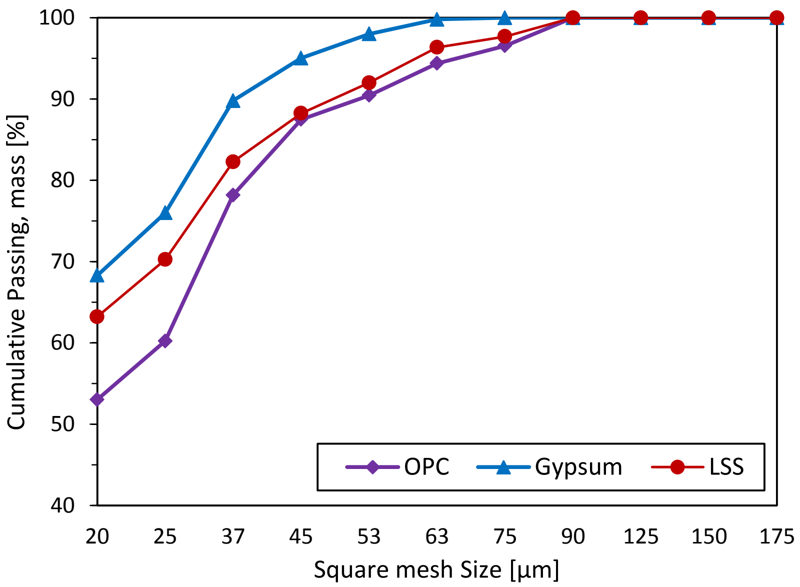

Figure 1. Particle size distribution of materials Used (Air Jet Sieve by ALPINE).

Standard specifications exist for the use of OPC [8]. However, no such specification exists for the use of steel slag. In the absence of a specification for LSS, the physical and chemical data obtained for this material and its suitability as a cementitious material has been assessed with reference to BS 6699: 1992 [9], specification for Ground Granulated Blastfumace Slag for use with Portland cement, Table 1 Shows the physical properties of the materials used.

Table 1. Physical properties of the materials used

Physical characteristics	Fineness (% retained on 90 micron sieve)	Bulk density (kg/m^3)	Specific Gravity (g/cm^3)	Standard Consistency (%)	Setting Time (min)	
					Initial	**Final**
OPC	0	2354.17	3.15	28	130	180
Libyan Steel Slag	0	-	2.752	-	-	-

Test Methods

The simplest definition of mix design is calculation of the quantities and ratios of main component materials of paste and mortar mixes for required characteristic strength, specific material properties and workability in order to get the best paste and mortar mix.

A simple approach has been adopted which involves partial replacement of the Ordinary Portland Cement (OPC) used in the 100% OPC control samples (Mix C), with an equal weight of LSS (Mix L). The levels of OPC replacement were 10%, 20%, 30%, 40% or 50%.

The following notation was used in identifying the various mixes. A letter prefix was used to denote the OPC replacement level and a letter suffix indicate the Gradient. This is shown schematically below:

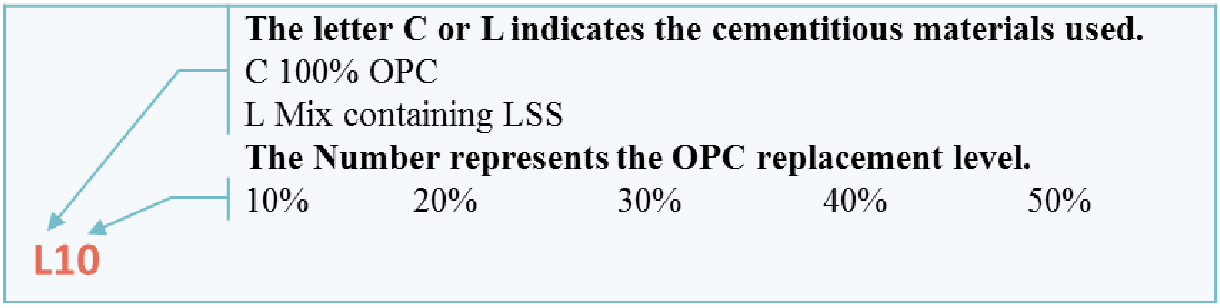

Figure 2. Scheme of mortar mixes for cement replacement

The direct replacement portion of Portland cement by steel slag powder by mass, which mainly consists of modifying an existing Portland cement mix to include steel slag powder without other adjustments, as shown in Table 3.

Table 3. Quantities and proportions of mixing materials for mortar mixes

Sample	Ratio	Cement		Steel Slag Powder		Gypsum		Water	W/C	CEN Standard sand
	%	%	g	%	g	%	g	mL	%	g
C	0	100	450	0	0	0	0	225	0.5	1350
L10	10	90	405	10	42.3	6	2.7	225	0.5	1350
L20	20	80	360	20	84.6	6	5.4	225	0.5	1350
L30	30	70	315	30	126.9	6	8.1	225	0.5	1350
L40	40	60	270	40	169.2	6	10.8	225	0.5	1350
L50	50	50	225	50	211.5	6	13.5	225	0.5	1350
L100	100	0	0	100	423	6	27	225	0.5	1350

C: Cement **L:** Libyan Steel Slag Powder

The testing procedures followed to determine the above mentioned properties are briefly explained below in the Table 4.

Table 4. Details of the tests performed

S. No.	Test Parameter	Method of test	REFERENCES
1	Chemical analysis	BS EN 196-2:2013	[10]
2	Standard consistence	BS EN 196-3:2016	[11]
3	Setting times	BS EN 196-3:2016	[11]
4	Soundness	BS EN 196-3:2016	[11]
5	Consistence of fresh mortar (by Flow table)	BS EN 1015-3:1999	[12]
6	Bulk density of fresh mortar	BS EN 1015-6:1999	[13]
7	Compressive strength	BS EN 1015-11:2019	[14]
8	Flexural strength	BS EN 1015-11:2019	[14]

Results and Discussion

Chemical Composition, Loss On Ignition and specific gravity

The analysis of chemical compounds of Steel Slag samples was done by the (S2 RANGER) device manufactured by (BRUKER) company, which was calibrated before use, and which analyzes by using X-Ray fluorescence technique (XRF), Table 5 shows the Chemical Compounds of the cement with steel slag powder.

Table 5. Chemical Compounds of the cement with steel slag powder

Compounds	OPC	LSS	L10	L20	L30	L40	L50
SIO_2	19.34	10.22	18.25	17.57	17.94	15.89	14.74
AI_2O_3	5.80	3.76	5.62	5.46	5.61	5.02	4.78
Fe_2O_3	3.19	9.61	3.85	4.37	5.05	5.72	6.42
CaO	62.44	45.26	60.50	59.25	58.50	56.12	54.23
MgO	2.47	3.56	2.68	2.82	3.09	3.15	3.25
Na_2O	0.08	0.57	0.29	0.29	0.14	0.12	0.35
K_2O	0.90	0.17	0.81	0.75	0.64	0.61	0.51
CI	0.005	0.53	0.045	0.070	0.11	0.13	0.17
So_3	3.69	3.49	3.67	3.63	3.83	3.59	3.65
Tio_2	0.36	0.57	0.38	0.40	0.43	0.44	0.46
MnO	0.046	1.46	0.20	0.31	0.46	0.59	0.75
P_2O_5	0.20	0.0	0.17	0.14	0.13	0.04	0.01

Loss On Ignition of cement and steel slag is not taken as a main parameter. The main purpose of using Loss On Ignition is for raw materials, but it is necessary as an indicator of the percentage of the material and its raw materials Loss On Ignition, as shown in Figure 3.

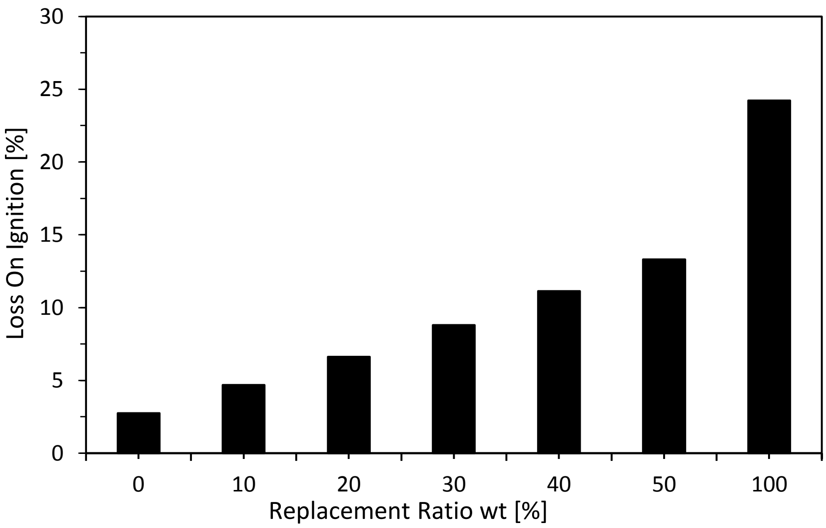

Figure 3. Loss On Ignition of motor with steel slag power

Since the specific gravity of cement is 3.15 g/cm^3 and the specific gravity of steel slag powder is 2.752 g/cm^3, therefore, the replacement samples that were calculated accurately are linearly proportional as shown in the figure 4.

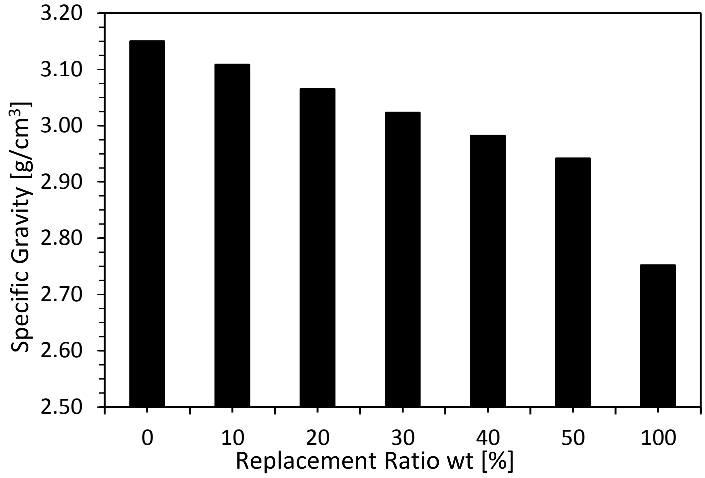

Figure 4. Specific Gravity of the cement with ultrafine steel slag powder

Normal Consistency Water Requirement, Setting Times and Soundness

Water consistency refers to the relative mobility of a freshly mixed cement paste or mortar or its ability to flow. The effect of replacing cement with steel slag powder on the consistency of water is illustrated in Figure 5 it can be seen that the consistency of water of the cement paste decreases at the ratio of 10% and becomes stable until the percentage of 30% and then begins to increase because the steel slag has become dominant in the mixture and not the clinker.

Setting times describe the stiffening behavior of cement paste. The results of the initial and final Setting time were given in Figure 5 for all samples. It can be seen in Figure 4 that the setting time decreases relatively with the increase of the replacement ratios.

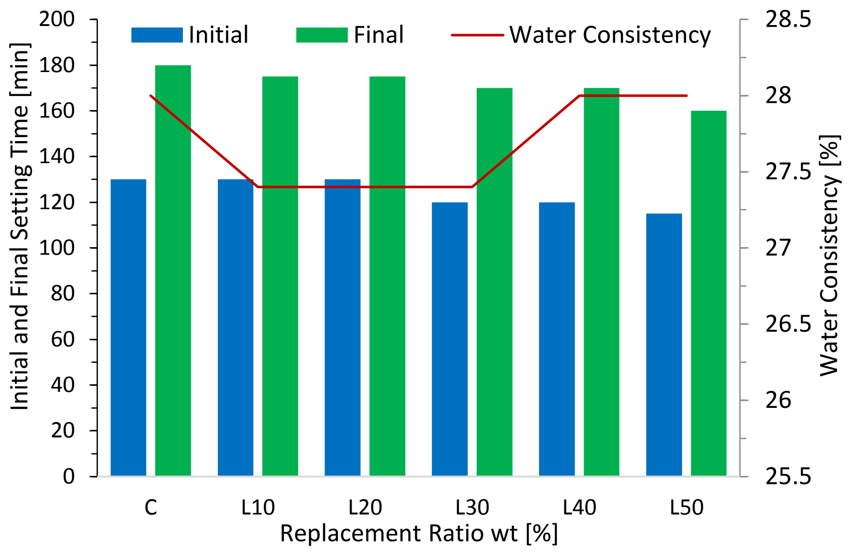

Figure 5. setting time and Water Consistency of motor with steel slag power

Figure 6 explain the soundness results of the cement paste containing steel slag powder, and it is noted that the soundness increases with the increase in the replacement ratio. The reason may be due to the steel slag powder containing high percentages of free magnesium as shown in Table 5.

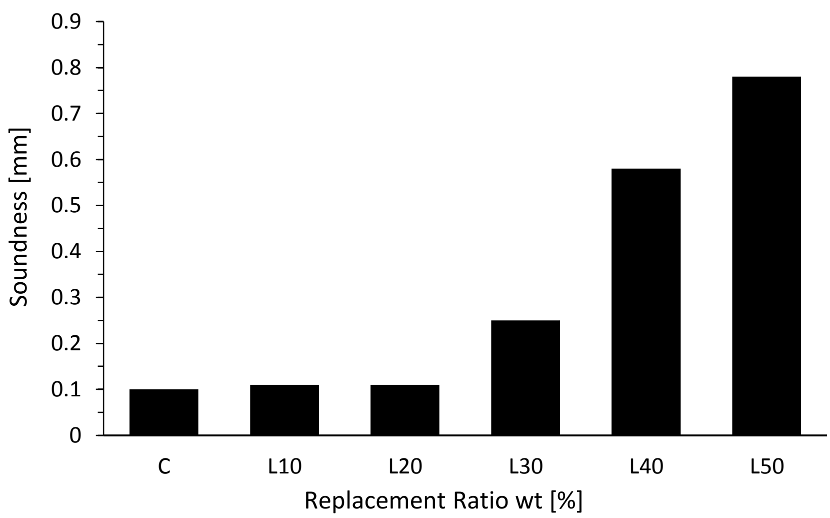

Figure 6. Soundness of motor with steel slag power

Consistence and Bulk Density of Fresh Mortar

Figure 7 shows the fluidity of the mortars. Due to the constant ratio of water to cement and steel slag (binder) the fluidity of the mortars without steel slag powder is relatively low. However, the fluidity of the mortars increases with the cement replacement ratio. When the cement replacement ratio is 20%, the fluidity of mortars containing steel slag powder is approximately 12 mm higher than that of mortars without steel slag powder. These results indicate that using steel slag powder as a mineral admixture could improve the fluidity of mortars, which is beneficial for the workability of mortar and concrete. This may be due to that the activity of steel slag powder is lower than that of cement. These results are consistent with a previous study [5].

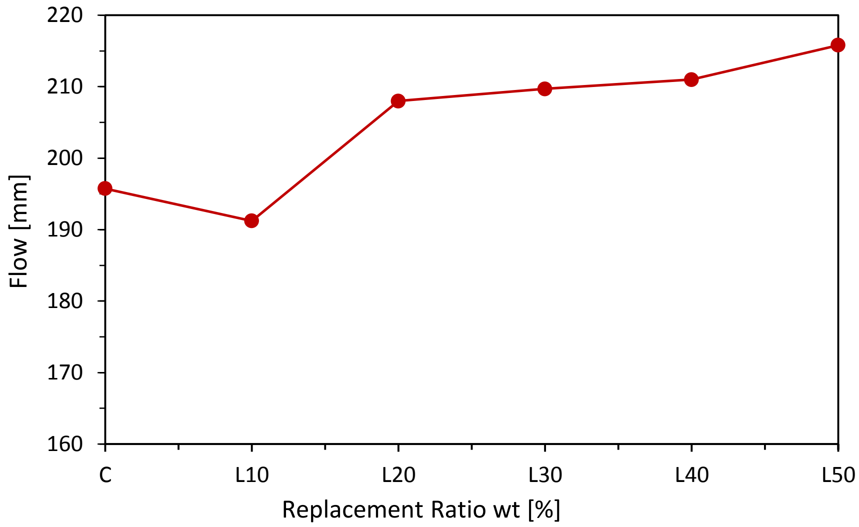

Figure 7. Fluidity of motor with steel slag power

Figure 8 shows the bulk density of fresh mortar. Due to the constant ratio of water to cement and steel slag (binder), the bulk density without steel slag powder is relatively high. However, the bulk density decreases with the cement replacement ratio. When the cement replacement ratio is 10%, the bulk density of fresh mortar containing steel slag powder is about 80 kg/m^3 lower than that of mortar without steel slag powder. These results indicate that using steel slag powder as mineral additives can reduce the bulk density of cement mortar.

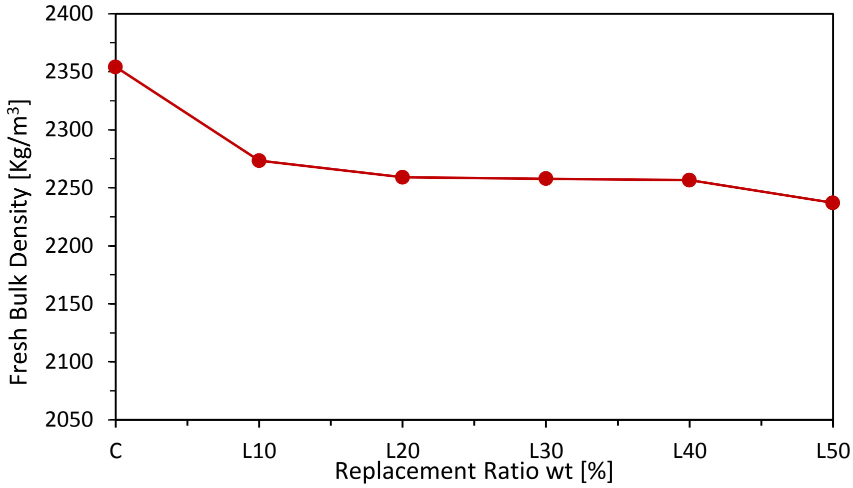

Figure 8: Fresh Bulk Density of motor with steel slag power

Compressive strength, Flexural strength and Activity index

For all cement mortar samples, the compressive strength increased with increasing curing time as shown in Figure 9. The compressive strength of slag steel powder with cement mortar was significantly lower. In the early ages, the cementitious fraction of slag steel powder is more inert than Portland cement, so the steel slag powder is only subject to very small chemical influence. However, the compressive strength at 56day cement mortar L10 (57.1 Mpa) increased rapidly. This is because the cementitious part of the steel slag is increasingly contributing to the development of strength with increasing curing age.

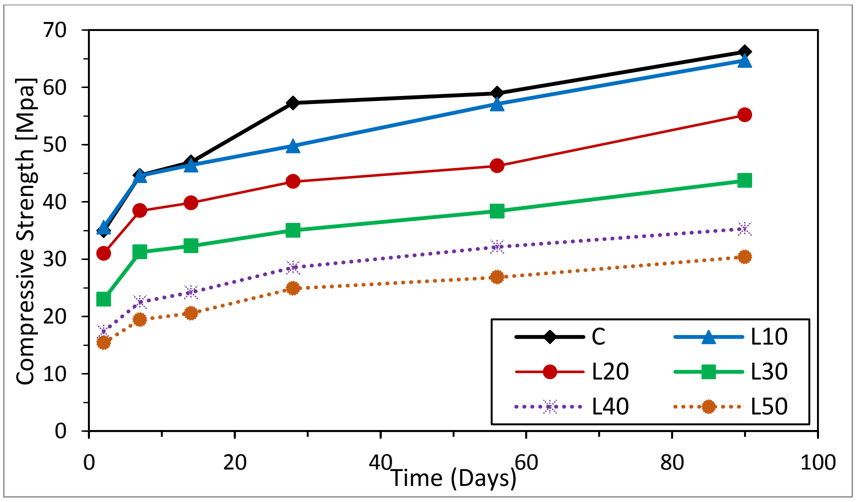

Figure 9. Compressive Strength of motor with steel slag power

According to the results, adding steel slag powder at early ages has unfavorable on the Flexural strength of cement mortar but it improve in a longer times. Steel slag powder may safely replace up to 10% of OPC but steel slag powder reduces mechanical properties of cement at early ages and does not improve until 90 days of curing. The results are shown in Figure 10.

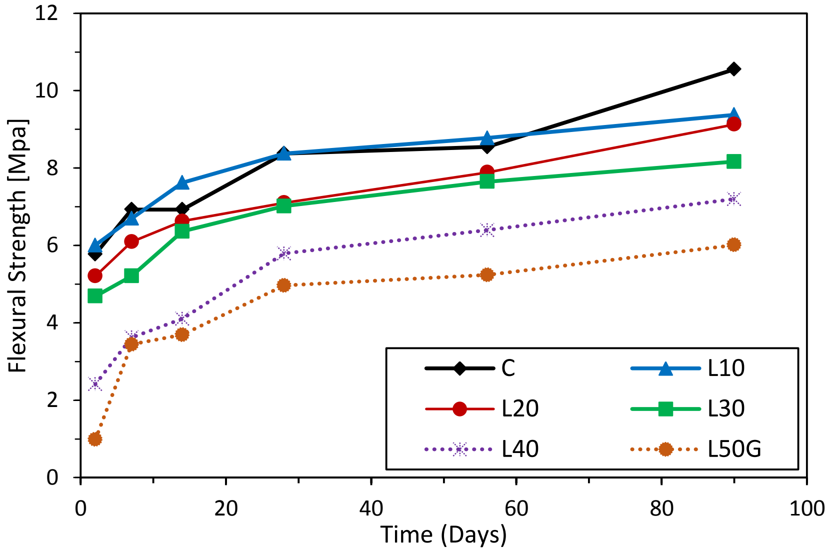

Figure 10. Flexural Strength of motor with steel slag power

Figure 11 shows the activity index of 2d, 7d, 14d, 28d, 56d and 90d of the mortar samples with different Steel slag powder contents. The activity index of mortar decreased with the addition of steel slag powder. It is clear that the activity index decreases significantly at the age of 28 days, but begins to improve at the ages of 56 and 90 days.

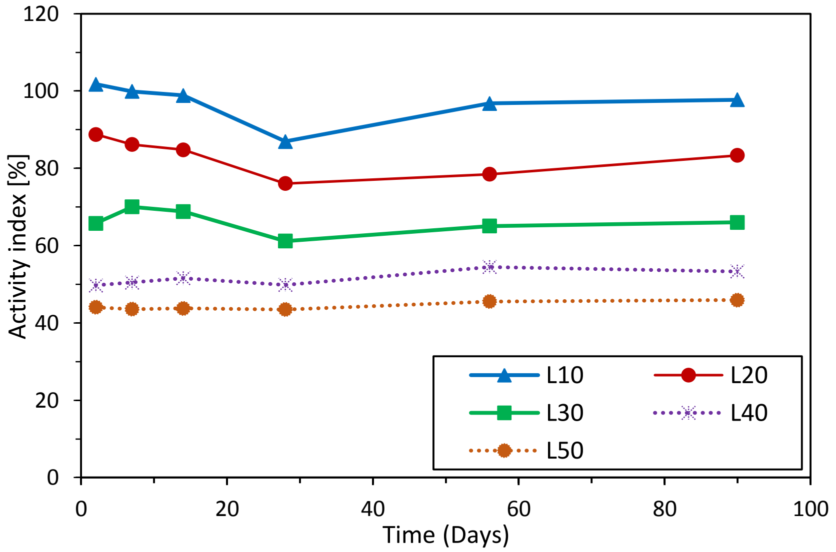

Figure 11. Activity index of mortars with steel slag power

According to EN 197-1, all results of the compressive strengths of the blended cement at 2, 7, 14, 28, 56 and 90 days satisfy EN 197-1 compressive strength limit for cement requirement of high early strength class 52.5 MPa [15].

Strength activity index test: Strength Activity Index is calculated as follows:

Strength Activity Index%= (Strength of pozzolan mix / Strength of control sample) × 100%,

(10%) Strength Activity Index of 90 Days= (64.696/66.204) × 100%=97.72%.

ASTM C989, 90% as the minimum of strength activity index, hence the locally produced electric arc furnace slag has higher strength activity index than the minimum required by ASTM C989.

Conclusion and Recommendations

In this study, the effect of adding electric arc furnace slag powder on the freshness and hardening properties of OPC was studied by measuring the physical properties of the paste and mortars, Normal Consistency, initial and final setting time, Soundness, fresh properties, fluidity, Bulk Density and mechanical properties of the mortar.

The consistency of the water for the cement paste decreases at the ratio of 10% and becomes stable up to the percentage of 30% and then begins to increase, because the steel slag has become dominant in the mixture, not the clinker, and the setting times are relatively reduced with the increase in the replacement ratios.

The Soundness increases with the increase in the replacement ratios, maybe because the steel slag powder contains high percentages of free magnesium.

Steel slag powder use can improve the fluidity of the cement mortars, which is beneficial to the workability of the mortar and concrete, and reduce the bulk density of the cement mortar.

The results of the chemical analysis showed that the main oxides present in EAF slag are mostly similar to those in OPC. The activity of EAF slag was evaluated in cement mortars and the results showed that EAF slag had poor hydraulic activity at early ages, but became active after 56 days of curing. The compressive strength of the blended cement mortars was similar to that of OPC at 90 days. This means that it has good hydraulic activity and can safely replace a portion of the OPC in the blended mortar by no more than 10% and 20% depending on the type of cement used.

according to the results obtained, it can be seen that the Flexural strength of the mortar with steel slag powder shows encouraging results in later ages. EAFS may safely replace up to 10% of OPC but steel slag powder reduces mechanical properties of cement at early ages and does improve until 90 days of curing.

This study recommends conducting laboratory experiments on durability requirements, SEM and XRD analyzes.

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