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Influence of Mechanically Activated Electric Arc Furnace Slag on Compressive Strength of Mortars Incorporating Curing Moisture and Temperature Effects

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Abstract: In this study, the influence of mechanically activated electric arc furnace slag (EAFS) was investigated through compressive strength tests on 50 mm mortar cubes. The objective was to convert the wasteful EAFS into a useful binding material to reduce the cement content in concrete without compromising strength and economy. Four different groups of mortar were cast which include control mortar, reference fly ash mortar, mortar containing EAFS to determine its optimum fineness and replacement with cement, mortar blend containing fly ash and EAFS of optimum fineness. EAFS were identified with respect to its fineness as slag ground (SG), slag-fine (SF) 100% passing 75 µm sieve, and slag-super-fine (SSF) 100% passing 45 µm sieve. Compressive strength was measured according to ASTM C109. Specimens were cured under different temperatures and moisture to incorporate the effects of normal and hot environmental conditions. Compressive strength of mortars increases with fineness of EAFS and its strength activity index matches the ASTM C989 blast furnace slag (BFS) Grade 80 up to 30% cement substitution and Grade 100 when 10% cement substituted with SSF. The influence of curing temperatures was also significant in mortars containing SG or 10% SF where strength decreased with increasing curing temperature. However, a 20–30% and 20% cement substitution with SF produced strength comparable to control and reference fly ash mortars under moderate (40 °C) and high curing temperature (60 °C), respectively. The utilization of EAFS as binder in concrete may reduce needs for cement, as well as save environment and natural resources from depletion.

Keywords: electric arc furnace slag; strength activity index; compressive strength; curing temperature

1. Introduction

Concrete is the most consumed man-made material on earth by society. It plays a vital role in our daily lives and has various applications. It is considered as the basis for our built environment. An estimated annual consumption of concrete was around 25 billion tons in 2006 [1,2]. The annual production of cement, which is the main constituent of concrete, was around 4.1 billion tons in 2014 [3]. Besides its beneficial usage, cement industry is responsible for the production of 5% of the worldwide man-made CO_2 emission [4]. The CO_2 emission causes climate changes and global warming issues. Recently, demands of producing low carbon concrete are increasing every day for climate change mitigation and adaptations. Among the various available technologies, the most effective is to substitute clinker, which is a main source of the CO_2 emission by alternate materials with pozzolanic or cementitious properties [5–7]. Pozzolanic and supplementary cementitious materials (SCM), such as fly ash, slag, silica fume and natural pozzolans, are widely used to partially substitute the clinker, therefore reducing the amount of clinker and associated CO_2 emission [8]. The factors such as availability of SCMs, its annual production level, cost effectiveness and engineering characteristic can decide the impact of this technology on future cement industry. Current estimated annual production of fly ash, slag and natural pozzolans are 500, 300 and 200 million tons, respectively [2]. To eliminate 1 billion tons of CO_2 per year by replacing 50% of clinker, 1.58 billion tons of substitution material is needed [9]. Thus, it is very important to investigate new cement substitute material to fulfill the demand of concrete industry to mitigate the emissions of CO_2. Different industrial byproducts are successfully being used for this purpose.

The different industrial processes' byproducts were being used successfully for numerous application in cement and concrete industries. For instance, ground granulated blast furnace slag, a byproduct of iron industry, and fly ash, a byproduct of coal power plants, were successfully used in high volume replacements of cement in mass concreting and found very effective in coping issues related to mass concreting [10,11]. Silica fume, a byproduct of silicon industry, has become very popular in terms of its effectiveness in attaining high strength and high performance concretes [12]. Other industrial wastes and byproducts such as ground glass waste or waste glass sludge, granite and marble waste, cement kiln dust, red mud, etc. were also used as a partial replacement of cement and found very effective in getting high later-age strength and improved durability as compared to control samples [13–15]. In addition to the above, many other researchers have investigated the potential of these industrial byproducts in the manufacturing of artificial aggregates [16,17]. These aggregates were effectively utilized in producing lightweight concrete as well as in controlling the autogenous shrinkage in high strength concretes [18]. This potential use of these industrial processes' byproducts as cement substitutes or artificial aggregates, would reduce the burden on cement and aggregate industries. This ultimately would lead to conserve natural resources and have multiple economic and environmental benefits.

Iron and Steel industry generates huge amount of waste as a byproduct called slag. Different types of slag are named for the furnace from which they are generated. Ironmaking slag called blast furnace slag (BFS) is generated when iron is produced in blast furnace while steelmaking slag, which include ladle slag, basic-oxygen-furnace slag (BOFS), and electric-arc-furnace slag (EAFS), are produced during steel manufacturing in their corresponding furnace and operating condition [19]. Annual estimated production of slag was around 399 million tons in 2010. Out of the total slag produced, the amount of BFS was 240 million tons and around 135 million tons was steel slag [20]. The demand of BFS to be used as a cement substitute is very high in cement industry. The total amount of slag produced by EU countries in 2008 was 45 million tons. About half of the slag (22.5 million tons) was utilized in cement industry [21]. South Korea is one of the largest steel producing countries in the world. Annually, about 13.4 million tons of BFS is produced from iron and steel making and 97% of this slag is used in cement and concrete industry [22].

However, nowadays, the supply of BFS is reducing because of the limited use of blast furnaces for the production of steel. The world has shifted to the use of mini mill and electric arc furnaces for steel production. Therefore, the importance of steel slag is increasing and its proper utilization in different industries is rapidly growing [20]. Due to the present and expected reduction in supply of BFS in future, there is a need to properly investigate the possible utilization of steel slag (EAF slag) as an alternate material in cement industry to get economic, environmental, and technical benefits.

Kingdom of Saudi Arabia per capita consumption of cement is one of the highest in the world. According to rough estimate, the annual production of cement in Saudi Arabia was 55 million tons in 2014 and 2015 [3]. Kingdom of Saudi Arabia imported SCMs such as ground granulated blast furnace slag (BFS), silica fume (SF), and fly ash (FA) to fulfill their local concrete industry requirements [23]. However, locally available industrial byproducts such as EAFS can be used as a partial substitute to Portland cement. This can also be a viable alternative for producing durable and sustainable construction/cementitious materials.

Until recently, very limited studies were devoted to investigate the potential use of EAF slag as partial substitute of cement in concrete industry. Mahmoud et al. [24] investigated the cementitious and pozzolanic potential of as received and treated (remelting and quenching) EAFS when used as partial replacement of cement in mortar. They found that untreated slag exhibit slight cementitious and pozzolanic behavior because of its crystalline nature. On the other hand, the treated slag showed better cementitious and Pozzolanic properties due to increased amorphous content. They further demonstrate that both untreated and treated EAFS when replaced by 15% and 30% with cement, show less compressive strength at initial stages (up to 14 days) but achieved more strength at 28 days compared to control samples. Despite of the crystalline nature and less cementitious and pozzolanic behavior, the as received EAFS showed almost equal strength at 15% but attained better strength at 30% replacement level as compared to treated slag at later age (28 days). Hekal et al. [25] observed that replacement of cement with EAFS up to 5% and 10% does not affect the compressive strength when compared to control sample especially at later ages. He further found that higher replacement of cement (20%) with EAFS shows least values of compressive strength to that of control samples at all ages.

In this study, cement was replaced by EAFS of different fineness levels to evaluate its potential as a binding material. In addition to control mortar (CM) containing 100% cement, several binary (EAFS or FA) and a ternary blends (10% fine EAFS + 10% FA) were designed. Binary blends contain different percentage replacements of cement (up to 30%) with EAFS of different fineness to determine the optimum rate and fineness of EAFS. This is an important requirement in attaining economic value and reducing the cement content. The FA as specified in ASTM C618 Type-F [26] was used as a reference pozzolanic material to compare the results of this study. Tests were conducted following ASTM C311 [27] and ASTM C109 [28] to calculate the strength activity index and the compressive strength of mortar cubes of size 50 mm^3, respectively. Since high temperature variations can occur within mass due to either hydration of cement or seasonal variations, the effect of different normal curing and high temperatures (20, 40 and 60 °C) was studied. The primary objective was to incorporate the influence of seasonal temperature conditions (normal and hot) which occurred in most eastern and western parts of Saudi Arabia. Finally, the slag-activity index of EAFS of different fineness was calculated and compared to ASTM C989 standard Grade-80 and Grade-100 of B.F. slag [29]. Moreover, the characteristics of EAFS, and the results of compressive strength with respect to (w.r.t.) fineness of EAFS, aging, and curing moisture and temperatures were presented and compared to those of control and the reference FA mortars.

2. Materials and Methods

2.1. Materials

ASTM C150 Type-I Portland cement was used as a main binder [30]. The physical and chemical properties of cement, and its substitute materials fly ash and EAFS are given in Table 1. A commercially available standard sand meeting the requirement of EN 196-1: 2016 [31] and ISO 679: 2009 [32] standards was used as a fine aggregate. Grain size distribution was done and the results were shown in Table 2. Its fineness modulus according to ASTM C125 [33] was found as 2.54, which lies well within the standard values of 2.3 to 3.1.

In this study, the locally available EAFS was collected in aggregate form with average particle size between 5 mm and 10 mm from ALTEMA contracting and industrial services, Jubail, KSA (Figure 1). Originally, this slag is produced as a waste material in steel making process by SABIC (Saudi Basic Industries Corp., Riyadh, Saudi Arabia) steel factory which is a leading company for steel production in Gulf region. According to rough estimate, the annual production of EAFS is about 350,000 tons in Saudi Arabia [34]. Majority of the EAFS produced is utilized as a partial replacement of natural aggregate in the asphalt and concrete industry [35]. According to Shi [36], steel slag should be given priority to be used as cementing component from technical, economical and environmental consideration.

Figure 1. Quarry site of electric arc furnace slag aggregates of size range 5–10 mm (courtesy of ALTEMA contracting and industrial services, Jubail, KSA).

Table 1. Physical and chemical analysis of cement, fly ash and electric arc furnace slag.

Item	C	FA	EAFS
Physical Properties			
Specific gravity (g/cm^3)	3.15	2.83	3.69
Fineness (m^2/kg) (Blaine)	344	-	-
Fineness (m^2/cc) by Microtrac S3500	0.5670	1.027	0.589—SG * 1.157 (<75 μm)—SF * 1.399 (<45 μm)—SSF *
Chemical Properties (Oxides, % by Weight)			
SiO_2	20.9	51.5	16.1
Al_2O_3	5.18	24.3	3.80
Fe_2O_3	3.04	8.87	31.7
(SiO_2 + Al_2O_3 + Fe_2O_3) **	-	84.7	51.6
CaO	63.9	5.15	30.6
MgO	1.65	3.50	9.84
Na_2O	0.10	2.38	0.56
K_2O	0.52	1.47	0.18
SO_3	2.61	0.23	Less Than 0.1
LOI ***	2.51	0.25	No Ignitable
Compounds (%)			
C_3S	52.1	-	-
C_2S	19.6	-	-
C_3A	8.17	-	-
C_4AF	8.81	-	-

* Slag as ground (SG), Slag fine (SF) passing 75 μm sieve, Slag super-fine (SSF) passing 45 μm sieve. ** ASTM C618; *** LOI = loss on ignition.

Table 2. Grain size distribution of standard sand (EN 196-1: 2016 and ISO 679: 2009) [31,32].

Sieve #	Sieve Size	Weight Retained (g)	Weight Retained (%)	Cumulative Passing (%)	Cumulative Retained (%)
3/8 inch	9.5 mm	0	0	100	0
No. 4	4.75 mm	0	0	100	0
No. 8	2.36 mm	0	0	100	0
No. 16	1.18 mm	134	26.8	73.2	26.8
No. 30	600 μm	179	35.8	37.4	62.6
No. 50	300 μm	49	9.8	27.6	72.4
No. 100	150 μm	98.8	19.76	7.84	92.16
Pan		39.2	7.84	0	-
Fineness Modulus (FM) = (0 + 0 + 0 + 26.8 + 62.6 + 72.4 + 92.16)/100 = 2.54					

2.1.1. Electric Arc Furnace Slag (Grinding and Sieving)

As mentioned above, the EAFS was originally procured in aggregate form (5–10 mm) and was subjected to grinding process to convert it into fine powder of required fineness. This was done in order to use it as a cement substitute to act as a cementitious material in the mortar mixes. For this purpose, high performance mills such as planetary mill (PULVERISETTE 5/4, Fritsch, Germany), planetary mono mill (PULVERISETTE 6, Fritsch, Germany) and a planetary micro mill (PULVERISETTE 7, Fritsch, Germany) were used (Figure 2). The purpose of using different grinding mills was to optimize the grinding process by obtaining the desired final particle sizes in less time and consuming less energy.

(a) (b) (c)

Figure 2. Mills used in this study to grind electric arc furnace slag aggregates of size 5–10 mm: (**a**) planetary micro mill PULVERISETTE 7; (**b**) planetary mono mill PULVERISETTE 6; and (**c**) planetary mill PULVERISETTE 5/4.

The grinding process was first started by using the Planetary Micro Mill PULVERISETTE 7 having two grinding bowls of capacity 80 mL and rotational speed up to 1100 rpm. The EAFS dose of 40 mL was fed into each bowl according to its recommended grinding capacity and ground for 30 min at 1000 rpm (two equal cycles) with a pause of 30 min between cycles to keep the bowl temperature as low as possible. After completion of set grinding process, instead of getting very fine particles of slag, all the slag material was stuck to the walls of the bowl. This happened due to high surface tension, softness and high ductility of slag. The hard metal tungsten carbide material was selected for both grinding bowl and balls. Around 25 spherical balls each of diameter 10 mm were used in this grinding process.

Consequently, in the second stage, the Planetary Mono Mill PULVERISETTE 6 was used, having a single grinding bowl of maximum capacity 250 mL and grinding speed up to 650 rpm. Similar to PULVERISETTE 7, the hard metal tungsten carbide material was selected for both grinding bowl and balls and this time 5 spherical balls each of diameter 30 mm was used in grinding process. Different trials were made by varying the grinding time, number of cycles, and speed of rotation. It was observed that longer grinding duration and higher rotation speed had negative impact on fineness. In addition, it was observed that the sticking quantity to the walls of bowl reduced by 50% with decreased grinding time and speed of rotation. As shown in Figure 3, slag (SG1) subjected to grinding process for 6.5 h (two cycles of 30 min each at 300 rpm with a pause of 10 min between cycles followed by two cycles of 15 min each at 300 rpm with a pause of 10 min between cycles followed by another cycle of 5 h at 550 rpm) give approximately same fineness to that of slag (SG2) ground for only 1 h (two equal cycles of 30 min at 300 rpm with a pause of 10 min between cycles). After each grinding process, the particle size curves of EAFS were drawn and compared to cement, and reference material FA. The purpose of drawing particle size curves of EAFS along with other materials was to take guide and device an appropriate grinding process that brings EAFS curves close to cement and FA. To carry out this particle size analysis, a laser diffraction technique using Microtrac S3500 (Microtrac Inc., Montgomeryville, PA, USA, complying with ISO 13320 [37]) was applied.

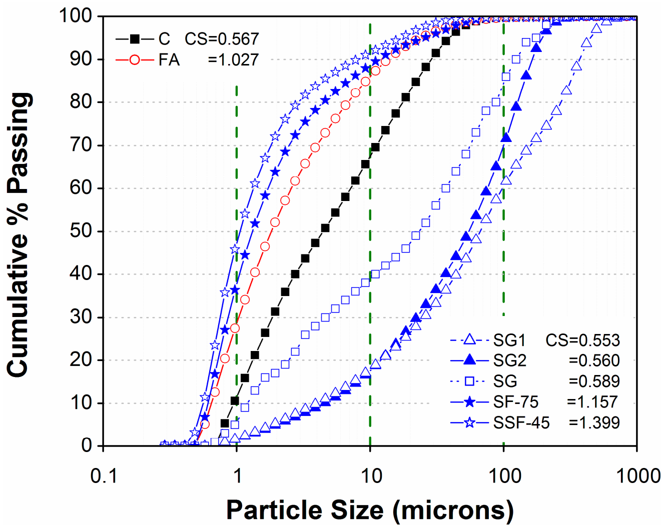


Figure 3. Comparison of particle size curves of ground electric arc furnace slag (EAFS) with cement and fly ash to obtain the optimum fineness results through grinding process.

Based on the results of previous stage, grinding time was further reduced which finally set after many trails to a total grinding time of 30 min (three equal cycles, each of 10 min duration with a pause of 10 min between cycles) at 300 rpm. The total grinding time was divided into cycles with pauses to maintain the grinding temperature low. The temperature of bowl rises due to intensive grinding process. A planetary mill PULVERISETTE 5/4 having four grinding bowls each of capacity 250 mL was used (Figure 2c). Again, the hard metal tungsten carbide material was selected for both grinding bowl and balls and 5 spherical balls each of diameter 30 mm were used. EAFS doses of 125 mL were fed into grinding bowls. As shown in Figure 3, the fineness of powdered slag (SG) was enhanced, which however, was still lower as compared to Portland cement. It was also observed that no EAFS stuck and all the material was easily detached from the walls of the bowls. The sticking of EAFS in previous stages of grinding can be attributed to rise of bowl temperature due to high grinding speed applied for long duration. As a matter of fact, the high percentages of Fe_2O_3 present in EAFS, when exposed to high temperature generated by the very fast movement of grinding balls become soft and stuck to the sides of bowl. It was observed that the chemical and mineralogical composition also affects the grinding ability of slag materials.

Previous studies suggest that high fineness is required to improve the reactivity of blended cements [38,39]. The fine grinding of cementitious materials results in more surface area which increases the reactivity and ultimately the strength [40,41]. Thus, to attain more fineness, the EAFS achieved in the final phase of grinding (SG) was subsequently subjected to dry sieving. Two different sieves of #200 (75 µm) and #325 (45 µm) were used to achieve different fineness levels of EAFS to examine its effect on engineering properties when used as a partial substitute of cement. The slag passing sieve No. 200 and No. 300 were identified as slag fine (SF) and slag super-fine (SSF), respectively.

2.1.2. Fly Ash

FA is a well-known pozzolanic material and has been extensively used all over the world for decades. It is generated as a byproduct when coal is used as a source of fuel in thermal power plants [42]. In 2006, its annual global production was estimated around 500 million tons [43]. The high demand of FA in concrete industry is due to its important role in enhancing the fresh as well as hardened (strength and durability) properties of concrete. It also plays vital role in reducing CO_2 emission from construction industry which significantly affects the environment. ASTM C618 Type F fly ash imported from India was used. In this study, FA was used as a reference cement substitute material. This is to compare the results of mortar containing EAFS of different fineness levels (SG, SF, and SSF) with those of containing FA.

2.2. Particle Size, SEM and XRD Analyses of Materials

Figure 4 shows the comparison of particle size curves of main binding material cement and its substitute cementing and pozzolanic materials EAFS and FA. The curves showed that both SF and SSF were much finer than main binder cement as well as well-known pozzolanic material fly ash. However, even after optimization of grinding process, the particle sizes of SG were still coarser as compared to cement or fly ash. A summary of particle size results is presented in Table 3. The particle size of materials can be compared by comparing their d_{10}, d_{50}, and d_{90} sizes.

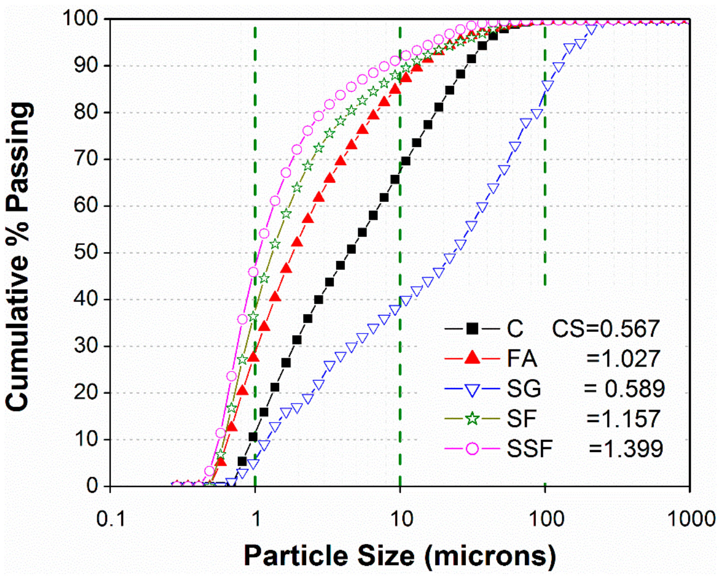


Figure 4. Particle size curves of cement and its substitute materials used in this study (FA, SG, SF, and SSF).

Table 3. Particle size analyses of cement, fly ash and electric arc furnace slag.

Materials	Mean (μm)	Standard Deviation	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)
Cement	10.58	10.01	0.954	4.440	28.63
FA	5.840	4.000	0.694	1.819	13.59
EAFS (SG)	10.85	25.13	1.130	24.13	130.5
EAFS < 75 μm (SF)	5.180	2.786	0.613	1.314	11.56
EAFS < 45 μm (SSF)	4.290	1.681	0.564	1.057	7.950

The powdered materials (Cement, fly ash, EAFS) are shown in Figure 5. Along with particle distribution curves (Figure 4), the Microtrac values of specific surface area (CS in m^2/cc) were also written against each material. The higher is the CS value, the greater will be the Blaine fineness and vice versa. To validate the reliability of CS value as a parameter of comparing fineness, the Microtrac

CS value of cement was converted from m^2/cc to m^2/kg. In conversion, the density of cement was taken as 3.15 g/cc. Following above, the surface area of cement was calculated as 360 m^2/kg, which is close to its Blaine fineness (Table 1), and thus authenticates the reliability of using CS values as a factor to compare the fineness of different materials.

Figure 5. Cement (**C**) and its substitute materials fly ash (**FA**) and electric arc furnace slag (**EAFS**) in aggregate form before grinding, slag after grinding (**SG**), SG passing sieve #200 (**SF**), and SG passing sieve #325 (**SSF**).

In addition to particle size analysis, scanning electron microscopy (SEM) of cement, FA, and EAFS w.r.t. its fineness was also performed using VEGA3 TESCAN (TESCAN, Brno, Czech Republic) to study their morphology and to authenticate their particle size results. The beam energy and the working distance in this SEM were set at 5 kV and 13 mm, respectively. The SEM pictures (view field: 104 µm and scale: 20 µm) show that the EAFS particles are comparatively finer and their shape seems nearly similar to those of cement (Figure 6). Unlike cement and EAFS, spherical particle shapes were observed for FA.

The powder samples of EAFS and FA were analyzed by using Rigaku MiniFlex II X-ray diffractometer (Rigaku, The Woodlands, TX, USA) between 10° and 85° (Figure 7). The step size was maintained at 0.02 and the Cu Kα radiation level was set at 30 kV and 30 mA throughout the tests. In this study, the purpose of X-ray Diffraction (XRD) was to study the different phases present in both EAFS and FA and their reactivity levels in mortar matrix.

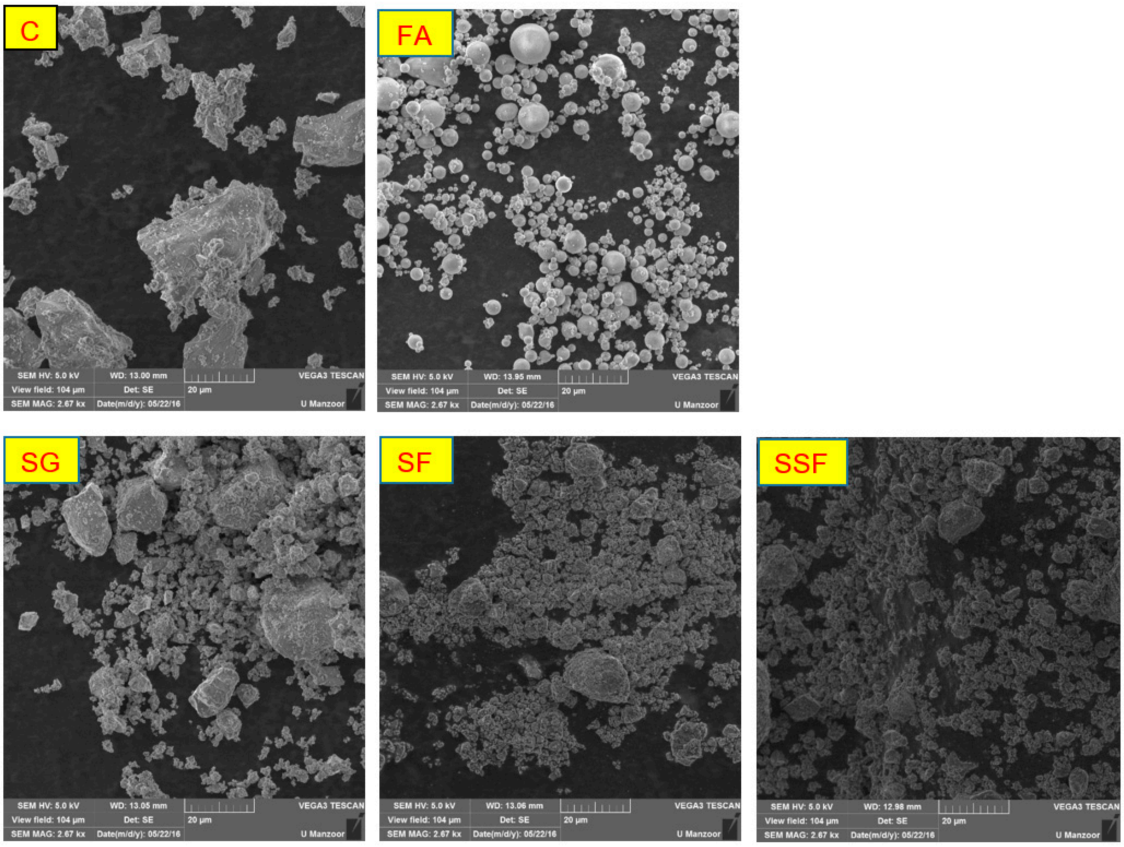
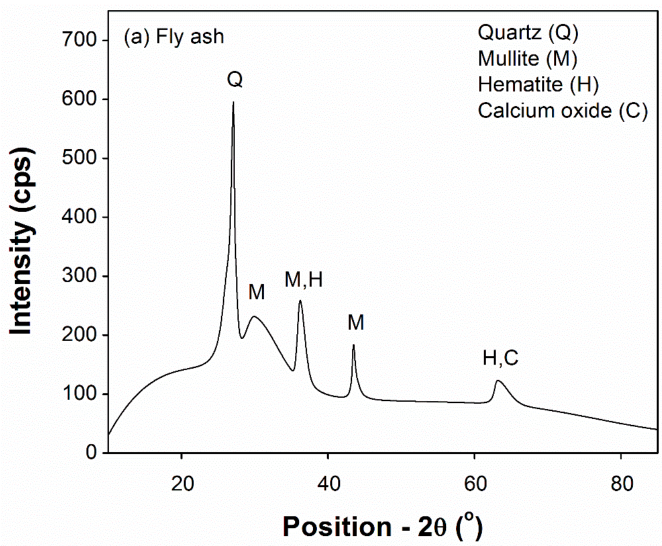
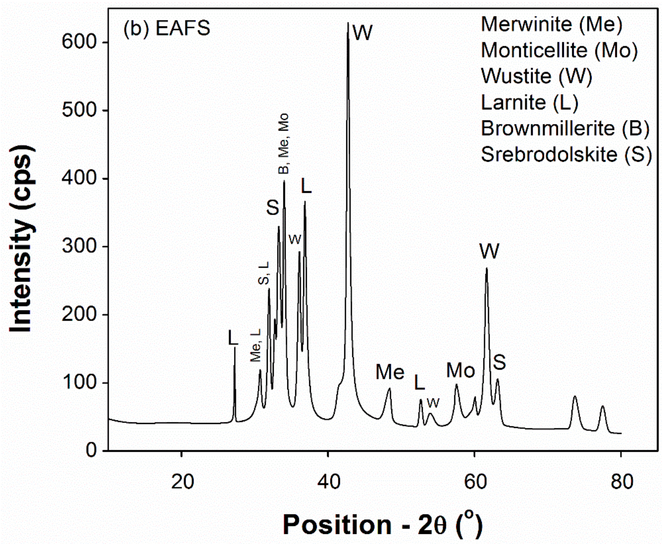


Figure 6. Scanning electron microscopy (**SEM**) images of cement (**C**) and its substitute materials fly ash (**FA**) and electric arc furnace slag (**SG**, **SF**, and **SSF**).



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. X-ray Diffraction (XRD) analyses of cement substitute materials: (**a**) fly ash and (**b**) electric arc furnace slag.

2.3. Mix Proportions and Test Methods

2.3.1. Mixture Proportions

In this study, several binary mixtures were prepared by replacing cement with FA and EAFS at various replacement levels. Detailed information of mixes is given in Table 4. As listed, 12 mixes were prepared including CM. After mixing for CM (100% cement), two binary mixes were prepared by substituting cement at different percentages with FA (10 and 20%) followed by eight binary mixes with EAFS of different fineness as SG (10 and 20%), SF (10, 20 and 30%), SSF (10, 20 and 30%).

Table 4. Mix proportions of control mortar and mortar containing FA and EAFS (w/cm = 0.485).

		Quantities Per Batch (g) for Nine 50-mm^3 Mortar Specimens						
Mix ID	**Cement Replacement (%)**	**W**	**C**	**FA**	**EAFS (SG)**	**EAFS (SF)**	**EAFS (SSF)**	**Sand (s)**
Control Mortar (**CM**)	0	364	750	0	0	0	0	2063
10% FA (**FA10**)	10	364	675	75	0	0	0	2063
20% FA (**FA20**)	20	364	600	150	0	0	0	2063
10% SG (**SG10**)	10	364	675	0	75	0	0	2063
20% SG (**SG20**)	20	364	600	0	150	0	0	2063
10% SF (**SF10**)	10	364	675	0	0	75	0	2063
20% SF (**SF20**)	20	364	600	0	0	150	0	2063
30% SF (**SF30**)	30	364	525	0	0	225	0	2063
10% SSF (**SSF10**)	10	364	675	0	0	0	75	2063
20% SSF (**SSF20**)	20	364	600	0	0	0	150	2063
30% SSF (**SSF30**)	30	364	525	0	0	0	225	2063
SF10FA10	20	364	600	75	0	75	0	2063

The purpose of casting the several binary mixtures containing EAFS was to investigate the influence on compressive strength development w.r.t. its replacement level and fineness. Two reference mixtures only contained FA for comparison of results with mortar containing EAFS. In the end, a ternary blends was also prepared by replacing 20% cement with 10% SF and 10% FA (SF10FA10). The purpose of casting the ternary mix was to investigate its influence on strength development and to attain the optimum compressive strength and high sustainability. Substituting FA alone or EAFS alone may adversely affects early and later age strengths, respectively. Moreover, replacing cement with EAFS in higher percentages (20% or 30%) may also not produce strength as comparable to CM. FA is a well-known pozzolanic material and can play its role in later age strength development, while slag possess cementitious properties can play its role at initial ages along with its high fineness. In addition to strength related benefits, using EAFS with FA would also improve workability of mix. This is due to the spherical particle shapes of FA. The quantity of each batch of mix was enough to cast nine 50 mm^3 specimens. This was required to keep uniformity in the mix and to test three identical specimens at 7, 28, and 91 days of age. As specified in ASTM C109, the water to cementitious materials and the sand to cement ratios in all mixes were maintained as 0.485 and 2.75, respectively.

2.3.2. Mixing Method

Mortar mixing was performed using the Hobart mixer following the standard method as specified by ASTM C305 [44]. At start, the calculated amounts of cement and water were mixed in mixing bowl for 30 s at slow speed mode. After that, the calculated amount of sand per batch was added and continue mixing in for another next 30 s [14]. After mixing for almost one minute, the speed mode was shifted from slow to intermediate to mix for 30 s more. A pause of 90 s was given after completing the initial 90 s of continuous mixing, followed by final phase of mixing for another 60 s. The mixing time limits at different steps were kept and repeated throughout the mixing batches to properly maintain the uniformity of the mixing procedure.

2.3.3. Casting of Mortar Cubes and Curing

Immediately after mixing, specimen were cast using 3-gauge 50 mm^3 steel molds. To cast mortar specimens, ASTM C109 was employed to fill molds in two layers followed by rodding of each layer. In total, 324 samples were cast in this study. For each mix (first 8 and last ternary mix as given in Table 4), 27 specimens were cast in three batches each of nine specimens. The amounts of mixing batches were decided according to the capacity of mixer. The mixing amount for 27 specimens was divided into batches such that three identical specimens were tested at ages 3, 7 and 28 days under different continuous moist curing (CMC) temperatures (20, 40 and 60 °C). However, only nine specimens (single batch) were cast for mixes containing SSF (SSF10, SSF20, and SSF30 as given in Table 4) to investigate strength development at 3, 7 and 28 days subjected to standard moist curing condition of temperature 20 °C. In addition to those above, 18 more specimens were cast for each of control mortar, and mortars containing 20% FA and 20% SF. This is to investigate the influence of continuous moist and partial moist curing conditions on strength developments (3, 7 and 28 days) under different curing temperatures (20, 40 and 60 °C). In the case of partial moist curing, the specimens were exposed to air after seven days of moist curing at relative humidity of 60% (7DM).

After casting, the molds were transported to a temperature and humidity controlled environment and covered with a waterproof polyethylene sheet. This was done to avoid any moisture loss from the specimens. The specimens were demolded after 24 h of casting under temperature and humidity controlled environment. Immediately after demolding, the specimens were cured under respective curing environment of temperature (20, 40 and 60 °C) and humidity (continuous and partial moist) until the age of testing. For the sake of clear understanding of experimental variables, a summary of all the aforementioned experimental variables is presented in Table 5.

2.3.4. Compression Test Method

After the completion of required curing periods, the specimens were removed from curing tank and chambers to test immediately under compression load. A universal displacement control testing machine (UTM) was used to apply load on mortar cubes in compression mode according to the specified method in ASTM C109. Special care was taken while placing specimens in the testing machine. This is to avoid experimental and testing errors by ensuring centers of specimen and upper bearing block in the same line. Loading rate in the testing machine was set (1 mm/min) such that maximum load reached between 20 s to 80 s as specified by ASTM C109. Testing data were logged automatically through built-in data acquisition system of UTM. Finally, the ultimate strengths were recorded by taking the average of three identical specimens.

Table 5. Experimental variables for each mix (curing conditions, number of specimens and testing age).

Mix ID	Curing		Test Age (Days)	# of Specimens Cast
	Temperature (°C)	Moisture		
CM	20, 40, 60	M * 7DM **	7, 28, 91 28,91	27 18
FA10	20, 40, 60	M	7, 28, 91	27
FA20	20, 40, 60	M 7DM	7, 28, 91 28, 91	27 18
SG10	20, 40, 60	M	7, 28, 91	27
SG20	20, 40, 60	M	7, 28, 91	27
SF10	20, 40, 60	M	7, 28, 91	27
SF20	20, 40, 60	M 7DM	7, 28, 91 28,91	27 18
SF30	20, 40, 60	M	7, 28, 91	27
SSF10	20	M	7, 28, 91	09
SSF20	20	M	7, 28, 91	09
SSF30	20	M	7, 28, 91	09
SF10FA10	20, 40, 60	M	7, 28, 91	27

* Continuous moist-cured. ** Exposed to air at relative humidity of 60% after the initial seven days of moist curing (7DM).

3. Experimental Results and Discussion

3.1. Characteristics of EAFS and FA

The EAFS used in current study mainly consist of CaO, SiO_2, Al_2O_3, MgO and some other metal oxides. The total concentration of these major oxides is 92.04%. Therefore, the EAFS can be characterized by CaO–MgO–SiO_2–FeO quaternary system. On the other hand, the fly ash (FA) is mainly composed of SiO_2, Al_2O_3 and Fe_2O_3. The sum of the major components SiO_2, Al_2O_3 and Fe_2O_3 in EAFS is 51.6% which does not meet the minimum limit of 70% as set by ASTM C618 [26], while FA is rich in these oxides (84.7%) and fulfill the criteria required by a material to be pozzolanic. The amount of sulfate ion (SO_3) in EAFS is around 0.1%, which is quite far from the upper limit of 4%, and thus clearly meets the standard requirements. The loss of ignition in EAFS is almost negligible.

The XRD pattern of fly ash was shown in Figure 7a. From XRD results, it was seen that the quartz and mullite are the two dominant phases present in FA sample. Due to its fine size and very high surface energy, quartz crystal demonstrate high pozzolanic reactivity in mortar matrix. However, mullite phase will remain chemically inert in mortar [45]. Additionally, two more phases namely hematite and calcium oxide were also found in XRD pattern of fly ash.

The XRD pattern of EAFS (Figure 7b) demonstrated presence of six different phases such as Monticellite ($CaMgSiO_4$), Merwinite ($Ca_3Mg(SiO_4)_2$, Wustite (FeO), Larnite (Ca_2SiO_4), Brownmillerite ($Ca_2(Al,Fe)O_5$ and Srebrodolskite ($Ca_2Fe_2O_5$). The presence of these phases also complying chemical analysis results of EAFS (Table 1), where the main oxides were CaO, FeO, MgO and SiO. The well-developed peaks in the XRD pattern shows high crystalline nature of most phases present in EAFS. However, a small amount of glassy or amorphous phase is also present. The merwinite phase is highly reactive and will exhibit a cementitious and pozzolanic behavior in the cement system [24].

3.2. Strength Activity Index of EAFS and Its Comparison with ASTM C989 Grades of BFS

The strength activity index values of EAFS and FA were calculated following the standard method specified by ASTM C311. This is used to evaluate the reactivity of mineral admixtures with cement. To match with the standard BFS Grade 80 of ASTM C989, the strength activity index value of mortar containing EAFS must be 75% or higher at 28 days. In other words, the 28 days compressive strength of mortar containing EAFS must be equal to or more than 75% of 28 days strength of control mortar (100% cement). However, to match with the standard BFS Grade 100, the strength activity index values should be at least 75% and 95% at 7 and 28 days, respectively. The overall compressive strength results of all mixes subjected to standard curing (water cured at 20 °C) and their corresponding strength activity index values were presented in Table 6.

Table 6. Comparison of EAFS strength activity index with FA and ASTM C989 Grades of BFS.

Mix ID	Curing Moisture	Compressive Strength (MPa)		Strength Activity Index (%)		Grades of BFS		
						80	100	100
		Age (Days)						
		7	28	7	28	28	7	28
CM	M *	40.9	53.6					
	7DM **	-	49.7					
FA10	M	33.3	44.6	81.4	83.2	75	75	95
FA20	M	32.3	41.5	79.0	77.4	75	75	95
	7DM	-	43.3	-	80.8	75	75	95
SG10	M	28.8	44.5	70.4	83.0	75	75	95
SG20	M	28.3	43.0	69.2	80.2	75	75	95
SF10	M	35.9	47.8	87.8	89.2	75	75	95
SF20	M	35.6	46.5	87.0	86.8	75	75	95
	7DM	-	51.7	-	96.5	75	75	95
SF30	M	31.2	44.0	76.3	82.1	75	75	95
SSF10	M	34.6	51.6	84.6	96.3	75	75	95
SSF20	M	34.7	45.7	84.8	85.3	75	75	95
SSF30	M	36.8	45.9	90.0	85.6	75	75	95
SF10FA10	M	33.6	42.7	82.2	79.7	75	75	95

* Continuous moist-cured. ** Exposed to air at relative humidity of 60% after the initial seven days of moist curing (7DM).

As shown in Table 6, mortar containing FA and EAFS demonstrated better strength activity index as compared to BFS Grade 80 as they attained 28 days strength more than 75% of control mortar irrespective of cement substitution (up to 20% by SG or FA, and 30% by SF or SSF) and fineness of EAFS. The influence of fineness was remarkable as strength activity index increased with increasing fineness. Unlike fineness, it decreased with increasing cement substitution. The highest strength activity index was found corresponding to highest fineness EAFS at 10% cement substitution (SSF10). Furthermore, it demonstrated that slag activity index was better than BFS Grade 100 as it attained 7 and 28 days strength more than 75% and 95% of control mortar, respectively. It seems that EAFS exhibited better filling, hydration and pozzolanic properties because of its high fineness [39,46,47]. Above results suggest that cement may be substituted up to 30% with SF or SSF and 10% with SSF to meet the slag activity index of BFS Grade 80 and Grade 100, respectively.

3.3. Compressive Strength

Influence of fineness of EAFS on compressive strength was investigated by varying its amount (up to 30%) as a cement substitute in mortar. Strength development was measured w.r.t. aging and curing moisture and temperatures.

As mentioned earlier, three different fineness levels of EAFS were used (SG, SF, and SSF). The SG is the EAFS directly obtained from optimized grinding process, and the slags 100% pass 75 µm (micro-sieve #200) and 45 µm (micro-sieve #325) were identified as SF and SSF, respectively. Influence of high cement substitutions of 30% was studied only for SF and SSF. The main purpose of this research was to find the optimum fineness of EAFS and its best percentage as a cement substitute without compromising rate and the ultimate compressive strength. Along with control mortar, tests on reference mortars containing commercially available FA (10% and 20% substitute of cement) were also performed. The purpose was to compare results and investigate the future potential of EAFS in local construction industry as an alternative of FA. The overall results of this study are listed in Table 7 and more comprehensive discussion of the results w.r.t. each experimental variable has been given in detail in the proceeding sections.

Table 7. Compressive strength (MPa) w.r.t. type of cement substitute, rate of substitution, aging, and curing conditions.

Mix ID	Curing Moisture	Curing Temperature (°C)								
		20			40			60		
		Age (Days)								
		7	28	91	7	28	91	7	28	91
CM	M *	40.9 (0.9) ***	53.6 (1.9)	61.3 (3.1)	41.2 (1.4)	52.5 (2.4)	60.3 (6.6)	42.7 (2.6)	53.2 (1.2)	55.0 (1.6)
	7DM **		49.7 (4.2)	56.6 (1.6)		52.9 (3.2)	50.2 (1.9)		48.2 (5.3)	51.4 (2.3)
FA10	M	33.3 (0.7)	44.6 (2.1)	56.4 (0.8)	38.8 (3.1)	51.2 (6.2)	59.3 (3.7)	38.2 (1.5)	51.2 (2.1)	55.1 (1.2)
FA20	M	32.3 (2.0)	41.5 (2.8)	57.3 (4.7)	39.7 (2.0)	57.5 (5.2)	63.8 (2.5)	43.2 (2.8)	52.0 (2.4)	56.7 (1.6)
	7DM		43.3 (1.2)	53.7 (2.6)		53.9 (0.7)	56.1 (0.2)		52.7 (3.1)	51.9 (5.4)
SG10	M	28.8 (4.5)	44.5 (1.3)	53.2 (2.6)	36.8 (4.5)	48.6 (3.6)	52.9 ()5.9	36.8 (2.4)	42.9 (0.5)	46.8 (1.1)
SG20	M	28.3 (1.7)	43.0 (3.3)	50.6 (3.6)	36.8 (2.3)	48.1 (2.4)	49.6 (3.4)	34.6 (0.2)	42.8 (0.7)	46.0 (1.0)
SF10	M	35.9 (2.3)	47.8 (2.5)	54.9 (0.1)	38.6 (1.2)	49.6 (1.6)	56.1 (0.4)	41.5 (2.7)	45.7 (1.1)	51.3 (1.5)
SF20	M	35.6 (1.0)	46.5 (1.7)	57.7 (1.3)	41.5 (2.1)	52.3 (1.5)	57.5 (2.8)	43.5 (1.9)	51.1 (2.5)	51.8 (0.7)
	7DM		51.7 (1.4)	53.6 (5.2)		47.3 (1.0)	55.9 (5.7)		49.6 (6.3)	51.6 (4.8)
SF30	M	31.2 (2.9)	44.0 (0.4)	49.8 (2.2)	38.9 (5.4)	55.0 (3.6)	56.9 (2.3)	41.5 (2.8)	55.4 (4.9)	46.5 (0.9)
SSF10	M	34.6 (0.6)	51.6 (1.4)	58.6 (2.8)	-	-	-	-	-	-
SSF20	M	34.7 (0.9)	45.7 (2.5)	59.7 (1.0)	-	-	-	-	-	-
SSF30	M	36.8 (1.7)	45.9 (2.0)	58.0 (0.9)	-	-	-	-	-	-
SF10FA10	M	33.6 (2.2)	42.7 (0.3)	57.7 (4.2)	40.3 (1.6)	51.1 (1.8)	64.9 (1.2)	46.1 (3.1)	48.8 (2.0)	57.5 (1.1)

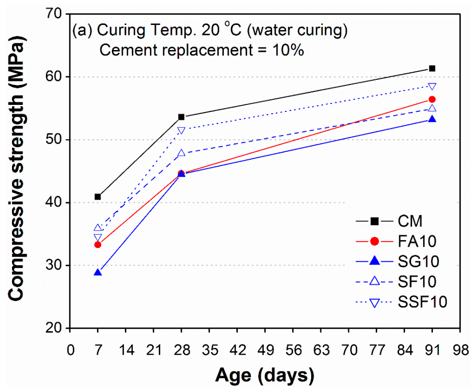
* Continuous moist-cured. ** Exposed to air at relative humidity of 60% after the initial seven days of moist curing (7DM). *** Standard deviation values indicated in parenthesis.

3.3.1. Influence of Cement Substitution with EAFS

A brief comparison of compressive strength of mortar containing different amounts of EAFS with those of CM and reference FA mortar is shown in Figure 8. The SG was used up to 20%, and the SF and SSF up to 30% of cement substitute. Results of a ternary blend of 20% cement substitution (SF10 + FA10) are presented in Figure 8b to compare it with those of corresponding binary mixes SF20, and reference FA20. All the specimens were subjected to standard curing (water cured at 20 °C) until the age of testing.

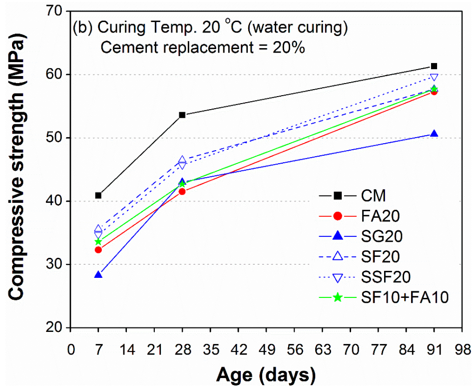
All cement substituted mortars demonstrated compressive strength lower than CM at all ages (Figure 8a–c) especially at early ages. The slow reactivity especially in FA was also confirmed by past research, according to which FA possess little pozzolanic activity and appeared to increase the mortar non-evaporable water content at early days [48,49]. According to Hanehara et al. [49], the pozzolanic reaction of FA in the hardened cement paste cured at 20 °C begins at the age of 28 days. However, according to expectation the influence of FA and EAFS was noticeable at later-ages especially at 91 days, which is due to their pozzolanic nature. According to previous research [50,51], the pozzolanic reaction of FA and slag mortars increased with aging as it reduces the permeability in concrete, thus leads to lower chloride ingress and steel corrosion than normal concrete. The lowest compressive strength was recorded against SG at all ages, which however, produced comparable to FA at 10% substitution (Figure 8a). Further reduction in strength particularly at later-ages (Figure 8b) prevents utilization of SG in higher amounts such as 20% or more. It was found earlier by Barnett [52] that, under standard curing conditions, the rate of strength gain in slag mortar remained slower than cement. Interestingly, mortars having SF and SSF up to 20% cement substitution exhibited comparatively better results as compared to corresponding FA mortars with similar cement substitutions (Figure 8a,b). As shown in Figure 8b, the ternary blend of SF and FA (20% cement substitution as SF10 + FA10) also demonstrated comparable or better results than corresponding FA mortar (FA20). Furthermore, Figure 8c demonstrates quite convincing results against 30% cement substitution with SSF as compared to 20% cement substitution with FA. This enhancement of compressive strength in SSF mortars must be due to its high fineness as compared to SF and FA as high fineness usually lead to accelerated early-age hydration reaction between slag and cement clinker and the later-age pozzolanic reaction.

Consequently, the results clearly emphasize the important role of EAFS in strength development as compared to commercially available FA. The results clearly indicated that the amount of EAFS (lesser or higher) as a cement substitute should be calculated according to its fineness level. Despite of its slight strength losses as compared to CM, a 10%, 20%, and 30% cement substitution with SG, SF, and SSF, respectively, may preferably be employed in construction as an alternative of FA. This would be useful in many ways in perspective of economy because of its local availability as compared to imported FA, environmental safety by bringing a wasteful material into a useful commodity, and preserving of natural resources.



(a)

Figure 8. *Cont.*



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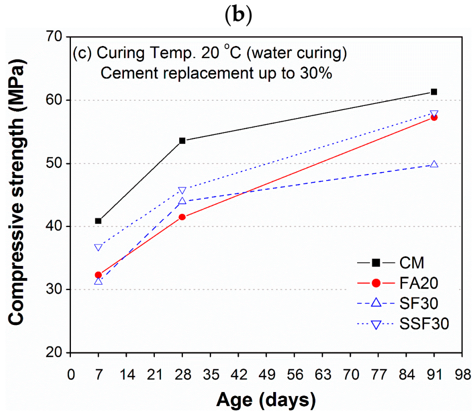


(**c**)

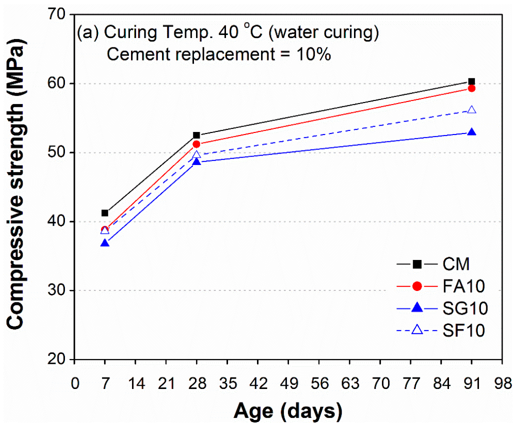
Figure 8. Strength development of mortar containing EAFS w.r.t. fineness (SG, SF, and SSF) and percent cement replacement, and its comparison with control and reference fly ash mortar: (**a**) 10%; (**b**) 20%; and (**c**) 30% cement substitution.

3.3.2. Influence of Curing Temperature and Its Comparison with CM and Reference FA Mortar

Under standard moisture and temperature curing conditions, the strength of mortar containing FA or EAFS was lower than CM especially at early-ages. As mentioned earlier in preceding section, despite of lowered strengths, there are several other benefits of using these materials in construction under different circumstances. In view of established fact that the reactivity of cementitious and pozzolanic materials enhanced under high curing temperatures [48,49,53,54], authors investigated the influence of different high curing temperatures (40 and 60 °C) on mortar containing FA and EAFS (SG and SF) and compared their results with those of standard curing. Such high curing temperatures were chosen considering the hot summer season in most parts of eastern Saudi Arabia where temperature rises to more than 50 °C.

Figures 9 and 10 show the comparison of results of different amounts of EAFS with those of CM and mortar containing FA according to different curing temperatures such as 40 and 60 °C, respectively. It was found that the strength of mortar containing FA and EAFS increased significantly when subjected to moderate curing temperature (Figure 9). It was revealed by Hanehara et al. [49] that the pozzolanic reaction largely depends upon the temperature. For instance, the pozzolanic reaction of FA in the hardened paste cured at 40 °C has started quite earlier (at the age of seven days) as compared to those cured at 20 °C where it started at 28 days [49]. In the case of mortars containing slag (SG and SF), the strength was enhanced only for SF corresponding to 20% and 30% cement substitution. These results were also confirmed by other research according to which slag mortar and concretes showed significantly greater resistance to chloride ingress by reducing chloride permeability and diffusion coefficients [48,51,53,54]. A 10% cement substitution with SF and 10–20% cement substitution with SG produced lower strength than CM and reference FA mortar. Moreover, their strength decreased further when curing temperature increased from 40 to 60 °C (Figure 10a,b). The current results revealed that the cement substitution with SF can be used successfully up to 20% for casting under moderately and high curing temperatures (water cured at 40 and 60 °C) as it produced strength comparable to CM at all ages, except slightly lower at 91 days (Figures 9b and 10b). Moreover, unlike standard curing (Figure 8c), current results also revealed that the cement substitution with SF up to 30% may also be adopted for casting under moderately high curing conditions (water cured at 40 °C) as it produced strength comparable to CM at all ages except slightly lower at 91 days (Figure 9c). While, under high curing temperature of 60 °C it produced significantly lower strength at 91 days, which consequently, restricting it to be substituted by 20% (Figure 10c) for casting under high temperature curing (water cured at 60 °C). Furthermore, the ternary blend of SF and FA (20% cement substitution as SF10 + FA10) has proven its significance as it demonstrated comparable 7 and 28 days strength to CM and better than CM and reference FA mortar (FA20) at 91 days (Figures 9b and 10b). Similar results were reported by Ortega et al. [51,55] as they found that the combined high relative humidity and high temperature produced more refined microstructure, thus leading to an increase in strength and improve durability properties of mortars containing FA and BFS.

The above discussion revealed that the rate of strength development and the ultimate strength values w.r.t. curing temperatures varied between control mortar and those containing EAFS and reference pozzolanic material FA. This can be attributed to different cementitious and pozzolanic potentials of these materials along with their different filling/packing effects because of different fineness. At early ages, a high temperature reduces the initial porosity of mortars containing slag due to accelerated hydration between clinker and slag [53,56].



(a)

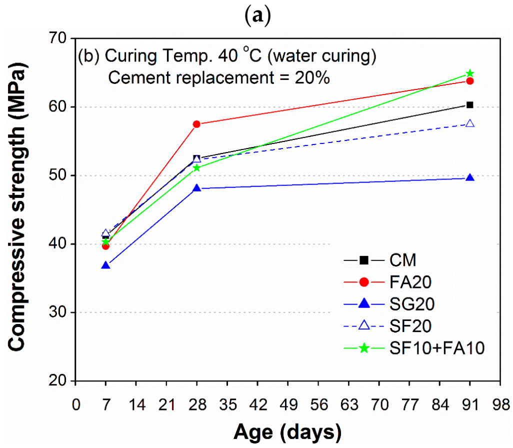


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Figure 9. *Cont.*

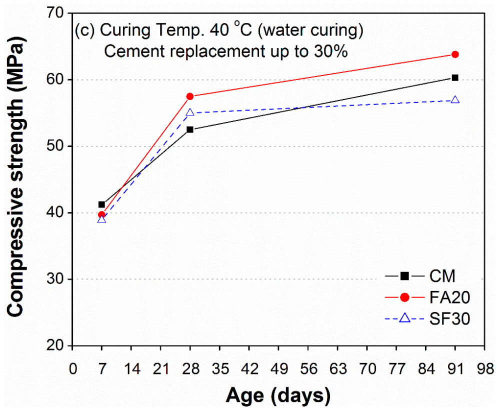

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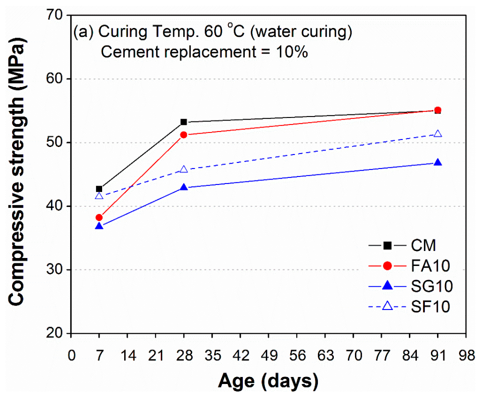
Figure 9. Influence of moderately high curing temperature (40 °C) on compressive strength of mortar containing EAFS (SG and SF) and its comparison with control and reference fly ash mortars: (**a**) 10%; (**b**) 20%; and (**c**) 30% cement substitution.

Control mortar subjected to high curing temperature after casting attained higher early and lower later-age compressive strength. Similar results were observed by other research in the past [48]. More and less similar trends were observed in mortars containing cement substitution with different fineness and amounts of EAFS and FA. According to the results of past investigations, the higher curing temperatures result in a coarser pore structure, thus reduce the long-term strength of concrete [57]. The high early and low later-age compressive strength with increasing temperature is known as "crossover effect" [58].



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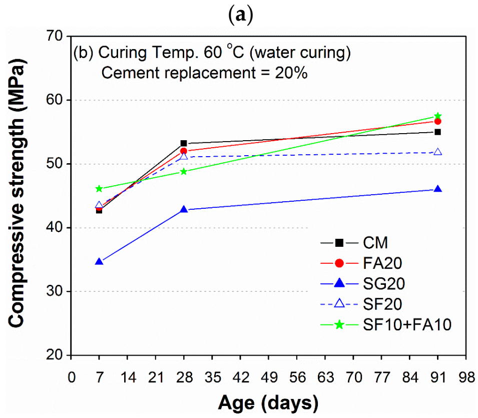

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Figure 10. *Cont*.

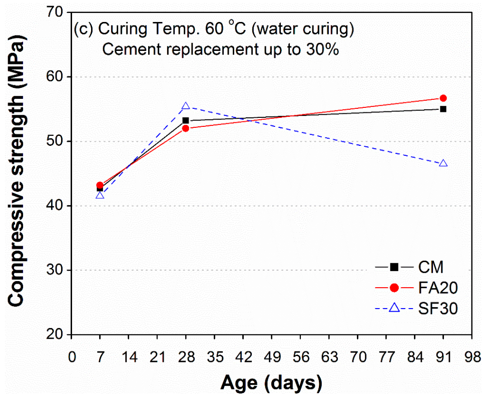

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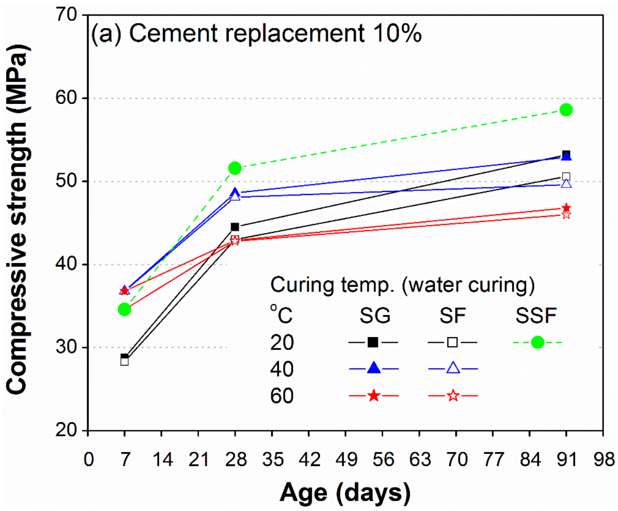
Figure 10. Influence of high curing temperature (60 °C) on compressive strength of mortar containing EAFS (SG and SF) and its comparison with control and reference fly ash mortars: (**a**) 10%; (**b**) 20%; and (**c**) 30% cement substitution.

The cross-over effect of temperature was clear in mortars containing EAFS, therefore, the influence of different curing temperatures can be predicted easily for its application under hot environmental conditions. Authors recommend that current research be extended to evaluate temperatures effects on concrete and propose new prediction models incorporating curing temperature effects to estimate different mechanical and durability properties of concrete.

3.3.3. Influence of Fineness of EAFS (SG, SF, and SSF) w.r.t. Aging and Curing Temperature

This section presented the influence of fineness of EAFS on compressive strength w.r.t. aging and curing temperatures (continuous moist at 20, 40, and 60 °C). For comparison, results of three different fineness levels of EAFS were used (SG, SF, and SSF). Figure 11 shows that different fineness of slag demonstrated different rates and ultimate compressive strengths. The difference in compressive strength w.r.t. fineness from SG to SF was found as insignificant at 10% cement substitutions (Figure 11a) regardless of the curing temperature, particularly at early-ages of 7 and 28 days. This, however, slightly increased with aging for normal to moderately high (20 and 40 °C) curing temperatures. Moreover, this difference further increased with increasing fineness from SF to SSF at all ages. This could be due to more refined pore structure of high fineness SSF and its accelerated hydration reaction with cement clinker [53,56]. A clear cross-over effect of temperature was observed between 7 days and 91 days [58], according to which moderate and high curing temperatures led to high early and lower later-age strength and vice versa for low or normal curing temperature.

The trend and the strength developments w.r.t. fineness was different for 10%, 20% and 30% cement substitutions (Figure 11a–c). Unlike 10% substitution, a significant increase of compressive strength was observed against 20% cement substitution with increasing fineness irrespective of aging (Figure 11b), especially under moderate as well as high curing temperatures. The cross-over effect of temperature was similar to that of 10% substitution, and the highest 91 days strength was observed corresponding to 20% cement substitution with SSF (59.7 MPa), which is slightly less than CM (61.3 MPa).



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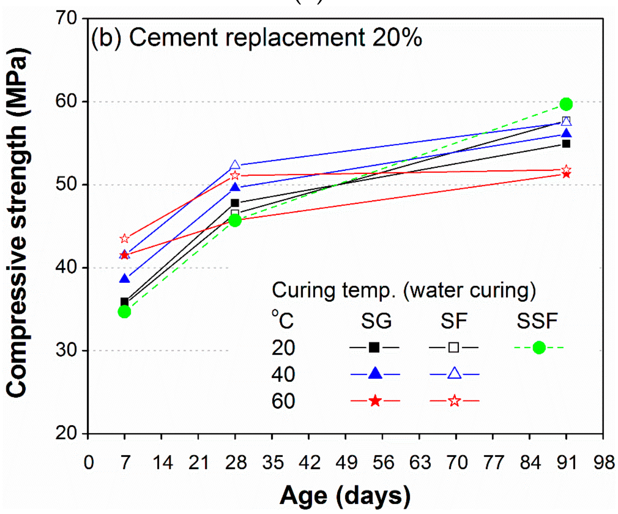

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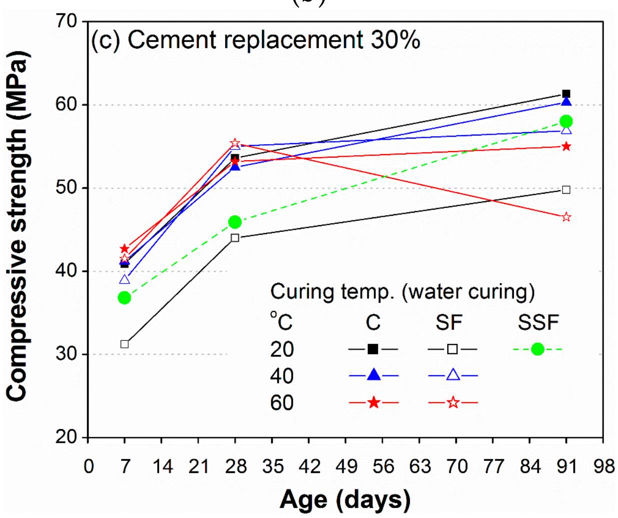

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Figure 11. Comparison of compressive strength development of mortar w.r.t. fineness of EAFS, and curing temperature: (**a**) 10%; (**b**) 20%; and (**c**) 30% cement substitution.

Based on the previous results of 10% and 20% cement substitution, authors also investigated the influence of 30% substitution for high fineness slag (SF and SSF) and a direct comparison was made with results of CM (Figure 11c). Comparison of results indicated that higher cement substitution with EAFS (30%) led to significant strength loss at all ages under normal curing conditions (water cured at 20 °C). However, this loss was minimized by increasing fineness from SF to SSF at all ages, especially at 91 days, as it reached close to that of CM (58 MPa as compared to 61.3 MPa of CM). Despite of negative impacts of high substitutions, a significant improvement in rate of strength gain was observed under moderately high (40 °C) and high curing temperatures (60 °C) particularly at 7 and 28 days. This is due to accelerated hydration reaction under high curing temperatures at early-ages because of increased surface area of EAFS. The results indicating that the pozzolanic reaction of slag was favored by the higher temperatures at early ages. Similar results were reported by others as they found maximum consumption of CH content in slag cements at early days and little or no change in CH content after seven days [59]. The strength dropped significantly at 91 days with increasing curing temperature because of cross-over effect of temperature and the maximum loss occurred corresponding to curing at 60 °C. As mentioned earlier, the continuous higher curing temperatures result in a coarser pore structure, thus reduce the long-term strength of concrete [57].

Consequently, the current results suggest that the fineness of EAFS plays important role in strength development of mortars. A 10% cement substitution with SSF can be used successfully, as it demonstrated better strength comparable to CM under normal curing conditions (Figure 11a). Its higher substitutions (20% and 30%) also produced comparable 91 days strength to CM. Moreover, a 20% and 30% cement substitutions with SF be used to attain comparatively better strength results under moderately high curing temperature (40 °C). A significant strength loss under high curing temperature of 60 °C suggesting not to use EAFS. However, research should be further extended to study the effect of moderate and high curing temperatures on strength development of mortar containing SSF up to 30% or more.

3.3.4. Comparison of Influence of Continuous and Partial Moist Curing on Compressive Strength of CM, FA20, and SF20

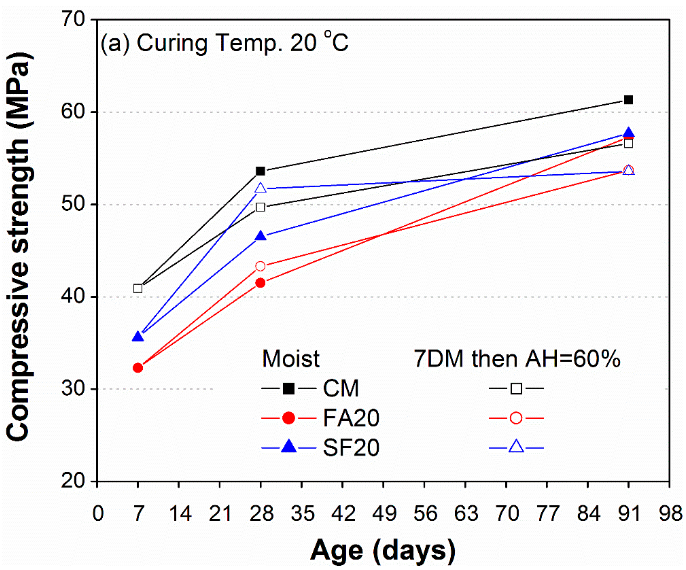
This section presents the compressive strength results between different mortars (control, 20% FA and 20% SF) subjected to standard laboratory curing such as continuous moist curing (CMC) and practice oriented curing also known as partial moist curing (PMC) where specimens were exposed to air at relative humidity of 60% after the initial seven days of moist curing (7DM). Along with different moisture conditions, effect of normal to high-range curing temperatures (20, 40, and 60 °C) was also incorporated. Identical specimens were cast for CM, mortars containing 20% FA (FA20) and 20% SF (SF20). All the specimens were subjected to above curing conditions until their testing age. A brief comparison of results for CM, FA20, and SF20 w.r.t. aging, curing moisture and temperatures is present in Figure 12. It is worth noting that the purpose of this comparison is to evaluate whether EAFS has the potential to be used as an alternative of popular pozzolanic material FA under different seasonal conditions without compromising the target compressive strength.

The compressive strength of CM was significantly reduced under PMC as compared to CMC at both 28 and 91 days (Figure 12a). However, this trend was different in mortars containing FA20 and SF20 than CM as they demonstrated slightly increased 28 days strength under PMC as compared to CMC and vice versa at 91 days. The decrease of later age strength under PMC (low humidity) was also confirmed by other research [60,61]. Moreover, it seems that the microstructure of cement was more influenced by relative humidity as compared to mortars containing FA and SF [56]. The higher 7 and 28 days strength of SF20 as compared to FA20 could be because of its high surface area which increased the rate of hydration reaction between slag and cement clinker.

Interestingly, 91 days strengths of SF20 and FA20 were identical irrespective of type of moisture curing. Moreover, their 91 days strength under CMC was identical to that of CM subjected to PMC which indicated that strength of mortars containing EAFS could be improved by applying moist curing for a longer period of time. This could be attributed to enhanced microstructure of slag mortars as more water was available under CMC to develop the clinker and slag hydration reactions [56]. Availability of more water under CMC also improves the capillary absorption properties and the resistance to chloride aggressive ingress in slag mortars [51,53].

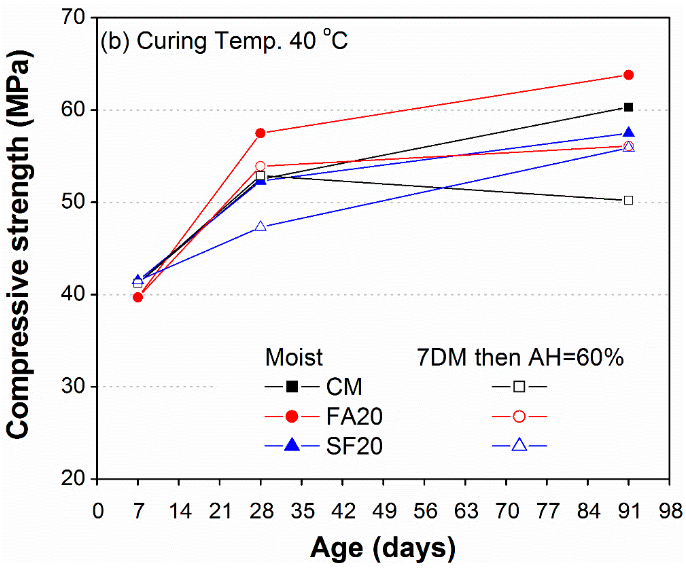
Unlike standard temperature curing (20 °C), the compressive strength of mortars (CM, SF20, and FA20) subjected to moderately high curing temperature (40 °C) reduced significantly under PMC as compared to CMC at both 28 and 91 days (Figure 12b). Very similar results were observed by other research in the past [61,62]. The trend of reducing strength was similar in all mortars and this reduction increased further with aging. No strength loss was observed in CM at 28 days, which however demonstrated maximum reduction at 91 days followed by FA20 and SF20. From results, it seems that the microstructure of mortar matrix can be influenced more under high environmental temperatures as compared to relative humidity [56]. Under high relative temperature, this can be related to formation of shrinkage microcracks caused by drying in a low relative humidity environment [53,60]. Interestingly, 91 days strengths of SF20 and FA20 under PMC were identical and at the same time higher than CM. As mentioned earlier, this might be due to their more refined pore structure than CM containing only cement [53,56]. Similar to moderately high curing temperature, the maximum strength reduction under PMC at high curing temperature (60 °C) was also observed in CM at both 28 and 91 days (Figure 12c). However, the strength loss was negligible in SF20 mortar and identical 91 days strengths were observed for all mortars (CM, SF20, and FA20) when subjected to PMC.

According to current findings, application of CMC is essential to attain the full potential strength with aging regardless of the curing temperatures (normal or high) and the type of cement substituting materials (FA or EAFS). The current results were confirmed by other research [62]. However, it must be un-economical or impractical to apply CMC up to 28 and 91 days especially under relatively high curing temperatures. Alternatively, use of SF up to 20% cement substitution subjected to PMC under moderately high and high temperatures conditions must be beneficial. According to current study, PMC strictly means exposing to air under 60% relative humidity after initial seven days of continuous moist curing. Therefore, authors suggest extending current research to study the influence of more wide range of curing regimes and high percentage replacements of cement with SF and SSF.

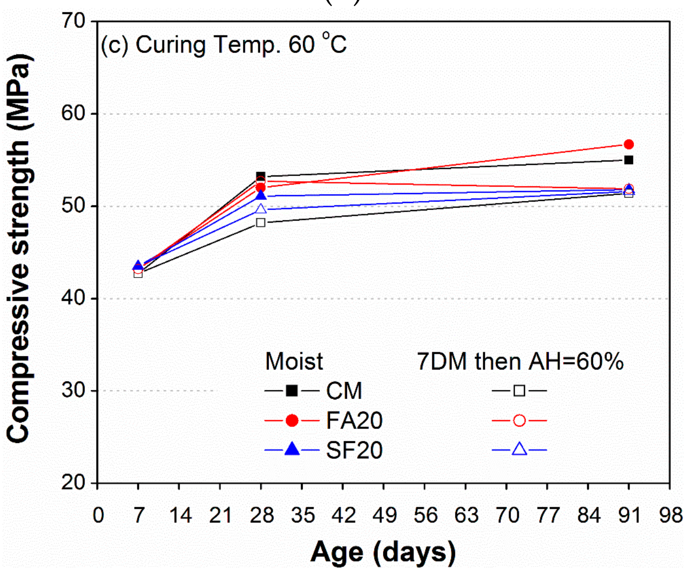


(a)

Figure 12. *Cont.*



(**b**)



(**c**)

Figure 12. Effect of partial and continuous moist curing on compressive strength of mortar containing 20% SF under different curing temperatures and its comparison with control and reference mortar containing 20% FA: (**a**) 20 °C; (**b**) 40 °C; and (**c**) 60 °C.

4. Conclusions

Influence of fineness of locally available EAFS on compressive strength of mortar was investigated in this study. Three different fineness levels of EAFS such as slag ground (SG), slag fine passing sieve #200 (SF), and slag super fine passing sieve #325 (SSF) were considered. For each fineness, cement was substituted up to 30%, while it was substituted up to 20% in the case of SG and in reference mortars containing fly ash (FA). The purpose of casting the reference FA mortar was to compare the results of commercially available pozzolana with those of locally available materials. The tests were conducted w.r.t. aging and different curing conditions of temperature and moisture (continuous moist and partially moist). Different curing temperatures (20, 40, and 60 °C) were selected to incorporate the seasonal effects of normal as well as hot local environmental conditions. Finally, the characteristics of EAFS and its strength activity index values were calculated according to ASTM C311 and compared to slag activity index of BFS Grade 80 and Grade 100 as specified in ASTM C989. A comparison of results between mortar containing EAFS with those of control and reference FA mortar was presented. According to the results, the following main conclusions were drawn from this study:

- Results indicated that the compressive strength of mortar subjected to standard curing (water cured at 20 °C) remained lower in all mortars containing EAFS or FA than that of CM. However, the strength activity index of mortars containing EAFS was comparatively better than BFS Grade 80. Moreover, the strength activity index of SSF up to 10% cement substitution was better than BFS Grade 100. Such results clearly emphasizing the important role of EAFS as cementitious and pozzolanic material to be used as binder of concrete like BFS.
- Result indicated that the compressive strength increased with increasing fineness of EAFS. Interestingly, the trend of strength development in mortar containing EAFS was turned out better as compared to commercially available FA. Therefore, despite slightly reduced strength as compared to CM, results suggest that 10%, 20%, and 30% cement substitution with SG, SF, and SSF, respectively, may preferably be employed in concrete as an alternative of FA.
- Strength of mortars having SG or 10% SF decreases with increasing curing temperature. However, a 20–30% and 20% cement substitution with SF produced strength close to control and reference FA mortar under moderate (40 °C) and high curing temperature (60 °C), respectively. The above results can be attributed to increased hydration reaction and high pozzolanic reactivity of high fineness EAFS (SF).
- Mortar without cement substitution attained higher early and lower later-age compressive strength when subjected to high curing temperature after casting. Very similar trends were also observed in mortars containing different fineness and amounts of EAFS and FA. The high early and low later-age compressive strength with increasing temperature is known as "crossover effect" [58]. Since the cross-over effect of temperature was clear in mortars containing EAFS, the influence of different curing temperatures can be predicted easily for its application under hot environmental conditions.

The maximum potential compressive strength was attained when specimens were continuously moist cured (CMC), irrespective of the curing temperature and the type of cement substituting materials, FA or EAFS. However, it must be un-economical or impractical to apply continuous moist curing up to 28 and 91 days especially under high curing temperatures. Alternatively, use of SF up to 20% cement substitution subjected to partial moist curing (i.e., exposing to air at 60% relative humidity after initial seven days of continuous moist curing) under moderately high and high temperature conditions must be beneficial. Therefore, authors suggest extending the current research to study the influence of more wide range of curing regimes and high percentages of cement substitution with SF and SSF.

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References

1. Humphreys, K.; Mahasenan, M. *Toward a Sustainable Cement Industry: Climate Change*; Substudy 8; World Business Council for Sustainable Development (WBCSD): Geneva, Switzerland, 2002.
2. Klee, H. *The Cement Sustainability Initiative: Recycling Concrete*; World Business Council for Sustainable Development (WBCSD): Geneva, Switzerland, 2009.
3. U.S. Department of the Interior USGS. *Mineral Commodity Summaries 2016*; U.S. Geological Survey: Reston, VA, USA, 2016.
4. IEA-WBCSD, Cement Technology Roadmap 2009—Carbon Emissions Reductions up to 2050. Available online: https://www.iea.org/publications/freepublications/publication/Cement.pdf (accessed on 5 January 2017).
5. Gartner, E. Industrially interesting approaches to low-CO_2 cement. *Cem. Concr. Res.* **2004**, *34*, 1489–1498. [CrossRef]
6. Ogbeide, S.O. Developing an optimization model for CO_2 reduction in cement production process. *J. Eng. Sci. Technol. Rev.* **2012**, *3*, 85–88.
7. Yang, K.H.; Jung, Y.B.; Cho, M.S.; Tae, S.H. Effect of supplementary cementitious materials on reduction of CO_2 emissions from Concrete. *J. Clean. Prod.* **2017**, *103*, 774–783. [CrossRef]
8. Mehta, P.K.; Monteiro, P.J.M. *Concrete: Microstructure, Properties, and Materials*, 4th ed.; McGraw-Hill: Berkeley, CA, USA, 2006.
9. Tomkins, C.D. *Gigaton Throwdown: Redefining What's Possible for Clean Energy by 2020*; Gigaton Throwdown: San Francisco, CA, USA, 2009.
10. Xu, G.; Tian, Q.; Miao, J.; Liu, J. Early-age hydration and mechanical properties of high volume slag and fly ash concrete at different curing temperatures. *Constr. Build. Mater.* **2017**, *149*, 367–377. [CrossRef]
11. Dadsetan, S.; Bai, J. Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash. *Constr. Build. Mater.* **2017**, *146*, 658–667. [CrossRef]
12. Siddique, R. Utilization of silica fume in concrete: Review of hardened properties. *Resour. Conserv. Recycl.* **2011**, *55*, 923–932. [CrossRef]
13. Kim, J.; Yi, C.; Zi, G. Waste glass sludge as a partial cement replacement in mortar. *Constr. Build. Mater.* **2015**, *75*, 242–246. [CrossRef]
14. Amin, M.N.; Khan, K.; Saleem, M.U.; Khurram, N.; Niazi, M.U.K. Aging and Curing Temperature Effects on Compressive Strength of Mortar Containing Lime Stone Quarry Dust and Industrial Granite Sludge. *Materials* **2017**, *10*, 642. [CrossRef]
15. Kim, S.Y.; Jun, Y.; Jeon, D.; Oh, J.E. Synthesis of structural binder for red brick production based on red mud and fly ash activated using $Ca(OH)_2$ and Na_2CO_3. *Constr. Build. Mater.* **2017**, *147*, 101–116. [CrossRef]
16. Colangelo, F.; Messina, F.; Palma, L.D.; Cioffi, R. Recycling of non-metallic automotive shredder residues and coal fly-ash in cold-bonded aggregates for sustainable concrete. *Compos. Part B Eng.* **2017**, *116*, 46–52. [CrossRef]
17. Colangelo, F.; Cioffi, R. Use of cement kiln dust, blast furnace slag and marble sludge in the manufacture of sustainable artificial aggregates by means of cold bonding pelletization. *Materials* **2013**, *8*, 3139–3159. [CrossRef]
18. Suh, J.; Jeon, D.; Yoon, S.; Oh, J.E.; Park, H.G. Development of strong lightweight binder matrix for lightweight concrete simply by increasing a water-to-binder ratio of cementless fly ash binder activated with $Ca(OH)_2$ and Na_2CO_3. *Constr. Build. Mater.* **2017**, *152*, 444–455. [CrossRef]
19. Yildirim, I.Z.; Prezzi, M. Chemical, mineralogical, and morphological properties of steel slag. *Adv. Civ. Eng.* **2011**, *2001*, 1–13. [CrossRef]
20. Sofilic, T.; Sofilic, U.; Brnardic, I. The significance of iron and steel slag as by-product for utilization in road construction. In Proceedings of the 12th International Foundrymen Conference, Sustainable Development in Foundry Materials and Technologies, Opatija, Croatia, 24–25 May 2012.

21. Bialucha, R.; Merkel, T.; Motz, H. European environmental policy and its influence on the use of slag products. In Proceedings of the 2nd International Slag Valorisation Symposium, Leuven, Belgium, 18–20 April 2011; Jones, P.T., Ed.; Katholieke Universitat: Leuven, Belgium, 2011; pp. 201–213.
22. Global Slag. Available online: www.globalslag.com/conferences/global-slag/review/global-slag-review-2016 (accessed on 22 January 2017).
23. Khan, M.I.; Alhozaimy, A.M. Properties of natural pozzolan and its potential utilization in environmental friendly concrete. *Can. J. Civ. Eng.* **2011**, *38*, 71–78. [CrossRef]
24. Muhmood, L.; Vitta, S.; Venkateswaran, D. Cementitious and pozzolanic behavior of electric arc furnace steel slags. *Cem. Concr. Res.* **2009**, *39*, 102–109. [CrossRef]
25. Hekal, E.E.; Abo-El-Enein, S.A.; El-Korashy, S.A.; Megahed, G.M.; El-Sayed, T.M. Hydration characteristics of Portland cement—Electric arc furnace slag blends. *HBRC J.* **2013**, *9*, 118–124. [CrossRef]
26. ASTM C618-15. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society for Testing and Materials. Available online: www.astm.org (accessed on 22 January 2017).
27. ASTM C311-16. Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete. American Society for Testing and Materials. Available online: http://www.astm.org (accessed on 9 June 2017).
28. ASTM C109/C109M-16a. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). American Society for Testing and Materials. Available online: www.astm.org (accessed on 22 January 2017).
29. ASTM C989/C989M-16e1. Standard Specification for Slag Cement for Use in Concrete and Mortars. American Society for Testing and Materials. Available online: www.astm.org (accessed on 19 June 2017).
30. ASTM C150/C150M-16e1. Standard Specification for Portland Cement. American Society for Testing and Materials. Available online: www.astm.org (accessed on 22 January 2017).
31. EN 196-1: 2016. Methods of testing cement—Part 1: Determination of Strength. European Committee for Standardization. Available online: https://standards.cen.eu (accessed on 9 June 2017).
32. ISO 679: 2009. *Cement—Test Methods—Determination of Strength*; International Organization for Standardization: Geneva, Switzerland, 2009; Available online: https://www.iso.org/standard/45568.html (accessed on 9 June 2017).
33. ASTM C125-16. Standard Terminology Relating to Concrete and Concrete Aggregates. American Society for Testing and Materials. Available online: www.astm.org (accessed on 22 January 2017).
34. Khan, Z.A.; Malkawi, R.H.; Al-Ofi, K.A.; Khan, N. Review of steel slag utilization in Saudi Arabia. In Proceedings of the 6th Saudi Engineering Conference, Dhahran, Saudi Arabia, 14–17 December 2002.
35. Harsco Metals and Minerals. Available online: http://797691.vps-10.com/139/Zero-Waste-Saudi-Arabia.aspx (accessed on 22 January 2017).
36. Shi, C. Steel slag—Its production, processing, characteristics, and cementitious properties. *J. Mater. Civ. Eng.* **2004**, *16*, 230–236. [CrossRef]
37. ISO 13320:2009. *Particle Size Analysis—Laser Diffraction Methods*; International Organization for Standardization: Geneva, Switzerland, 2009; Available online: https://www.iso.org/standard/44929.html (accessed on 9 June 2017).
38. Boldyrev, V.V. Mechanical activation of solid and its application in technology. *J. Chem. Phys.* **1986**, *83*, 821–822. [CrossRef]
39. Sanjay, K.; Bandopadhyay, A.; Rajinikanth, V.; Alex, T.C.; Rakesh, K. Improved processing of blended slag cement through mechanical activation. *J. Mater. Sci.* **2004**, *39*, 3449–3452.
40. Patzelt, N. Finish grinding of slag. *World Cem.* **1993**, *24*, 51–57.
41. Purdon, A.O. The action of alkalis on blast-furnace slag. *J. Soc. Chem. Ind.* **1940**, *59*, 191–202.
42. Malhotra, V.M.; Mehta, P.K. *High-Performance, High-Volume Fly Ash Concrete*; Supplementary Cementing Materials for Sustainable Development, Inc.: Ottawa, ON, Canada, 2002.
43. Thomas, M.D.A. Optimizing Fly Ash Content for Sustainability, Durability, and Constructability. In Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy, 28–30 June 2010.

44. ASTM C305-14. Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. American Society for Testing and Materials. Available online: www.astm.org (accessed on 22 January 2017).
45. ACI Committee 232. *Use of Fly Ash in Concrete*; ACI 232.2R-96; American Concrete Institute: Farmington Hills, MI, USA, 1996.
46. Fathollah, S. Mechanical activation of cement–slag mortars. *Constr. Build. Mater.* **2012**, *26*, 41–48.
47. Fathollah, S.; Shafigh, P. Optimum level of replacement slag in OPC-slag mortars. *J. Civ. Eng. Archit.* **2010**, *4*, 11–19.
48. Maltais, Y.; Marchand, J. Influence of Curing Temperature on Cement Hydration and Mechanical Strength Development of Fly Ash Mortars. *Cem. Concr. Res.* **1997**, *27*, 1009–1020. [CrossRef]
49. Hanehara, S.; Tomosawa, F.; Kobayakawa, M.; Hwang, K. Effects of Water/Powder Ratio, Mixing Ratio of Fly Ash and Curing Temperature on Pozzolanic Reaction of Fly Ash in Cement Paste. *Cem. Concr. Res.* **2001**, *31*, 31–39. [CrossRef]
50. Chalee, W.; Ausapanit, P.; Jaturapitakkul, C. Utilization of fly ash concrete in marine environment for long term design life analysis. *Mater. Des.* **2010**, *31*, 1242–1249. [CrossRef]
51. Ortega, J.M.; Sánchez, I.; Climent, M.A. Influence of different curing conditions on the pore structure and the early age properties of mortars with fly ash and blast-furnace slag. *Mater. Constr.* **2012**, *63*, 219–234.
52. Barnett, S.J.; Soutsos, M.N.; Millard, S.G.; Bungey, J.H. Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies. *Cem. Concr. Res.* **2006**, *36*, 434–440. [CrossRef]
53. Ortega, J.M.; Sánchez, I.; Climent, M.A. Durability related transport properties of OPC and slag cement mortars hardened under different environmental conditions. *Constr. Build. Mater.* **2012**, *27*, 176–183. [CrossRef]
54. Thomas, M.D.A.; Scott, A.; Bremner, T.; Bilodeau, A.; Day, D. Performance of slag concrete in marine environment. *ACI Mater. J.* **2008**, *105*, 628–634.
55. Ortega, J.M.; Sánchez, I.; Antón, C.; De Vera, G.; Climent, M.A. Influence of environment on durability of fly ash cement mortars. *ACI Mater. J.* **2012**, *109*, 647–656.
56. Ortega, J.M.; Sánchez, I.; Climent, M.A. Impedance spectroscopy study of the effect of environmental conditions in the microstructure development of OPC and slag cement mortars. *Arch. Civ. Mech. Eng.* **2015**, *15*, 569–583. [CrossRef]
57. Detwiler, R.J.; Kjellsen, K.O.; Gjorv, O.E. Resistance to chloride intrusion of concrete cured at different temperatures. *ACI Mater. J.* **1991**, *88*, 19–24.
58. Alexander, K.M.; Taplin, J.H. Concrete strength, paste strength, cement hydration, and the maturity rule. *Aust. J. Appl. Sci.* **1962**, *13*, 277–284.
59. Escalante-García, J.I.; Sharp, J.H. Effect of Temperature on the Hydration of the Main Clinker Phases in Portland Cements: Part II, Blended Cements. *Cem. Concr. Res.* **1998**, *28*, 1259–1274. [CrossRef]
60. Çakir, Ö.; Aköz, F. Effect of curing conditions on the mortars with and without GGBFS. *Constr. Build. Mater.* **2008**, *22*, 308–314.
61. Mohd Zain, M.F.; Radin, S.S. Physical Properties of High-Performance Concrete with Admixtures Exposed to a Medium Temperature Range 20 °C to 50 °C. *Cem. Concr. Res.* **2000**, *3*, 1283–1287. [CrossRef]
62. Ramezanianpour, A.A.; Malhotra, V.M. Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash or silica fume. *Cem. Concr. Compos.* **1995**, *17*, 125–133. [CrossRef]