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Cementitious and pozzolanic behavior of electric arc furnace steel slags

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ABSTRACT

The cementitious and pozzolanic behavior of electric arc furnace steel slag, both as received and treated has been studied in detail. The as received slag was completely crystalline and multi-phasic with Fe-substituted monticellite as the predominant phase. Treatment of this slag, remelting and water quenching, results in reduction of Fe-oxide content coupled with an increase in basicity index which makes it more hydraulic compared to the as received slag. The remelted slag has several phases with merwinite as the dominant phase. Thermal analysis of the hydrated slag shows that treating the as received slag increases the water absorption capacity, a property essential for cementitious behavior. Compression strength of the slag blended cements was studied and it was found that substitution of 20% ground granulated blast furnace slag with electric arc furnace steel slag does not decrease the strength beyond 28 days. The control cement has a strength of 58.6 MPa compared to 58 MPa for the cement comprising of 20% untreated slag. The substitution of this untreated slag with treated slag exhibits the highest strength, 61 MPa and a potential for further strength increase after 28 days. In the case of cement mix with no blast furnace slag, substitution of 15% clinker with steel slag does not decrease the strength significantly, 64.4 MPa compared to 66.5 MPa for the control cement. Substituting 30% clinker in the cement mix with electric arc furnace slag however results in significant decrease in strength, 53.4 MPa. The pozzolanic strength of the slag was found to increase significantly due to remelting from 2.0 MPa for the as received slag to 8.0 MPa for the treated slag.

1. Introduction

Slag in general is a byproduct of various metals extraction and refining processes. In the specific case of making steels, the slag is generated at 3 different stages of processing and accordingly classified as: blast furnace slag, electric arc furnace slag and ladle slag. Among these the blast furnace slag constitutes the maximum tonnage with electric arc furnace slag coming close to the blast furnace slag. The blast furnace slag liquid when poured into water granulates and also becomes highly amorphous due to the high rate of cooling. Grinding the amorphous granules into a fine powder renders them highly active during the process of hydration in the presence of cement clinker and hence makes them suitable for the manufacture of blended cements [1]. The chemical composition of the granulated blast furnace slag is quite different compared to that of the cement clinker as seen from Table 1. It is however still used in the manufacture of blended cements because of its latent hydraulic activity and also the blended cements have been found to provide comparable compressive strengths [2–4].

The electric arc furnace slag (EAFS) on the other hand has a chemical composition more close to that of the cement clinker compared to the blast furnace slag as seen from Table 1. Hence recently it was shown to have potential application as partial substitute for raw materials in clinker production. Addition of up to ~20% EAFS in the kiln feed was found to improve burnability index of the raw material mix [5]. It is however not used in the manufacture of blended cements because of its lack of hydraulic or pozzolanic activity [6–8]. The high Fe-oxide content coupled with the highly crystalline nature of the slag are proposed to be the reasons for its chemical inactivity during the process of hydration in the presence of clinker or lime. Hence the EAFS is used mainly as aggregates for landfills and roads [9–11]. The electric arc furnace technology facilitates recycling of steel scrap but also leads to production of EAFS. Due to increasing contribution of electric arc furnace made steel to the total quantum of steel produced, the EAFS quantity is increasing annually. This is far in excess of the requirement for landfills and aggregates and is leading to unused EAFS production. Hence the objective of our work has been to find alternate uses for EAFS and in this context the cementitious and pozzolanic properties of both as received and treated slag have been investigated. The as received slag is made by cooling the electric arc furnace steel liquid slag in air at the industrial production site. This as received slag was subjected to a remelting treatment followed by quenching into a pool of water. This was done in order to increase the amorphous content which will have a hydraulic behavior, as found in the case of blast furnace slag. The chemical composition, microstructure and phase analysis of the slag both before and after treatment was studied by X-ray fluorescence, scanning electron microscopy and X-ray diffraction. The various tests to characterize

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Table 1
Typical composition range of the major oxides found in clinker, ground granulated blast furnace slag (GGBFS) and electric arc furnace slag (EAFS)

Mineral	Blast furnace slag (wt.%)	Clinker (wt.%)	EAF slag (wt.%)
SiO_2	35–39	21–27	8–18
Al_2O_3	8–12	5–8	3–10
Fe_{TOT}	<1	2–5	20–30
CaO	36–42	57–66	25–35
MgO	4–12	1–4	3–9
SO_3	2–3	<3	<0.5
Na_2O	0.32	0.3	<0.1
K_2O	0.57	0.8	<0.1

the cementitious and pozzolanic behavior of the slag were performed as per industrial standards and the results are discussed in correlation to the microstructure.

2. Experimental methods

The electric arc furnace steel slag investigated in the present work was obtained from an integrated steel plant located in Western India. After removing from the electric arc furnace, the liquid slag was cooled by a combination of spraying water and air. This as received slag from the steel plant was melted again in a graphite crucible by induction heating in the laboratory. It was held for about 10 mins. in the liquid state before quenching by pouring into stationary water. Typically, the volume of water is about 10 times the volume of the melted slag and this ensures a relatively high cooling rate. The granulated slag obtained after quenching was dried, crushed and powdered to completely pass through # 200 sieve, <75 μm. This powder was used for structural characterization as well as cementitious and pozzolanic behavior testing. Compositional analysis was performed by X-ray fluorescence while the phases present and microstructure were investigated by X-ray diffraction and scanning electron microscopy respectively. The X-ray diffraction was performed using Cu Kα radiation and the electron microscopy was done with an accelerating voltage up to 25 kV. The X-ray diffraction patterns were analyzed using the X-pert Highscore Plus program to determine the various phases present. Since the EAFS, clinker and the hydration products have multiple phases with the possibility of non-stoichiometric composition in some of the phases, a more detailed quantitative analysis is not undertaken. The cementitious and pozzolanic characteristics of the slag powder and slag blended cements were determined using the standard industrial tests. Both the untreated and treated slags were ground in a laboratory ball mill to a fineness of ~ 400 $m^2\ kg^{-1}$ to investigate the hydraulic behavior. Briefly, the hydration test was performed using deionized water to cementitious material ratio of 0.5 and for different durations of time, 3, 7, 14, up to 28 days. These samples were kept in polyethylene jars for hydration testing. The hydration process was stopped by rinsing with acetone and drying after specific periods. The pH of the supernatant solution was measured using a standard pH meter. The consistency and setting time of the pastes were determined using the Vicat needle apparatus at 27±2 °C and a relative humidity of 65±5% [12–17]. The consistency of the cement paste is defined as that which will permit the Vicat plunger to penetrate to a point 5 to 7 mm from the bottom of the Vicat mould. The initial and final setting times are also measured using the same Vicat plunger and mould as per standard criteria. The compression strength of the cast cubic blocks of size 70.6 mm was determined using standard methods at specified conditions.

3. Results and discussion

The water quenched electric arc furnace slag has a physical appearance which is partly granular and partly flaky. After drying to remove the moisture, it was crushed to pass through a # 6 sieve. The grindability of this crushed powder was determined as per standard procedure using the Bond mill with steel balls as the grinding media [16]. The amount of energy required to grind a material to pass through # 200 sieve gives an estimate of the grindability. The grindability of as received EAFS together with that of the clinker is given in Table 2 and it can be seen that it is higher compared to the clinker. This indicates that EAFS is less friable and hence requires more energy to grind to the same size as that of the clinker powder. The energy required to grind the melted and quenched slag is lower, 21.5 kWh ton^{-1}, compared to that required to grind the as received slag, 32.3 kWh ton^{-1}. The specific gravity, measured by a helium pycnometer, on the other hand is nearly same for the clinker and treated slag while it is higher for the untreated or as received slag. These results show that the grindability as well as the specific gravity depend on the chemical composition and phase mixture present in the different materials. The chemical composition of both the clinker and the slag was determined by X-ray fluorescence and the results are given in Table 2. The chemical composition of slag, as received untreated and treated, is compared to that of the clinker. The CaO content in the clinker is approximately twice that in the slag, 30.8 wt.%, while the MgO content in clinker is very low, 2.1 wt.% compared to 12 wt.% in untreated slag and 21.4 wt.% in the treated slag. The Fe-oxide present in the untreated slag reduced drastically from 24.1 wt.% to 1.2 wt.% due to melting and this leads to an apparent increase in MgO content in the slag. The FeO/Fe_2O_3 present in the as received slag reacts with carbon of the graphite crucible during melting and the resulting reduction reactions can be written as;

$$C + 2(FeO) \rightarrow 2[Fe] + \{CO_2\}$$

$$3C + 2(Fe_2O_3) \rightarrow 4[Fe] + 3\{CO_2\}$$

The Fe metal formed by the above reactions which is very heavy could be easily recovered from the quenched slag due to the large density difference and phase separation. The hydraulic nature of cementitious materials depends on its basicity index which is the ratio of basic oxides to acidic oxides. This basicity index of the clinker vis-à-vis the two EAFS and also the blast furnace slag is shown in Fig. 1 in a ternary representation with acidic oxides, basic oxides and Fe-oxide forming the 3 vertices. It can be clearly seen from Fig. 1 that clinker and treated slag are close to each other with basicity index of 2.76 and 1.88 respectively compared to 1.64 for the untreated slag and 1.18 for the ground, granulated blast furnace slag (GGBFS). Treating the as received slag reduces the Fe-oxide content leading to an increase in basicity index and thus rendering it more hydraulic compared to both untreated EAFS and blast furnace slag. The basicity index is only one of the parameters which indicate the hydraulic nature of a cementitious material. The cementitious behavior however also depends on the phases present within the chemical composition space. Hence in order to determine the different phases present, X-ray diffraction was performed on all 3

Table 2
The chemical composition, wt.%, and physical parameters of clinker, GGBFS and EAFS used in the present work

	Clinker	Untreated EAFS	Treated EAFS	GGBFS
Al_2O_3	5.5	6.1	5.9	20.3
CaO	65.7	30.8	38.8	31.7
Free CaO	1.4	0.4	0.1	0.1
FeO/Fe_2O_3	3.6	24.1	1.2	0.4
MgO	2.1	12	21.4	17.4
MnO/Mn_2O_3	0.1	1.5	1.4	0.04
P_2O_5	0.1	0.6	0.5	0.1
SiO_2	22.2	23.3	29	31.3
TiO_2	0.3	0.9	0.7	0.7
Basicity Index	2.76	1.64	1.88	1.18
Specific Gravity, g cm^{-3}	3.18	2.8	2.8	–
Grindability Index, kWh short ton^{-1}	17.5	32.3	21.5	–
Blaine, $cm^2\ g^{-1}$	183.9	312.6	228	–

The specific surface area, Blaine, of both untreated and treated EAFS is higher than the clinker indicating that the powder size is smaller than that of clinker powder.

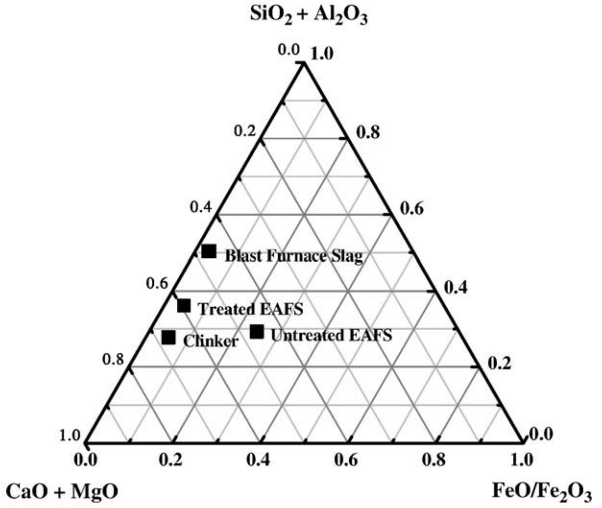

Fig. 1. The chemical composition of clinker, GGBFS and EAFS, untreated and treated, are represented in a ternary diagram mode with acidic oxides, basic oxides and Fe-oxides content as the 3 vertices. It shows that chemical composition of treated EAFS is closer to clinker compared to GGBFS.

powders, clinker, untreated and treated EAFS, and the results are shown in Fig. 2 (a), (b) and (c). A careful analysis of the XRD patterns for the different phases present shows that the clinker has predominantly tricalcium silicate phase along with small quantities of dicalcium silicate as shown in Fig. 2 (a). The untreated EAFS does not show the presence of either of these silicates, Fig. 2 (b), and the predominant phase is found to be $CaMg_{1-x}Fe_xSiO_4$, a Fe-substituted monticellite phase along with small quantities of merwinite, Ca_3MgSiO_4. The presence of monticellite and merwinite phases is in agreement with the chemical composition, Table 2, which shows the presence of Fe-oxide along with CaO, MgO and SiO_2. The untreated slag shows the presence of small amounts of glassy phase. This is partly due to the cooling process used in the plant, cooling using a combination of spraying with water/air mixture, and also the Fe-oxide rich chemical composition which plausibly promotes glass formation in a chemically heterogeneous liquid slag. The melting and quenching of this slag in a reducing carbon environment leads to a reduction in Fe-oxide content and hence, a large change in the chemical balance of the slag. Water quenching following melting is expected to result in the formation of significant glass content. However it is seen from Fig. 2 (c) that the XRD pattern shows well developed peaks indicating the near absence of amorphous or glass phase following water quenching. This is due to the fact that the chemical composition requires a significantly higher cooling rate to avoid crystallization. Also, absence of chemical agents which promote glass formation in the slag composition leads to a lack of glassy phase. An analysis of the peaks indicates the predominant phase to be merwinite, Ca_2MgSiO_4, in agreement with the chemical composition of the slag given in Table 2. The microstructural features, shown in Fig. 3, of the slag before and after treatment exhibit marked differences in accordance with the difference in the phase mixtures in the two cases. The slag before treatment has monticellite, merwinite and magnesioferrite phases which change to a predominantly merwinite phase after treatment. The length scale of the different phases reduces on water quenching due to short transformation times compared to long time available in the air quenching process.

The hydration behavior of pure slag, before and after treatment, was studied together with that of the clinker and the results are shown in Fig. 4. The pH of the supernatant liquid which is a measure of the chemical reactivity in the presence of water alone is nearly independent of time in all the cases. The clinker phase supernatant liquid has the highest pH followed by that above the treated slag. These results clearly show that treatment of the slag lends it more reactivity in the presence of water and hence a cementitious behavior. The hydration behavior was also studied by thermogravimetric analysis, TGA and differential thermal analysis, DTA of the hydration paste powder. The magnitude of weight lost on heating to 1000 °C for different durations of time is shown in Fig. 5(a). This quantity indicates the amount of water taken-up by the slag during the hydration process and it is found to be ~ 8% on an average for the treated slag, twice that compared to ~3.5% for the

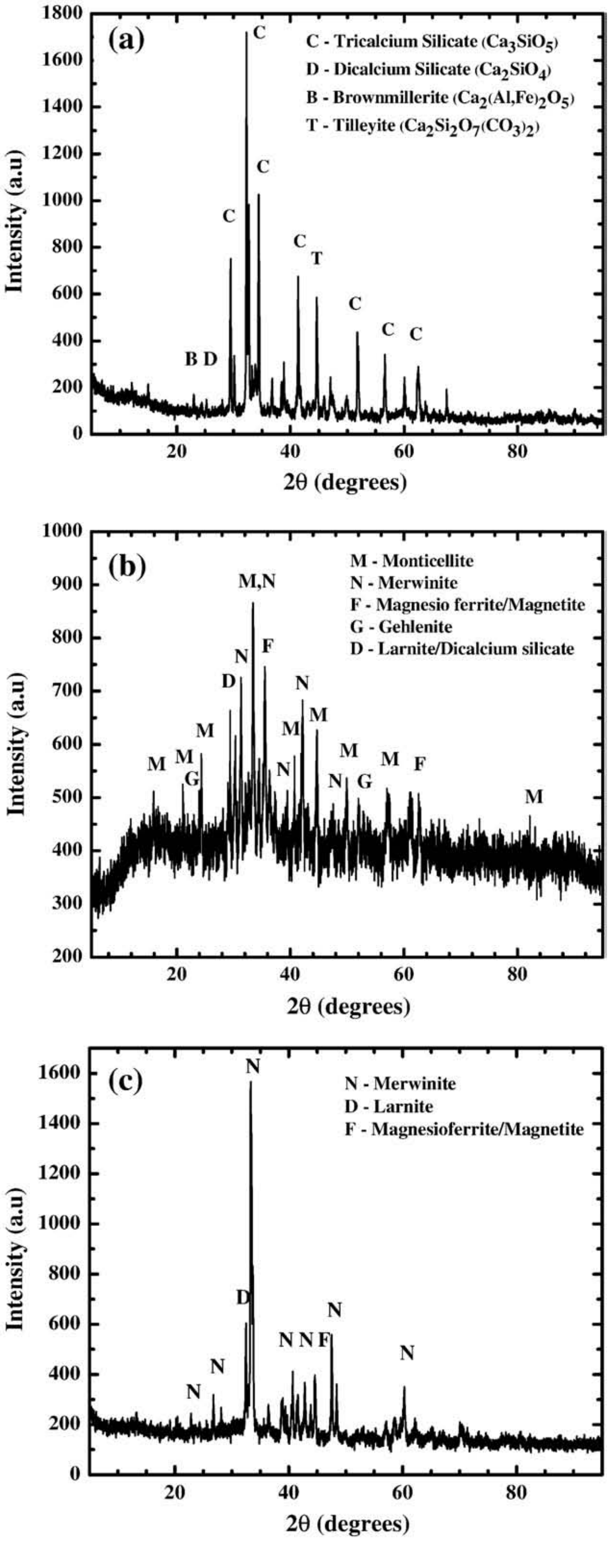

Fig. 2. The X-ray diffraction pattern from the clinker, (a), untreated EAFS, (b) and treated EAFS, (c) shows that the phase mix in the three cases is different. The clinker has predominantly Ca-silicates whereas it is Ca–Mg-silicates in EAFS.

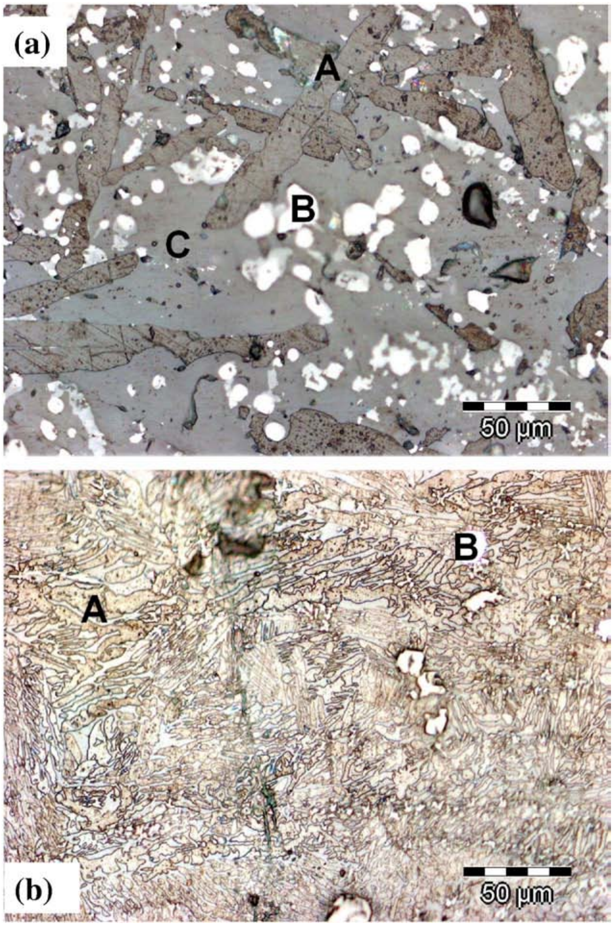

Fig. 3. The scanning electron micrographs of untreated EAFS, (a) and treated EAFS (b) show clearly the difference in phases and their size in the two cases. Melting and water quenching the slags results in changing the phase mixture and also refining the grains size. A = Merwinite, B = Magnesioferrite and C = Monticellite.

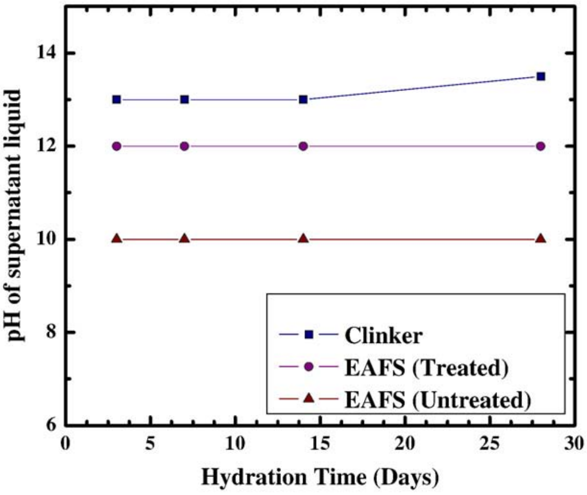

Fig. 4. The pH of supernatant liquid during hydration for different times shows that it is higher for treated EAFS compared to the untreated EAFS. This is an indication of higher hydraulic nature of treated EAFS but still less than that of the clinker.

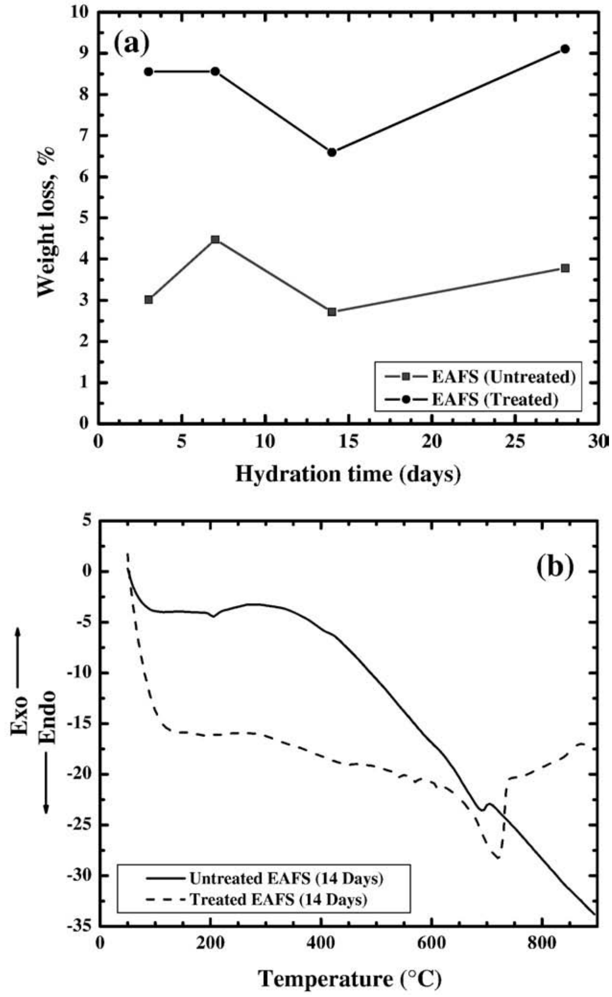

Fig. 5. The thermogravimetric analysis (a) of EAFS shows that treating the slag results in higher water absorption capacity. The differential thermal analysis (b) reaffirms this result showing a clear endothermic peak at ~670 ^{0}C in the case of treated EAFS corresponding to decomposition of $CaCO_3$ which forms due to hydration of slag. The behavior shown here is representative of the identical behavior exhibited at different hydration times in both the cases.

untreated slag. This is also observed in the DTA thermogram shown in Fig. 5(b) which indicates that the amount of heat absorbed to attain the same temperature by treated slag is much higher compared to the as received slag. The DTA of the untreated and treated EAFS after hydration shows an endothermic peak in the range 660–690 °C corresponding to the decomposition temperature of $CaCO_3$. The presence of $CaCO_3$ in the hydrated slag can be understood by considering the chemical changes that occur during the hydration process. The Ca present in the combined form gets released into the aqueous medium as Ca^{2+} which in the presence of water and atmospheric CO_2 forms $CaCO_3$. The decomposition endothermic peak in the DTA is more prominent for the treated slag compared to the untreated slag indicating that the quantity of Ca^{2+} released is higher. This is in good agreement with the higher supernatant liquid pH for the treated slag shown in Fig. 4 and hence this slag has a higher hydraulic nature. To investigate the phase changes that accompany the hydration process, X-ray diffraction studies were performed of the slag samples as a function of hydration time and the results are shown in Fig. 6. The predominant phase in the unhydrated sample was found to be monticellite which was found to be present even after hydration up to 28 days. A qualitative analysis of the X-ray diffraction patterns based on peak intensity changes indicates that the merwinite phase increases slightly with increasing hydration time due to slow conversion of the monticellite phase in water. The hydration behavior of the treated slag on the other hand indicates that the merwinite phase which is present in the unhydrated but treated slag decreases with increasing hydration time. This is indicated by the decrease in the intensity of the merwinite phase peaks and a gradual increase in the background intensity of the overall X-ray diffraction spectrum. Formation of an amorphous phase together with crystalline

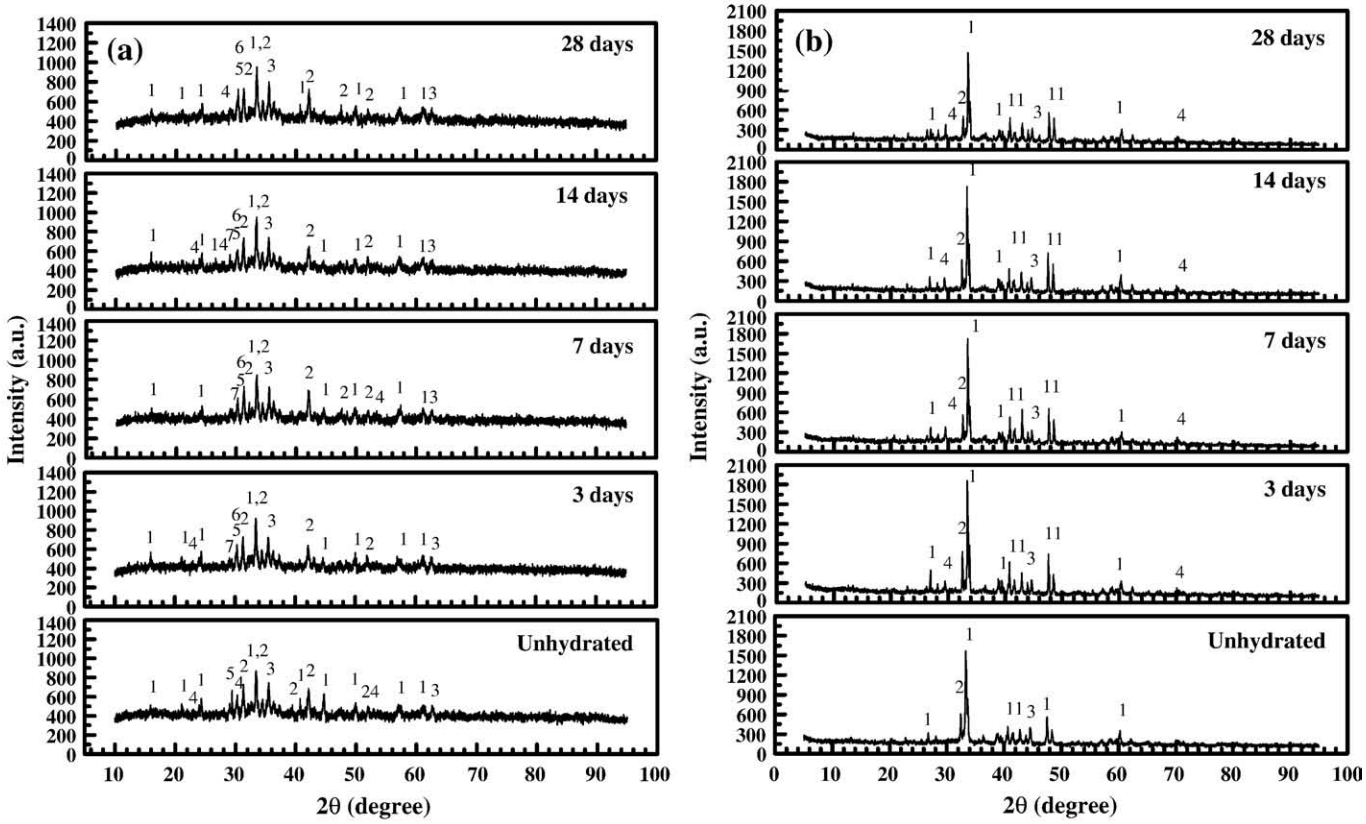

Fig. 6. The phase changes that accompany hydration of the untreated (a) and treated (b) slag were studied by X-ray diffraction. The major crystalline phase in the untreated slag is Monticellite while that in the treated slag is Merwinite. Hydration is found to decrease the amount of Monticellite in the untreated slag while the Merwinite phase decreases in the treated slag.

phases generally manifests in the form of increased background and this is a clear indicator of the hydraulic nature of the treated slag, which is also observed as pH increase of the supernatant liquid. The morphological changes that occur due to hydration of the slag were studied both by scanning electron microscopy as well as infrared spectroscopy. Scanning electron microscopy shows that significant morphological changes do not occur even after 28 days of hydration in both cases, untreated and treated slag. Partial dissolution and re-precipitation takes place in both the cases, Fig. 7, in agreement with the X-ray diffraction results. The infrared spectrum in the range 500–4000 cm^{-1} indicates further the presence of carbonates and silicates in hydrated slags which are formed due to slag dissolution in water.

The hydration behavior of electric furnace slag in the presence of quartz powder and under hydrothermal conditions was investigated at different temperatures by Quin et al. [18]. It was found that merwinite, predominant phase in the slag, transforms mainly to tobermorite at 200 C together with minor phases which contain the Mg-oxide. This phase, tobermorite, is commonly observed during the hydration process of both di- and tri-calcium silicates in Portland cements. The tobermorite phase that forms as a result of hydration at low temperatures however is poorly crystallized and hence normally described as ‘tobermorite gel’ [2,3]. Because of the partially crystalline nature of the reaction product as a whole and poor crystallinity of the tobermorite phase, it cannot be observed clearly by X-ray diffraction. The hydration of treated EAFS with time in the present work exhibits a nearly identical behavior — decrease in the intensity of the merwinite phase X-ray diffraction peaks with an increase in the background indicating formation of an amorphous phase. This similarity in the hydration behavior of treated EAFS to that of di- and tri-calcium silicates prompted the synthesis of slag blended cements and study the effectiveness of partly substituting the clinker or ground granulated blast furnace slag with untreated and treated electric arc furnace slag on the compressive strength development.

The microstructural and hydration results discussed above clearly indicate the cementitious behavior of melt quenched slag. These results however do not provide a direct evidence of the strength properties when this slag is used as a partial substitute in the cement. Hence various standard tests that assess the quality of cement such as consistency of cement paste and its setting behavior and compressive strength of the cast blocks were performed. These tests were carried out on two types of mixes — (1) blast furnace slag blended cement wherein part of the blast furnace slag is substituted with EAFS, and (2) conventional cement with only EAFS as the substitute for clinker. In both the cases pure cements which are commercially used are also investigated as controls, control 1 and control 2 to compare the results and all these results are given in Table 3. The minimum amount of water required to make a workable paste of the cement mix is known as the standard consistency. It is seen that addition of EAFS, untreated or treated, to the standard cement mixes reduces the water demand in both the cases. The presence of GGBFS together with clinker and gypsum, control 1, has the highest water demand, higher than control 2. The presence of EAFS in both types of mixes is found to reduce the amount of water required to make a paste of workable consistency. This is a significant result in view of the savings that can be achieved in the consumption of a precious resource such as water by the extremely large construction industry. The setting time of the cement paste which is a measure of the hardening rate, is measured by the standard Vicat needle piercing instrument. The setting times and the difference between the initial and final setting times do not show significant deviations compared to the control in both the cases. This clearly indicates that the workability of the mix paste remains nearly the same in spite of EAFS addition.

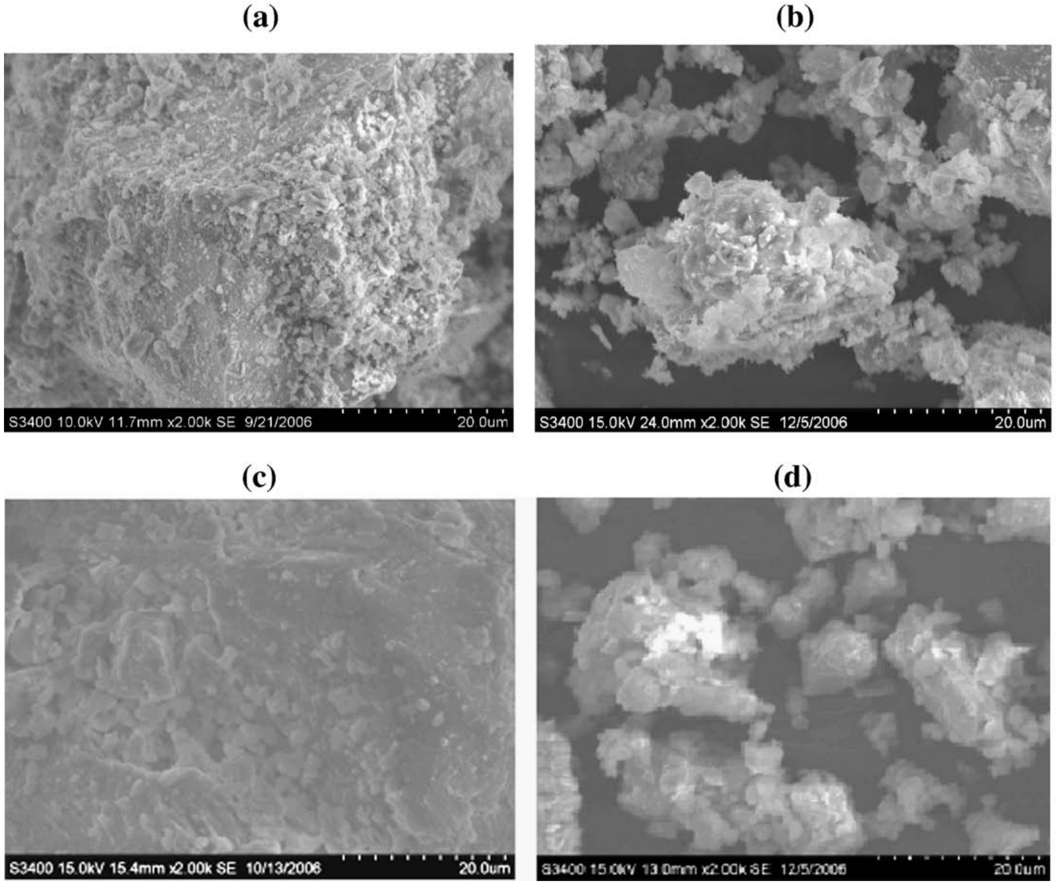

Fig. 7. The scanning electron microscopy of hydrated slags as a function of time shows morphological changes due to dissolution and re-precipitation. (a) 3, (b) 7, (c) 14 and (d) 28 days of hydration for the untreated slag. (e) 3, (f) 7, (g) 14 and (h) 28 days of hydration for the treated slag.

The compressive strength of differently blended cement mixes along with the controls was studied as a function of time using standard test procedures. The results are given in Table 3 and also in Fig. 8(a) and (b). The compressive strength of both GGBFS and EAFS blended cement mixes is very comparable to that of the control mix 1 which has only GGBFS together with clinker. The initial strength of as received EAFS blended mix is slightly lower compared to the control but increases significantly after 3 days and attains a value of 58 MPa after 28 days compared to 58.6 MPa for the control. The strength of treated EAFS mixed cement on the other hand is equal to that of the control up to 7 days and increases to 61 MPa after 28 days, a value higher than the control mix indicating high later stage strength development. In the case of cement mix without any GGBFS the early stage strength, ≤7 days, is lower for the EAFS blend compared to control 2 and significant later stage strength development takes place. In the case of cement mix without any GGBFS addition, the overall compression strength decreases when compared to the control mix 2 and the decrease is more pronounced for 30% clinker substitution compared to 15% substitution. The rate of strength development due to EAFS addition however is comparable to that of the control and

Table 3

The cementitious properties of EAFS mixed cements were compared with the controls to determine its influence on the physical properties

Composition, wt. %	Control 1	Mix A	Mix B	Control 2	Mix C	Mix D	Mix E	Mix F
Clinker	45	45	45	95	80	65	80	65
Gypsum	5	5	5	5	5	5	5	5
GGBFS	50	30	30	0	0	0	0	0
EAFS Untreated	0	20	0	0	15	30	0	0
EAFS Treated	0	0	20	0	0	0	15	30
Standard Consistency, %	29.5	26.5	26.5	27.5	25.5	24.7	26.3	26.5
Setting time, min								
Initial	120	130	120	70	75	90	95	105
Final	210	220	220	115	125	140	135	150
Compressive strength, MPa at 27 °C								
1-Day	14.1	13.8	14.1	22.4	13.7	10.6	15.3	12
3-Day	32.2	28	31	40.3	30.6	25.4	35	27.8
7-Day	47	45	44.8	53.5	44.2	36.1	41.5	36.7
28-Day	58.6	58	61	66.5	63.3	53.4	64.6	51.4

In the first set of cements, control 1, mix A and mix B, GGBFS was partially replaced with EAFS. In the second set of cements, control 2, mix C, D, E and F, there was no GGBFS and the clinker was replaced with EAFS only.

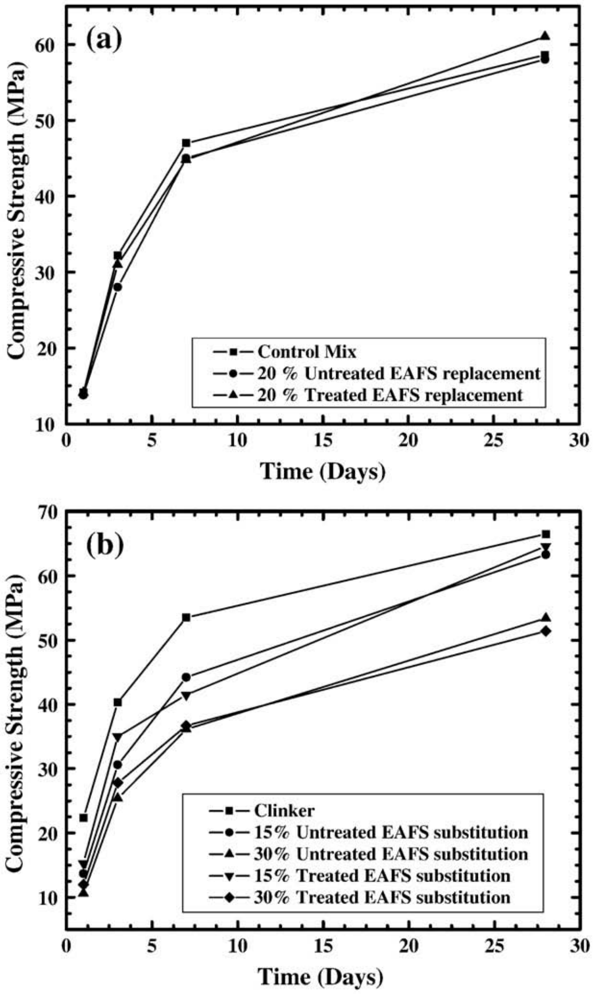

Fig. 8. The compression strength of cubic blocks at 27 C and at different times, of different cement mixes is compared with controls which do not have EAFS. In (a) GGBFS present in control 1 is replaced with 20% EAFS. In (b) there is no GGBFS and the control has only clinker and gypsum. Up to 30% of clinker in this case is replaced with EAFS.

exceeds that of the control at later stages, after 14 days. The EAFS added cements thus show a great potential for later stage strength development compared to the control. The slow rate of strength development is due to the presence of phases such as monticellite and merwinite in the slags which have slower dissolution kinetics in the presence of gypsum and water compared to tricalcium silicate and dicalcium silicate which are present in the clinker.

Pozzolans are materials when mixed with lime and water will harden like cement. These materials generally contain reactive SiO_2 and or Al_2O_3 and have little or no binding property on their own. These are generally added to Portland cements to make pozzolanic cements which are known to have better hydraulic binding and also provide impermeability to the concrete made with this blended cement. Since the EAFS has both these oxides, the pozzolanic behavior was investigated as per standard procedure. Cubes of 50 mm size were made with a paste comprising of slag and lime powder with a ratio of 1:3. The water to cementitious powder ratio was taken as 0.76. The compressive strength after 8 days of curing at 50 C in a relative humidity of 90–100% was measured. As per standard definition a material which has a minimum compressive strength of 4 MPa is said to possess pozzolanic behavior [19]. The untreated EAFS had a compressive strength of 2 MPa, well below the minimum compressive strength specified for a pozzolanic material. The treated EAFS on the other hand had a compressive strength of 8.5 MPa, well above the minimum value required. These results clearly show that the treated EAFS is highly pozzolanic. The SiO_2 present in untreated EAFS in the form of modified monticellite phase is strongly bound and hence does not react with lime easily. The SiO_2 present in the treated EAFS is mainly in the merwinite phase and hence highly reactive with lime in the presence of water to form Ca-silicates. These pozzolanic test results are in complete agreement with the hydration results of slag which also show that treated EAFS has more dissolution capability and higher supernatant liquid pH, compared to untreated EAFS.

4. Conclusions

Electric arc furnace steel slag because of its high Fe-oxide content and complete crystallinity is currently used mainly for landfills and road aggregates. In order to find an alternate application which has a higher economic value, the cementitious and pozzolanic behavior of the slag have been studied in detail. The slag was also subjected to a remelt and water quench treatment in order to change its composition and phase mixture. The electric arc furnace steel slag in the as received state exhibits slight cementitious behavior which is significantly enhanced due to reprocessing. The reduction of Fe-oxide and separation of Fe metal from the slag changes the overall chemical composition and hence the nucleation preference during water quenching. The predominantly monticellite phase present before treatment does not nucleate preferentially and instead merwinite phase forms. The reduced grain size of the merwinite phase enhances its dissolution kinetics in water which makes it highly hydraulic. The chemical composition of treated slag is similar to that of the clinker but mineralogically they are very different. The merwinite phase present in the treated slag has a hydration behavior similar to that of di- and tri-calcium silicates and forms a gel like tobermorite phase. The compressive strength of two types of cement mixes studied, 1) blended cement with both blast furnace slag and electric arc furnace steel slag, and 2) only electric arc furnace steel slag blended cement, exhibits strength comparable to that of the controls which do not have any electric arc furnace slag. In the case of blast furnace slag blended cement, up to ~20% of the blast furnace slag could be substituted with electric arc furnace slag without loss of 28 days compressive strength. The maximum amount of clinker that could be substituted with electric arc furnace slag in the case of cement mix without any blast furnace slag however is ~30% and this substitution still exhibits a compressive strength of 50 MPa after 28 days. Treatment of the slag has a significant effect on the pozzolanic strength, which is enhanced by 4 times compared to the untreated slag. This behavior, high reactivity of the merwinite phase in the presence of lime and tobermorite-gel like phase formation on hydration has been observed experimentally. The exact reasons for this behavior are not clearly known at present and need more detailed investigations of the structure for an understanding of the basic mechanisms. In conclusion, it can be stated that treatment of the electric arc furnace slag makes it both cementitious and pozzolanic in nature.

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