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Research Paper

Enhancement of Slag Aggregates Quality by Polymeric Immersion

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ABSTRACT

Utilization of steel slag aggregate (SSA) has been significantly developed in recent years. According to the volume expansion of SSA caused by F-CaO content, finding a suitable way to replace this type of aggregate in concrete has always been one of the crucial concerns. In the current study, enhancing a type of SSA, obtained from the waste of short casting furnaces called cupola furnace slag, is studied by utilizing different coating materials. In general, a positive effect can be observed on the enhancement of physical properties and microstructure of SSA by polyvinyl alcohol (PVA), polydimethylsiloxane (PDMS), and sodium silicate (SS) immersion. More specifically, porosity and water absorption of SSA were improved between 40 and 70%, which is notable. In addition, its impact value increases about 25% in some categories. More importantly, XRD diffraction analysis illustrates details about the reduction of F-CaO content, which occurred by the coating process. Therefore, immersion of SSA in these polymeric materials can be suggested as an appropriate method to improve its quality for utilization in concrete.

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1. Introduction

Aggregate in concrete plays an important role in achieving mechanical and durability properties, so it makes researchers interested in the detailed studies on different aggregates and the techniques to improve their properties. Preserving natural resources and the environment makes humans use recycled materials in the construction industry. This intention has been accompanied by several problems, such as reducing concrete qualities. Therefore, it is necessary to find appropriate ways to produce recycled aggregates for concrete. In this paper, a type of aggregate as the waste of short casting furnaces called cupola furnace slag aggregates (CFSA) is explored. Generally, steel slag aggregate (SSA) has a rough surface and porous structure [1]. Some techniques, such as the polymeric saturation method, which involves soaking in polymeric materials such as polyvinyl alcohol (PVA), can be effective to reduce the voids in aggregates [2]. Steel slag can be categorized into three groups based on the method of production, including Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF), and Ladle Furnace (LF) slags [3]. BOF and EAF have similar raw materials, such as iron, steel scrap, lime, dolomite, etc. There are limited differences between BOF and EAF slags [4]. A ladle furnace is used for secondary refining and needs fluxing agents like calcium aluminate to finish the final desulfurization and decarburization to remove impurities. Alloys such as manganese, chromium, and vanadium are also added to improve steel quality and produce stainless steel, which all influence the properties of LF slag. Therefore, LF slag is quite different from BOF and EAF slags in terms of composition and physical properties. BOF steelmaking requires the heat of the molten iron and other reactions. In the final part of steelmaking, BOF slag floats on the top of the molten steel and is composed of the impurities combined with burnt lime or dolomite. EAF relies on graphite electrodes that transmit electricity to the metal to provide sufficient heat [5]. One of the important characteristics of steel slag is its porosity, which results in higher water absorption than natural aggregate (NA). The roughness and high angularity of SSA are considered other characteristics. The impact value and crushing value of SSA are also lower than NA [6]. The uneven texture of SSA leads to an increase in the bonding between aggregates and cement paste, so it makes a rise in the strength of concrete [7]. The mineral composition in slag is similar to Portland cement, and generally, it includes CaO, SiO_2, Fe_2O_3, and Al_2O_3 [8]. The main limitation of using slag is the F-CaO that is present on the slag surface, which causes volume expansion in concrete. Free calcium oxide or free magnesium oxide participates in the hydration reaction and turns into calcium hydroxide or magnesium hydroxide that leads to volume expansion in concrete [9]. Activated silica on the slag surface can be hydrated and increase the bonding between slag and cement, which improves the quality of the interfacial transition zone (ITZ) [10].

The microstructure of slag shows that the use of polydimethylsiloxane (PDMS) has a positive effect on the filling of pores and reduces water absorption [11]. Immersion of SSA in water repellents such as silane and paraffin wax for 24 hours can reduce its porosity and water absorption [12]. Ekaterina et al. [13] showed that using PVA can increase CO_2 absorption by steel slag. Immersing aggregates in silicon can reduce the water absorption of samples, and using sodium silicate for immersing SSA can play an effective role in reducing water absorption and increasing the abrasion resistance of the samples [14]. In addition, using silicone to modify SSA can reduce water absorption and control its volume expansion [15]. Therefore, the necessity of treating SA to decline its free-CaO content and enhance the properties of concrete is revealed. Different methods can be employed to upgrade SSA. In the current study, surface coating techniques were conducted to enhance SSA before being used in concrete. The pores of SSA are supposed to be obstructed by immersing them in PVA, PDMS, and sodium silicate that lead to enhancement of SSA quality for utilization in concrete.

2. Materials and methods

2.1. Materials

Fig. 1 illustrates information about materials used in the current study. Generally, two types of aggregate were discussed: natural aggregate (NA) and steel slag aggregate (SSA). SSA was obtained from waste of short casting furnaces called cupola furnace slag (CFS) in Najaf Abad industrial town. Similarly, NA was selected from the stockpile of stone materials, concern to the Islamic Azad University of Najaf Abad branch.

(a) CFSA (b) NA (c) PVA (d) Sodium silicate (e) PDMS

Fig. 1. Materials used in the current study

Table 1 highlights details about surface coating materials utilized in this paper. Polyvinyl alcohol (PVA) and polydimethylsiloxane (PDMS) as polymers were employed to create a coating on the top layer of SSA. PVA is a synthetic polymer, colorless, odorless, and soluble in water, which is mainly used in the treatment of textiles and paper. PDMS is the most common polysiloxane used as a binder. In its structure, two methyl groups are placed on the silicon atom. This oil-type silicone is optically transparent and generally neutral, non-toxic, and non-flammable. Therefore, silicone oil was selected to conduct surface treatment. Sodium silicate is an inorganic chemical compound with a chemical formula of Na_2SiO_3 and a molar mass of 122.07 g/mol. Sodium silicate is produced with a mixture of silica (usually as quartz sand), caustic soda, and water with hot steam in a reactor. Also, by dissolving silica in sodium carbonate, sodium silicate is obtained. From the reaction of sodium sulfate, silica, and carbon as a reducing agent, sodium silicate is produced. Sodium silicate is often in the form of granules or transparent, colorless solids or white powders. In this research, sodium silicate powder was used as a coating material.

Table 1. Properties of the materials used for coating in the current study

Material	Name	Chemical formula	Melting point	Boiling point	Solubility in water	Density gr/cm^3	Physical state
PVA	PVA 24-88	C_2H_4O	200 °C	228 °C	Soluble	1.19-1.31	Solid powder
PDMS	Silicone oil 1000	$R_1R_2SiO_2$	-49 °C	315 °C	Soluble	0.00097	Liquid
Sodium silicate	Sodium silicate	Na_2SiO_3	1088 °C	<1088 °C	Soluble	2.61	Solid powder

2.2. Methods

In this research, assessment can be divided into two different parts: one coating process and the other aggregate tests. Enhancing SSA before being employed into concrete mixture was followed to achieve eco-friendly concrete that carries high performance. In order to compare the results of treatment, physical properties and microstructure of aggregates were discussed.

2.2.1. Coating process

It is necessary to upgrade SSA to control its volume expansion caused by F-CaO content and enhance the quality of SSA. In this paper, polymeric immersion was employed to achieve this goal. It was expected that the pores on the SSA are filled or obstructed by conducting surface treatment. The whole process starts when appropriate materials, listed in Table 1, were prepared. The first thing that is needed is the concentration value of the materials in water. Therefore, to decide on this item, previous studies, economic remarks, and practical considerations were remarked. Hence the concentrations of 5% and 10% were applied to all categories, and then the coating process was conducted by immersing SSA in the solutions for 1 hour. This time period has been chosen based on the sedimentation test. In the last step, modified slag aggregate (MSA) was obtained after being placed in the atmosphere in order to sun-dry. The process of coating is shown by Fig. 2.

(a) PVA (b) PDMS (C) Sodium silicate

Fig. 2. Materials in coating process

Fig. 3 highlights information about the sedimentation test, conducted to decide how long SSA should be held in the solution. By trial and error method, under completely identical conditions, the settling situation of selected materials was investigated inside transparent containers with a concentration of 10% polymeric material. For this purpose, 20 grams of the coating material were mixed with 200 ml of water, and then the sedimentation condition was evaluated in different periods of time. All polymeric solutions were prepared at the zero moment. It was observed that after 40 to 60 minutes, all particles in the solution were completely settled. Hence, the appropriate time for immersing SSA in the solution was estimated between 45 and 60 minutes. Therefore, according to the results and the economic factors, concentration values of 5% and 10% were applied separately for the coating of SSA.

(a) 20 minutes *(b) 60 minutes*

Fig. 3. Sedimentation observation

2.2.2. Aggregate tests

Physical properties and microstructure of aggregates were measured to compare the results of treatment. More specifically, water absorption, porosity, impact value, and X-ray diffraction (XRD) have been studied, which is shown by Fig. 4. A water absorption test was performed based on the ASTM C128. Aggregates with lower water absorption can be more suitable for concrete strength and durability. According to ASTM D2216, a porosity test is carried out to determine the amount of pores on the surface of aggregates. The porosity of aggregate is measured by filling its voids with water such that the aggregates are fully submerged. The porosity is given by the volume of the pores divided by the total volume. In order to calculate the resistance of the aggregates against sudden loads, an impact value test was performed according to the IS2386-PART(IV)-1963 standard. Generally, SSA has less impact value than NA. Aggregates that carry lower results against the applied load are stronger. Finally, the XRD test was applied to check crystalline phases in the SSA. It is expected that the F-CaO content can be reduced by surface treatment. XRD patterns illustrate details on the differences in the slag phases.

(a) Preparing for water absorption (b) Impact value

Fig. 4. Sample preparation and testing of samples

3. Results and Discussions

3.1. Physical Characteristics

Table 2 provides information about the differences between the characteristics of NA and SSA. In general, the figures show that the SSA needs to be treated due to the lower results. A research study by Kim et al. [16] mentioned that the amount of water absorption of SSA is 1.58%. In the present research, SSA water absorption is 4%, which is very high and 88.25% more than NA. Aggregate strength has direct effects on the compressive strength of concrete. According to Palankar et al. [6], the impact value for SSA was 21%, which is similar to the results of the present research. The necessity of improving SSA is revealed by the obtained results. Surface coating technique was employed to upgrade SSA.

Table 2. Physical characteristic of aggregates before coating

Type of aggregate	Water absorption (%)	Porosity (%)	Impact value (%)
NA	0.47	1.3	8.6
SSA	4.0	9.0	21.7

Table 3 highlights details about the differences between physical properties of SSA treated by the coating process at 5%. The figures show that the biggest overall decrease concerns the PVA immersion when it comes to water absorption value. In addition, PVA coating has been more influential on the porosity and impact value. Kumar et al. [17] revealed that the water absorption of recycled aggregates was between 1.5% and 4.9%. It can be seen that the value of water absorption of 1.47% is even less than the minimum value reported for recycled aggregates. The obtained results for the porosity test illustrate that the voids on the slag surface can be reduced between 13.1 and 57.7 percent by covering the top layer of them. Moreover, modified slag aggregate (MSA) provides a stronger structure compared to other categories against sudden loads, such as PVA-SSA (5%), with a figure of 18.12%.

Table 3. Effect of coating on physical characteristics (5%)

Type of aggregate	Water absorption		Porosity		Impact	
	Value (%)	Compared to SSA	Value (%)	Compared to SSA	Value (%)	Compared to SSA
NA	0.47	-88.25	1.3	-85.6	8.6	-60.4
SSA	4.0	-	9.0	-	21.7	-
PVA-SSA (5%)	1.47	-63.25	3.72	-58.7	18.12	-16.5
PDMS-SA (5%)	2.07	-48.25	4.74	-47.3	18.78	-13.5
Sodium silicate-SSA (5%)	3.1	-22.5	7.82	-13.1	18.26	-15.8

When using 10% coating material, as in Table 4, PVA has again become more effective. In this case, a significant rise is observed to enhance SSA characteristics. More specifically, water absorption decreased from 4 to 1.07% by PVA (10%), which indicates a 73.25% enhancement. In addition, improvements of 69.8% and 25.3% are reported for porosity and impact value of SSA, respectively.

Table 4. Effect of coating on physical characteristics (10%)

Type of aggregate	Water absorption		Porosity		Impact	
	Value (%)	Compared to SSA	Value (%)	Compared to SSA	Value (%)	Compared to SSA
NA	0.47	-88.25	1.3	-85.6	8.6	-60.4
SSA	4.0	-	9.0	-	21.7	-
PVA-SSA (10%)	1.07	-73.25	2.72	-69.8	16.2	-25.3
PDMS-SA (10%)	1.55	-61.25	3.68	-59.1	16.7	-23.0
Sodium silicate-SSA (10%)	2.27	-43.25	5.34	-40.7	17.93	-17.4

Large differences between the values of water absorption, porosity, and impact for NA and SSA reveal the necessity of modification for SSA. In addition, all three coating materials have become effective in reducing this difference. In a general view, 10% PVA has become more effective to minimize this difference and enhance SSA structure. Results show that polymeric coating can make a positive effect on the physical characteristics of SSA, especially when 10% coating materials are applied. It should be mentioned that the smallest overall enhancement concerns the sodium silicate immersion.

3.2. XRD diffraction Analysis of Phases

XRD diffraction was employed to compare the phase composition. Table 5 highlights data about XRD analysis conducted in this paper on the SSA and NA. The obtained results for NA show that the main crystalline phases in this sample are $CaCO_3$, SiO_2, Al_2O_3, CaF_2, and Fe_2O_3. Also, the figure indicates that the SSA phases are mainly included: Fe_2O_3, Al_2O_3, SiO_2, Cr_2O_3, $CaCO_3$, and F-CaO. Therefore, F-CaO content on the slag surface is confirmed by the XRD diffraction pattern. Calcium oxide on the slag surface can participate in the hydration reaction and increase the volume expansion of concrete. Hence, volume expansion should be controlled by appropriate methods. In the present research, a surface coating method was used to reduce the free calcium oxide content on the slag surface. In other words, coating can provide a positive effect to control F-CaO content on the slag surface. In fact, there is a high probability of reaction between polymer and F-CaO that limits later reactions of F-CaO with cement. Figs. 5 and 6 illustrate details on the differences of phases that occurred on the SSA by coating methods. It is clearly visible that the changes happened in the slag phases to some extent. As it seems, there are some peaks that present specific crystalline phases. According to the differences of fluctuations, it can be stated that the percentage of slag phases shifts to change. More importantly, the biggest overall enhancement occurred with 10% coating materials. In fact, MSA with PDMS (10%) is considered an important category to reduce F-CaO content on the slag surface, while sodium silicate is the least.

Table 5. Results of X-Ray Diffraction

Aggregate type	Crystalline phases					
NA	$CaCO_3$	SiO_2	Al_2O_3	CaF_2	Fe_2O_3	-
SSA	Fe_2O_3	Al_2O_3	SiO_2	Cr_2O_3	$CaCO_3$	Free CaO

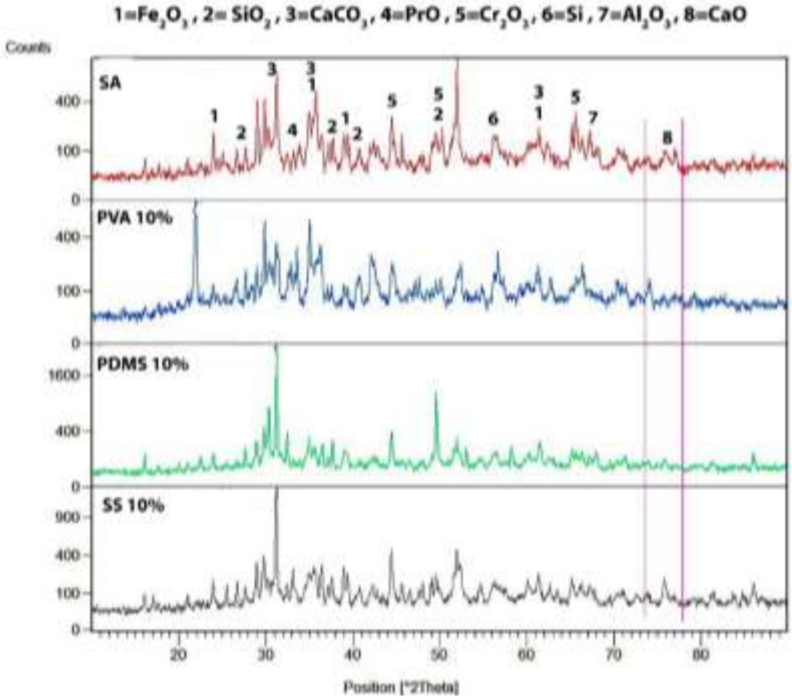

Fig. 6. Effect of coating by 10% material on the slag phases

4. Conclusion

According to the investigations that are conducted in this paper, SSA needs to be treated due to its porous structure and F-CaO content on its surface before being used in concrete. Therefore, polymeric immersion was applied to enhance SSA by PVA, PDMS, and SS. All in all, a positive effect can be observed on the enhancement of physical properties and microstructure of SSA by utilizing different coating materials. The figures show that the porosity, water absorption, and impact value of SSA can be improved by surface coating treatment. More specifically, porosity and water absorption of SSA can be increased between 40 and 70%. Moreover, XRD diffraction illustrates details on the enhancement of slag phases to reduce F-CaO content. Hence, modified SSA is more suitable to be used in concrete mixtures.

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Competing interests

The authors declare no competing interests.

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