PROPERTIES OF HIGH STRENGTH CONCRETE USING STEEL SLAG COARSE AGGREGATE

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Abstract

Steel slag, which has low CaO content, is a by-product of steel processing. The steel slag consisting iron oxides is ground into sizes as coarse aggregates used for concrete. In this paper, the steel slag was characterized by chemical, physical and mineralogical analysis, and then the steel slag was used to replace 100% coarse aggregates in high strength concrete which has various compressive strengths as 60, 70 and 80MPa. Results showed that the strength of the concrete using steel slag aggregate was equivalent to that of the conventional concrete, whereas, the durability of the steel slag aggregate concrete was better than that of the conventional concrete in terms of chloride penetration resistance and resistivity. Moreover, dimensional stability of the steel slag cement mortar was detected.

Keywords: Durability, High strength concrete, Steel slag aggregate

Introduction

Basically, coarse aggregates occupy a major volume in concrete, the occupying coarse aggregate volume can be various from 50% to 70%. Up to now, we have been using natural coarse aggregates with huge volumes such as andesite, basalt and limestone in concrete production. As a result, the natural coarse aggregate resource becomes exhausted. Also, in some cases, constructions are far from the good quality aggregate resource or the natural aggregates are not easily available for concrete production [1]. Nowadays, the industrial manufacturing of metals increases, and the amount of solid wastes exhausted becomes an environmental problem for society. Generally, the steel slag is formed by a direct reduction of iron in an electric arc furnace. Due to slow cooling in atmosphere, the steel slag has large size fractions, also it contains low percentage of amorphous silica, a low content of free lime and high content of ferric oxides, this characteristic makes the steel slag consequently have very low, or no pozzolanic activities in comparison with blast furnace slag (BFS) [2]. There are many researches on using steel slag in asphalt concrete for road construction. Regarding to using the steel slag in the concrete, there is a few researches conducting to evaluate the potential usage of the steel slag as aggregates for the concretes. Steel slag aggregate makes the mechanical properties of the concrete in terms of compressive, tensile and flexural strength and modulus of elasticity be higher than those of the concrete using natural aggregate. The same results also proposed by Maslehuddin et al. [1] and Pellegrino et al. [3]. In another comprehensive study on utilizing the steel slag as aggregates in the concrete, Etxeberria et al. [4] showed that the steel slag was classified as inert materials due to satisfying expansion and leaching limitations, the steel slag aggregate makes the density of the concrete increase and makes the workability of the fresh concrete decrease, moreover, the mechanical properties of the steel slag aggregate concrete were comparable to those of the natural aggregate concrete. Qasrawi et al. [2] conducted research on using low CaO unprocessed steel slag as fine aggregate in concrete. Results concluded that the use of the steel slag as fine aggregate had a negative impact on the workability of concrete, but it had positive effect on mechanical properties, and the best results of compressive strength were obtained as the steel slag content was 15% and 30%. The steel slag aggregate produced by a steel plant is also utilized in asphalt concrete. Regarding to this application, Pasetto et al. [5] proposed that mix designs of asphalt concretes using the steel slag aggregate satisfied technical requirements which had good values of Marshall stability and Marshall quotient. Also, the asphalt concrete containing the steel slag aggregate had good stiffness and fatigue resistance.

It can be seen that the utilization of the steel slag in concrete is still a replacement of some percentages of aggregates, the research on using the steel slag in the concrete as a whole replacement of the coarse aggregate is very limited. Moreover, at present, surrounding HoChiMinh City - Vietnam, at Phu My industrial zone, there are many steel processing plants which exhaust the steel slag with large volume. Therefore, in this paper, an experimental program was conducted to investigate the properties of concretes as the steel slag replaced the whole natural coarse aggregate. The properties of high strength concretes were investigated including compressive strengths at various curing time with different water to binder ratios, *w/b*, as 0.33; 0.36 and 0.39, unit weight of concrete, the chloride penetration resistance such as charge passed and chloride diffusion coefficient, the resistance of the concrete, compressive strength under thermal cycle, also the expansion of the steel slag cement mortar was evaluated. In order to determine utilizing potential of the steel slag as the coarse aggregate, the properties of the steel slag were researched, and then the properties of the steel slag coarse aggregate concrete were compared to those of the natural coarse aggregate concrete.

Materials and Experiments

Materials

In this paper, materials used include ordinary portland cements (OPC), fine aggregate, natural coarse aggregate, silicafume (SF), and steel slag. Fine aggregate is river sand having fineness modulus of 2.62. The chemical and physical properties of OPC cement were quantified by XRD and XRF analysis and shown in Table 1. Natural coarse aggregate, which satisfies ASTM C33-84, is altered basalt and belong to extrusive igneous rock with a maximum size of 20mm. The steel slag, which has large sizes, was ground into various smaller sizes. Because of free lime included in the steel slag, to make the lime stabilized, after grinding, the steel slag was exposed to atmosphere with water spray for one month, and then the steel slag was sieved into separated sizes and combined various sizes together to generate the best grading as shown in Figure 1, with a maximum size of 20mm. The petrography characteristic of the natural coarse aggregate and the steel slag aggregate were evaluated by ASTM C295. The petrography analysis showed that the steel slag aggregate consists of opaque minerals (49.3%) and clay minerals (12.3%). The opaque minerals with very fine-grained are magnetite and iron oxides, which were scattered in the aggregate. In the steel aggregate, the pore shape is circular and slit-shaped pores with interconnectivity, as shown in blue color in Figure 2. The pore diameter is commonly from 0.1mm to 1.0mm. Moreover, the chemical composition of the steel slag coarse aggregate contains high content of ferric oxides, calcium oxide and silica oxide as shown in Table 2.

Table 1. Chemical Composition and Constituent of OPC Cement (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	C_3S	C_2S	C_3A	C_4AF	LOI
21.66	5.58	2.79	63.92	2.55	2.32	0.15	0.34	58.34	22.65	6.42	10.14	0.72

LOI: Ignition loss

Table 2. Chemical Composition of the Steel Slag Coarse Aggregate (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	P_2O_5	TiO_2	Cr_2O_3	MnO	ZnO
16.3	6.07	39.2	28.9	1.68	0.72	0.36	1.02	1.34	4.02	0.32

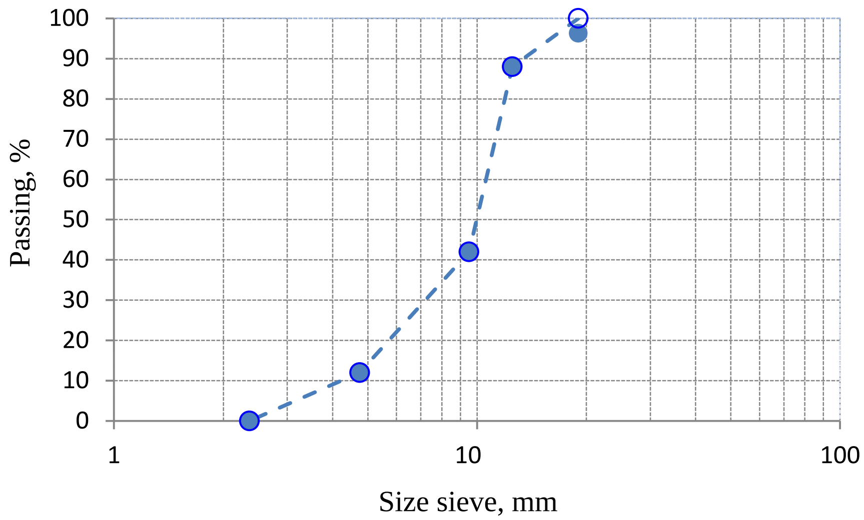

Figure 1. Grading of the steel slag coarse aggregate

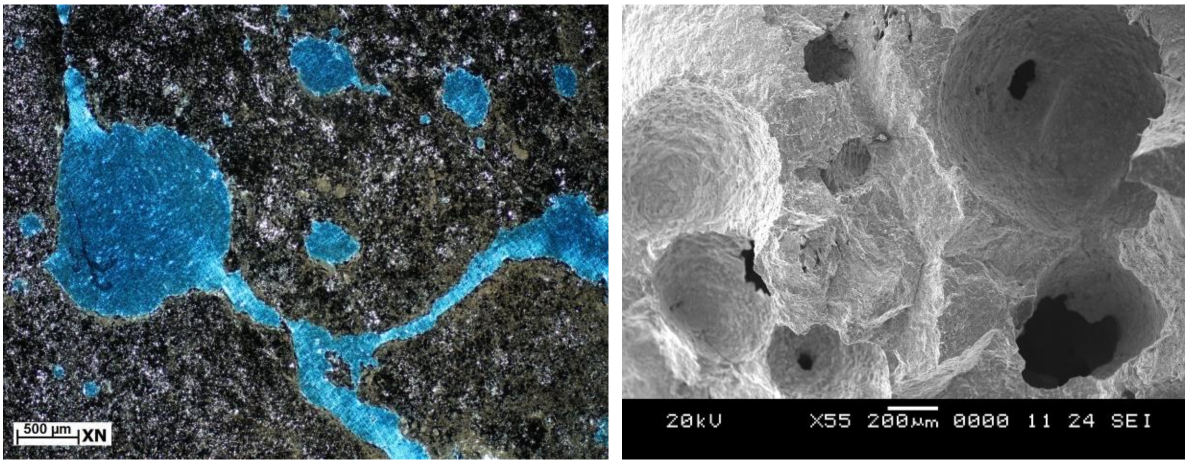

Figure 2. The shape and interconnectivity of pores in the steel slag coarse aggregate

To make comparison of concretes using basalt coarse aggregate and steel slag coarse aggregate, the steel slag coarse aggregate is compared to the basalt aggregate in terms of dry density, water absorption, compressive in cylinder, abrasion loss, wet dynamic crushing and sulphate soundness. These properties of both the basalt aggregate and the steel slag aggregate are presented in Table 3. From the Table 3, it can be seen that the steel slag aggregate is much heavier than basalt aggregate due to high content of ferric oxides in its composition. Also, with interconnected pores, the steel slag aggregate has higher water absorption, higher cylinder crushing value and higher wetting dynamic crushing value than that of the basalt aggregate. Whereas, the abrasion loss of the steel slag is higher when compared to the basalt aggregate, the ferric oxide which has good friction resistance may contribute to good abrasion loss of the steel slag. Regarding to soundness of the aggregate, the steel slag coarse aggregate is significantly stable in the magnesium sulphate and superior to that of the basalt aggregate. In general, the steel slag aggregate has properties which are comparable to the basalt aggregate. So, it is obviously potential to utilize the steel slag as coarse aggregate in the concrete. However, we need to consider mixture design of the concrete as the steel slag aggregate is significantly heavy.

Table 3. Mechanical and Physical Properties of Basalt Coarse Aggregate and Steel Slag Coarse Aggregate

Property	Basalt Aggregate	Steel Slag Aggregate
Water absorption by ASTM C127, %	0.56	1.85
Dry density by ASTM C127, g/cm^3	2.76	3.37
Abrasion loss by ASTM C131, %	4.24	6.03
Crushing in cylinder by BS 812, %	13.65	16.83
Wet dynamic crushing by CIRIA 83, %	3.72	6.14
Soundness in magnesium sulphate for 5 cycles by ASTM C88, %	0.76	0.18

Experiments

Concrete specimens were prepared using the steel slag coarse aggregate and basalt coarse aggregate with *w/b* as 0.33, 0.36 and 0.39. The concrete mix proportion was designed following ACI 211 with controlled slump of fresh concrete of 8 ± 2cm, and shown in Table 4. With each mixture, cylinder specimens 150mm in diameter and 300mm high were prepared for determination of compressive strength, thermal cycles and resistivity, while the cylinder specimens 100mm in diameter and 200mm high were used for the evaluation of the chloride penetration resistance. The concretes were cast in steel moulds and covered with plastic sheets after casting. The cylinder specimens were demoulded at one day of age and after that cured in lime saturated up to 28 day age for tests. Mixing and casting were performed in the control room with temperature of 22 ± 2^oC and relative humidity of $60 \pm 5\%$. Concerning with the test of chloride penetration resistance according to ASTM C1202, also, after 28 days of curing, cylindrical specimens with a diameter of 100 mm and a thickness of 50 mm are sliced from cast cylinders. Then, all sides of the test specimen are sealed with epoxy except two exposed surfaces. The sealed specimens are saturated in a calcium hydroxide solution and rinsed with tap water. After that specimens are placed between two chambers: a chamber with 3% sodium chloride and the other chamber with 0.3N sodium hydroxide, and an external electrical potential of 60V is applied axially across the specimen for 6 hours to force the chloride ions outside to migrate into the specimen. After 6 hour testing, the chloride penetration resistance of the concrete is determined in term of charge passed and chloride diffusion coefficient [6, 7]. During this test, the automatic data processing equipment is used to perform the integration and to display the coulomb value. The total charge passed is a measure of the electrical conductance of the concrete during the period of the test. In this research, the automatic data processing equipment will collect and display the values of both the current and the coulomb every 1 minute. The automatic data processing equipment used to test the charge passed and the chloride diffusion coefficient is shown in Figure 3. Regarding to the chloride diffusion coefficient, a modified test which is combined ASTM C1202 and NTBUILD 492 was used [6]. In this test, after 6 hour external electrical applying, the concrete specimen was split axially and silver nitrate solution sprayed onto one of the fresh split section. The chloride penetration depth could be measured from visible while silver chloride precipitation, then the chloride diffusion coefficient was calculated from this penetration depth together with equation described in NTBUILD 492 [7].

Table 4. Mixture Proportions Used in Research

Series	*w/b*	OPC, kg/m^3	Superplasticizer, Litre/m^3	SF, kg	Fine Aggregate, kg	Basalt Coarse Aggregate, kg	Steel Slag Coarse Aggregate, kg	C/A*
M.1	0.33	423	5.6	47	722	1089	-	0.60
M.1S	0.33	423	5.6	47	722	-	1400	0.66
M.2	0.36	396	5.1	34.4	761	1089	-	0.59
M.2S	0.36	396	5.2	34.4	761	-	1400	0.65
M.3	0.39	365	4.8	31.8	790	1089	-	0.58
M.3S	0.39	365	4.8	31.8	790	-	1400	0.64

*Mass ratio of coarse aggregate to total aggregate content

Figure 3. The automatic data processing equipment used to test the charge passed

The concrete structures, in some cases, are exposed to fire. Also, the steel slag aggregate contains high ferrite oxide content which may cause expasion during thermal cycle and make bond strength between aggregate and mortar reduce or fracture. So, in this research. After completing 28 day curing at laboratory condition, concrete specimens using the steel slag and basalt aggregate were exposed to thermal cycles. In one thermal cycle, the specimens were exposed to a dry period of 12 hours with a temperature of 100^{o}C, and then to a wet period with 22^{o}C for 12 hours. The compressive strength of concretes prepared with basalt aggregate and steel slag aggregate was determined and compared to after 45 thermal cycles. Regarding to dimensional stability of steel slag cement mortar, specimens were evaluated using expansion values of mortar bars 25x25x285mm. In this test, the mortar specimens casted with different mix proportions consisting of the steel slag were cured in the water with the controlled temperature of 22^{o}C, then the length changes of the mortar bars were determined at intervals of 7 days following ASTM C497. The standard sand was used in the test, and that the sand and steel slag fine aggregate have similar finess modulus of 2.48 and particle size distribution. The particle size distribution of the sand and steel slag fine aggregate is continuous and in range of the specification of the standard.

Results and Discussion

Unit Weight

The steel slag has significant effect on the unit weight of the concrete. This effect is presented in the Table 5. Results shown in Table 5 propose that the unit weight of the concrete increases with increasing the proportion of the coarse aggregate and varies from 2693 to 2718 kg/m^3 as the *w/b* reduces from 0.39 to 0.33 which corresponds to the increase of the steel slag coarse aggregate proportion from 0.64 to 0.66. At a specific *w/b*, the unit weight of steel slag coarse aggregate concrete is significantly higher than that of the concrete using basalt coarse aggregate. The higher density of the steel slag aggregate as shown in Table 3 is considered as a major factor which contributes to the higher unit weight of concrete using the steel slag aggregate.

Table 5. Effect of Steel Slag Coarse Aggregate on Concrete Unit Weight

Series	***w/b***	**C/A***	**Unit Weight, kg/m^3**
M.1S	0.33	0.60	2718
M.1	0.33	0.66	2406
M.2S	0.36	0.59	2706
M.2	0.36	0.65	2395
M.3S	0.39	0.58	2693
M.3	0.39	0.64	2382

*Mass ratio of coarse aggregate to total aggregate content

Compressive Strength

The compressive strength of the concrete was determined for 3, 7, 14 and 28 days after casting. At a give curing time, compressive strengths of both concretes using basalt aggregate and steel slag aggregate were evaluated and compared. The compressive strengths of the concrete by time at various curing periods are shown in Figures 4 and 5.

From Figures 4 and 5, the compressive strength of the concrete increased with the whole replacement of basalt coarse aggregate by the steel slag aggregate, and with an increase of steel slag aggregate proportion in total aggregate content. At various *w/b* ratios, with the whole basalt coarse aggregate, the steel slag aggregate made the concrete compressive strength increase about 5% to 17%. The steel slag aggregate including many pores, which are interconnected and have hard walls along the pores, contributed to a self curing regime for the concrete as the water absorbed in the interconnected pores supported for cement hydration at first days, this formed a mature cement hydration and a superior bond at an interface between the steel aggregate and mortar, as a result, the concrete compressive strength increased with the whole replacement of basalt aggregate by the steel slag aggregate. This tendency is also found in case of using porous waste ceramic aggregate for internal curing of high performance concrete [8].

There was no difference in the compressive strength development between basalt aggregate concrete and that of steel slag aggregate concrete. Basically, the compressive strength approached nearly 70% and 80% of final compressive strength at 3 and 7days respectively. And, at a specific *w/b* ratio, in general, the compressive strength characteristic of the steel slag aggregate was equivalent to that of the basalt aggregate concrete.

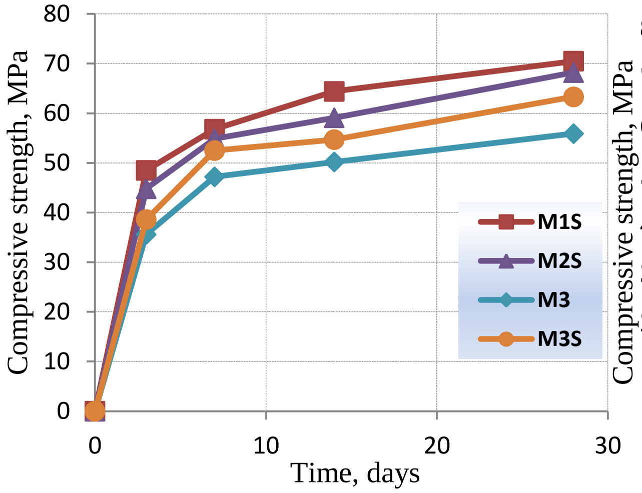

Figure 4. Compressive strength of concrete using basalt and steel slag coarse aggregate at various time

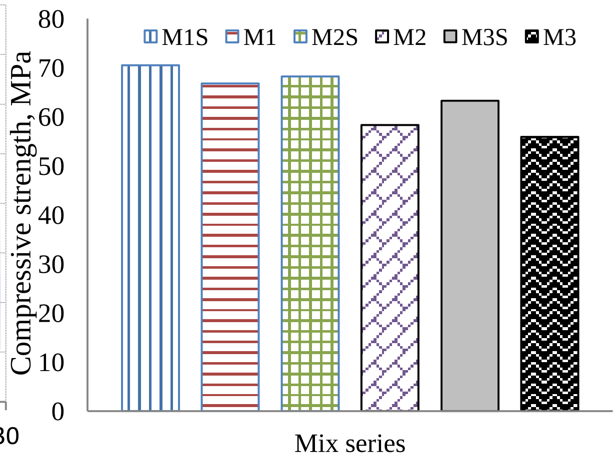

Figure 5. Comparison of compressive strengths of concretes at 28 days

Compressive Strength under Thermal Cycles

The compressive strength of the concretes prepared with basalt aggregate and steel slag aggregate exposed to thermal cycles is expressed in Figure 6. There is a strength reduction of 7 – 20% in both steel slag aggregate concrete and basalt aggregate concrete subjected to 45 thermal cycles. The strength reduction of the concrete could be due to micro cracks formation at the interface between the coarse aggregate and mortar under thermal changes. Basically, under thermal cycles, the temperature change generates differential expansion and contraction in concrete constituents. The differential expansion and contraction cause moments and result in tensile stresses at the interface, as these tensile stresses rise over the tensile strength of the concrete, the micro cracks are formed. According to Maslehuddin et al.[1], during temperature decrease, the tensile stress is set up in the cement paste, whereas, the compressive stress is formed in the coarse aggregate. And, when the temperature increases, the tensile stress in the cement paste is transferred into the interface between the cement paste and the coarse aggregate and fractures the bond at this interface with many micro cracks. Therefore, under thermal cycles, the concrete strength reduces due to the interface fracture between the paste and the coarse aggregate. However, the compressive strength decreases, in thermal cycling, are not really significant in both the basalt and steel slag aggregate concrete.

Chloride Penetration Resistance

The chloride penetration resistance of both basalt and steel slag aggregate was evaluated in terms of charge passed and chloride diffusion coefficient. The charge passed and the chloride diffusion coefficients of the concretes are shown in Figures 7 and 8, respectively.

The values of chloride diffusion coefficients and the charge passed of concretes measured at different 28 days using the basalt and steel slag coarse aggregate with various *w/b* propose that *w/b* is a major effect on both the charge passed and chloride diffusion of the concrete. The lower *w/b*, the lower charge passed and the chloride diffusion are. However, at a specific *w/b*, the chloride penetration resistance of the steel slag aggregate is better than that of the basalt aggregate concrete as both charge passed and chloride diffusion coefficient of concrete made with steel slag aggregate are significantly low when compared to those of the basalt aggregate concrete. The dense microstructure may contribute to the superior chloride penetration resistance of the steel slag aggregate concrete. As mentioned above, the interconnected porous characteristic of the steel slag is useful for matured cement hydration at first days as cement reactions need more water. The matured cement hydration forms high contents of hydrates, which are present in pores of concrete, especially at the interface between the paste and the coarse aggregate, and results in the dense structure where the pore system of the concrete becomes finer and interrupted. The finer pore system blocks mass transfer including chloride ion penetration. This particularity could be the major factor that generates the superior chloride penetration resistance of the steel slag aggregate concrete.

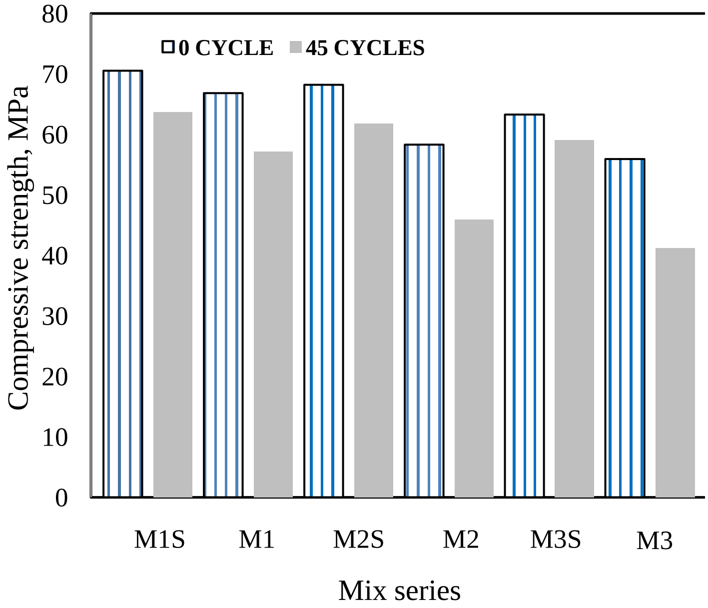

Figure 6. Compressive strength of the concrete using basalt aggregate and steel slag aggregate under thermal cycling

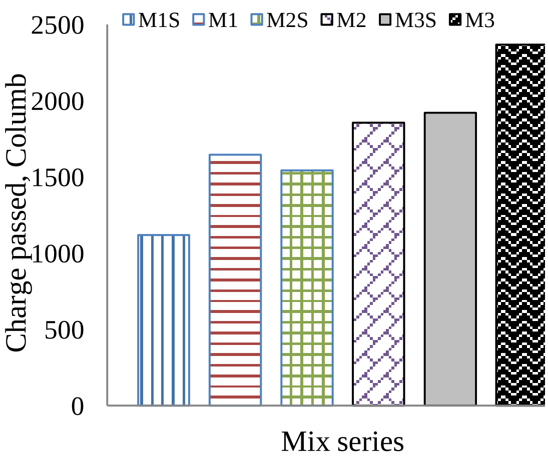

Figure 7. Charge passed of concrete prepared with basalt and steel slag coarse aggregate

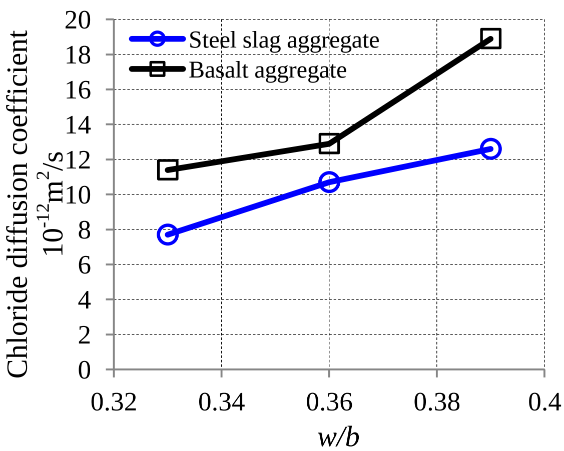

Figure 8. Chloride diffusion coefficient of concrete prepared with basalt and steel slag aggregate

The dense microstructure is one of the factors used for evaluating durability of concrete. Also, there are various methods to determine the dense particularity of the concrete involving the resistivity of the concrete. The resistivity of the concrete prepared with the basalt and steel slag aggregate was tested following the Wenner four – electrode method of ASTM WK37880 and presented in Figure 9. The resistivity results of concretes shown in Figure 9 propose a similar tendency to results of chloride penetration resistance that the concrete prepared with steel slag aggregate is denser than the concrete casted with basalt aggregate, as a result, at any *w/b*, the resistivity of steel slag aggregate concrete is always higher than that of concrete using basalt aggregate. In other words, the denser concrete, the higher resistivity of the concrete presents. Also, the resistivity property is consistent with the chloride penetration resistance. Hence, in general, the concrete casted with steel aggregate concrete is more durable than that prepared with natural basalt aggregate in terms of the chloride penetration resistance.

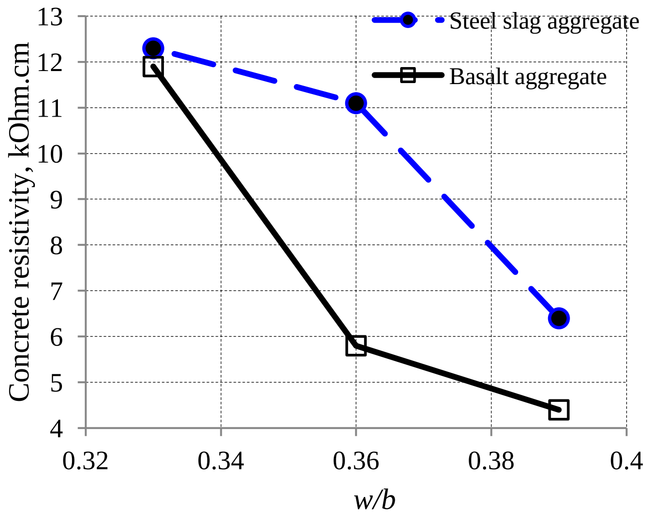

Figure 9. Resistivity of concrete prepared with various *w/b* using basalt aggregate and steel slag aggregate

Expansion of Steel Slag and Sand Cement Mortars

The expansion as length change of steel slag and sand cement mortar bars immersed in water up to 126 days is presented in Figure 10. At beginning, around the first 21 days, both steel slag and sand cement mortar were shrunk. Afterward, the steel slag and the sand cement mortars started to expand, especially with the steel slag mortar. However, expansion rate of the steel slag mortar is clearly different to that of the sand cement mortar. Figure 10 clearly shows that expansion rate of the steel slag mortar is significantly higher as compared to expansion of the sand cement mortar. At 126 days of water immersion, the expansion in length change of the steel slag mortar was 0.036%, whereas, the length change of the sand cement mortar was almost 0%. One reason for the high expansion of the steel slag mortar is that the steel slag may consist of free lime which expands slowly with water adsorption. For this problem, when the steel slag aggregate is considered to use as aggregate in the concrete, it was recommended that the steel slag aggregate should be stabilized by a method that can dismiss the free lime in the steel slag aggregate, for example, before utilizing, water spray applies regularly to the steel slag aggregate exposed to atmosphere for months. By this method, the free lime content of 0.6% in the steel slag is reduced into 0.1%.

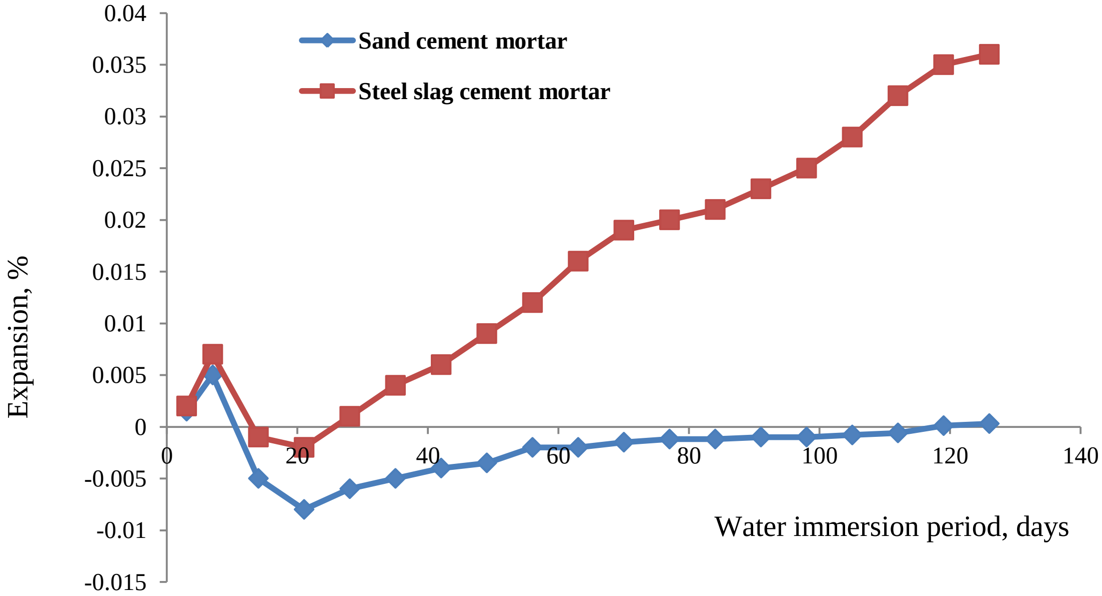

Figure 10. Expansion of the steel slag and sand cement mortars

Conclusions

The results of this investigation suggest the following conclusions:

- The steel slag coarse aggregate consisted of many interconnected pores, its bulk gravity was significant higher than that of basalt aggregate. The physical and mechanical properties of steel slag coarse aggregate were equivalent to those of basalt aggregate. However, the steel slag aggregate was superior to basalt aggregate in term of sulphate soundness.
- The unit weight of steel slag coarse aggregate concrete was significantly higher than that of the concrete using basalt coarse aggregate.
- There was no difference in the compressive strength development between basalt aggregate concrete and that of steel slag aggregate concrete. Generally, the compressive strength characteristic of the steel slag aggregate was equivalent to that of the basalt aggregate concrete.
- There was a strength reduction of 7 – 20% in both steel slag aggregate concrete and basalt aggregate concrete subjected to 45 thermal cycles. The strength reduction of the concrete could be due to micro cracks formation at the interface between the coarse aggregate and mortar under thermal changes.
- The concrete casted with steel aggregate concrete was more durable than that prepared with natural basalt aggregate in terms of the chloride penetration resistance.
- At 126 days of water immersion, the expansion in length change of the steel slag mortar was 0.036%, whereas, the length change of the sand cement mortar was almost 0%. One reason for the high expansion of the steel slag mortar was that the steel slag may consist of free lime which expands slowly with water adsorption.

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