COMBINED EFFECT OF STEEL SLAG AS A PARTIALLY REPLACED MATERIAL FOR COARSE AGGREGATES AND WATER–CEMENT RATIO ON THE CHLORIDE RESISTANCE OF CONCRETE

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Abstract

Test was carried out to study the effect of the utilisation of steel slag (SS) as a coarse aggregate for concrete work to assess the chloride resistant in Concrete. Seventy-two (72) specimens were prepared with three water-cement ratios (0.58, 0.64 and 0.70). For each series of water-cement ratio twenty-four (24) specimens were prepared for each series, and concrete was designed with various amount of aggregate proportion with Natural aggregate (NA) and steel slag (10%, 50%, and 100%). The size of specimens used was 150 mm diameter x 60 mm height and 1M sodium chloride (NaCl) solution was prepared for 90-days immersion test. Weight change, dimension changed and depth of chloride penetration were monitored throughout the duration period. Effect of steel slag aggregate and water-cement ratio (w/c) proportion on chloride resistant are presented and analysed. There is no significant change in weight and dimension with respect to SS replacement was found. Specimens with 100% SS have a lower chloride depth penetration compared to concrete those made of 100% NA, 10% SS, and 50% SS. The value of weight change decreased with increasing w/c, but the optimal effect on the dimension and chloride penetration increased with increasing w/c for all mixes.

Keywords: Natural aggregates; concrete; steel slag; chloride diffusion

1.0 INTRODUCTION

Nowadays, concrete still is one the most important building materials in the works of civil engineering all over the world. The primary requirements of good concrete in its hardened state are strength and durability. For this reasons a great number of research projects have been directed towards various factors influencing its strength or causing its disintegration. Since aggregate constitutes the major part of the mix, the more aggregates in the mix, the cheaper is the cost of the concrete, provided that the mix is of reasonable workability for the specific job for which it is used. Properties of the coarse aggregate affect the final strength of the hardened concrete and its resistance to disintegration, weathering, and other destructive effects.

The American Society for Testing Materials (ASTM) defines steel slag as a none- metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminium, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces. This slag can have a high concentration of heavy metals. There are hundreds of grades of steel ranging from basic carbon steel to high grade stainless (Ziemkiewicz, 1998). Most of the SS that was produced from the steel making was sent to the waste disposal site (National Slag Association, 1918). Most SS is used as an aggregate and one example is SS

use as unbound for asphalts concrete pavement in many countries (Emery, 1981 and Collins, 1994). SS has been used successfully for many years as a construction aggregate. SS aggregates are typically used within close proximity (50 miles) of the producing steel mill, therefore, restricting availability and application in many parts of North America. Where SS is available, its use in base applications can be considered, providing that both the material and the application have been carefully evaluated. SS had also been crushed to be reused as roadbed, parking lots, base and subbase of highway and landfill materials (National Slag Association, 1918). However, the use of SS as coarse aggregate should be given a priority from technical, economical, and environmental considerations (Abdulkerim, 2005). Large tonnages of slag waste produced in the iron and steel industry and space for dumping them has become a problem. Any means of utilizing the slag would be welcomed. Although blast furnace slag is known to be widely used in the manufacture of cement, the use of SS for civil engineering purposes has not been given much encouragement in the literature. This study will assist the Malaysian steel industry in easing the problem of waste disposal. An effort has been made to make their slag potentially useful in civil engineering with hopefully, some revenue earned from the disposal of the now unwanted material.

Chloride ingress into concrete is the factor that affects the durability and service life of concrete. The chloride diffusion in concrete commonly present in two ways as known as external and internal. Internal factor such as chloride occurs during the mixing of concrete and external factor such as chloride ion penetrates into the concrete from external environment during the service life of concrete. The rate of the ingression of chlorides into concrete depends on the pore structure of the concrete, which is affected by factors including materials, construction practices, and age. The penetrability of concrete is obviously related to the pore structure of the cement paste matrix. This will be influenced by the water-cement ratio of the concrete, the inclusion of supplementary cementing materials which serve to subdivide the pore structure (McGrath, 1996), and the degree of hydration of the concrete. The older the concrete, the greater amount of hydration has occurred and thus the more highly developed will be the pore structure. This is especially true for concrete containing slower reacting supplementary cementing materials such as fly ash that requires a longer time to hydrate (Tang and Nilsson, 1992; Bamforth, 1995). The rate of chloride penetration into concrete is affected by the chloride binding capacity of the concrete. Concrete is not inert relative to the chlorides in the pore solution. A portion of the chloride ions reacts with the concrete matrix becoming either chemically or physically bound, and this binding 4 reduces the rate of diffusion. However, if the diffusion coefficient is measured after steady-state conditions have been reached, then all the binding can be presumed to have taken place and this effect will not then be observed. If a steady state condition has not been reached, then not all the binding will occur and this will affect the results. The chloride binding capacity is controlled by the cementing materials used in the concrete. The inclusion of supplementary cementing materials affects binding, though the exact influence is unclear (Byfors, 1986; Rasheeduzafar, et al., 1992; Sandberg and Larrson, 1993; Thomas, et al, 1995). Also, the C3A content of the cement influences its binding capacity, with increased C3A content leading to increased binding (Holden, et al., 1983; Midgely and Illston, 1984; Hansson and Sorenson, 1990).

According to Timothy (2000), the deterioration of concrete structure due to reinforcement corrosion is a major problem facing the construction industry worldwide. Reinforcement corrosion is caused either by chloride ion or carbonation (Dehganin and Lock, 1981; Rasheeduzzafa et al., 1990; Lambert, 2002;). Chloride may present into concrete with two ways as internal and external. Hence, there is a need to study the chloride resistant on concrete containing SS as coarse aggregates to make a comparison in chloride resistant between concrete with and without SS and various of w/c ratios.

2.0 MATERIALS AND METHOD

2.1 Materials

All materials used in the experiments were produced in Malaysia. Commercially available Ordinary Portland Cement (Type I) was used for this purpose. This cement has a specific gravity of 3.15. Potable

drinking water obtained from Concrete Laboratory, Universiti of Teknologi MARA, Malaysia was used for this work. This water is, therefore, suitable for concrete work (BS3148, 1980).

Coarse aggregate used in this research is mixed with the natural aggregate and SS which are available at UiTM Concrete Laboratory as shown in Figure 1. The size of aggregates used is 10 mm and 20 mm. Both types of aggregate crushed stone having an angular shape and rough surface texture with air-dried condition. The size chosen is as described in BS8110 (1997) and specifications issued by Public Work Department of Malaysia. The size 10 mm is defined when an aggregate passing 14 mm sieve and retaining at 10 mm. The size 20 mm is defined when an aggregate is passing 28 mm sieve and retaining at 20 mm according to BS8110 (1997). The fine aggregate is normal sand obtained from a borrow pit. A preliminary laboratory investigation was conducted to ascertain the suitability of using the aggregates for construction work.

The SS was added into the mix with different proportions to the total aggregate. The proportions of the SS that was added into the mixed material together with natural aggregate to produce concrete are 0%, 10%, 50% and 100%. These aggregate proportions were utilized to evaluate the effect of quantity of coarse aggregate on the properties of hardened SS concrete.

2.2 Mixture Proportions

A nominal mix ratio of 1:2:4 (Cement: Fine Aggregate: Coarse Aggregate) was adopted for the purpose of this work. Table 1 provides mix proportion of the SS series in which binder composition is invariable and water to binder ratio 0.58, 0.64 and 0.70 were used. The mix composition was computed using the absolute volume method and the batch compositions are shown in Table 1. Single tests were performed on the control specimen without SS to avoid the effect of coarse aggregate on concrete behaviour. In an attempt to optimize SS content with respect to the behaviour, the coarse aggregate was partially replaced in concrete at four replacement levels (0%, 10%, 50%, 100% by volume of coarse aggregate). It should be noted that the w/c ratio dosage of SS was initially designed to be invariable for these mixes. However, as the SS replacement level increases, a satisfied fluidity (slump >100 mm) of the fresh mixture was needed to realize the good dispersion of coarse aggregate and good homogeneity of a matrix. The preferred formulation was further fixed to investigate the effect of w/c ratio and SS dosage.

(a)   (b)

Figure 1 Aggregates; (a) Natural aggregate, (b) SS aggregate

2.3 Specimen preparation curing and Experimental methods

The specimen preparations were conducted at the temperature of $20 \pm 5°C$ and relative humidity of about 65%. A forced single-axis mixer with a rotational speed of 45 rpm was used to prepare the mixture. The mixture with SS was casted in a mould and vibrated for 10 s after workability test. Specimens were

covered with plastic sheets and stored at room temperature for 1 day, then moved to a standard curing room with a temperature of $20 \pm 2°C$ and relative humidity of greater than 95%.

(a)   (b)

Figure 2 Specimen with NA at 0.58 w/c ratio immersed in 1M NaCl Solution after 28 days (a) before spraying with AgNO₃ (b) after spraying with AgNO₃.

To assess the weight changed, expansion changed and depth changed between normal aggregate and SS matrix, a type of cylinders mould with a dimension of 150 mm x 60 mm was adopted. All specimens were then immersed into the saturated 1M NaCl solution until 90 days after 28-day water curing and 1-day air drying. After 28 days each specimen with different w/c ratio and percentages of SS was tested. 0.5M AgNO₃ has been used for determining the depth of penetration for chloride on the specimens. After specimens were cut into 2 sides, 0.5M AgNO₃ were sprayed to observe the changes in colour as shown in Figure 2. The presence of whitish precipitation on the concrete surface after spraying with 0.5M AgNO₃ indicates the presence of chloride.

All specimens were tested based on the immersion of the specimen into 1M NaCl solution. The test solution was prepared and stored in a plastic container and fully covered by the hood to minimize the evaporation that might occur. After 28 days the specimen was taking out from curing tank. The change of weight was determined by using weight scale. The weight after immersion into 1M NaCl solution was reduced. The change of expansion was determined by using digital calliper. The weight after immersion into 1M NaCl solution was also reduced. After measuring the weight and expansion, the specimen was cut into 2 slides as shown in Figure 3. Silver nitrate was sprayed onto the surface after it has been cut. After a while, the depth of chloride penetration was measured by looking the changes in colours. The white colours mean chloride occurs and the brown area means no chloride occurs. Six (6) reading has been taken and the average depth is the total depth of chloride penetration. The depth has been measured by a ruler in millimetres (mm).

(a)   (b)
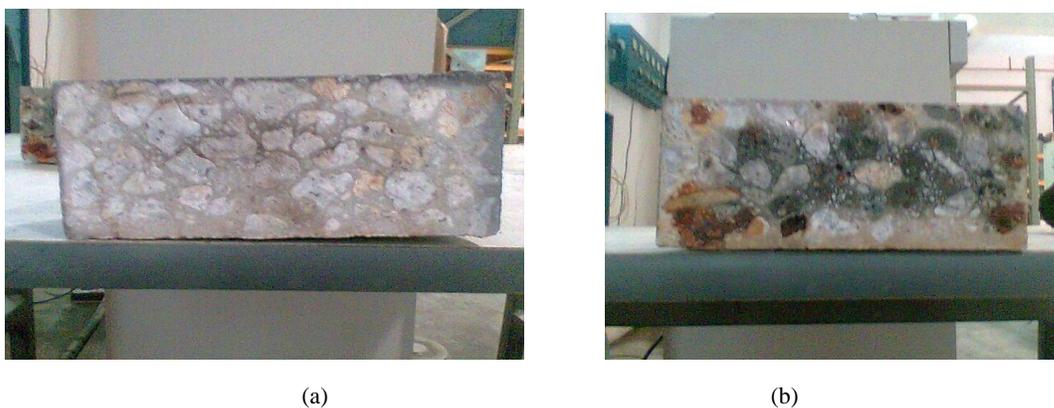
(c)

Figure 3 Specimen has been immersed in 1M NaCl solution until 90 days for 0.70 w/c ratio (a) NA after spray with AgNO₃ (b) 10% SS after spray AgNO₃ (c) 100% SS after spray with AgNO₃.

3.0 RESULTS AND DISCUSSIONS

Table 2 shows the results of weight change, expansion and chloride penetration depth of all specimen series with a replacement of 0, 10%, 50% and 100% SS when immersed in 1M NaCl solution up to 90 days made of a various w/c ratio.

3.1 Effect of Concrete Specimens for Different SS Replacement

It is accepted that another key parameter affecting the weight changes behaviour of a concrete specimen is SS dosage. In this section, with the coarse aggregate replacement level fixed at 0.58, 0.64 and 0.70 w/c ratio, four smooth SS dosage were adopted as shown in Table 2 (0, 10%, 50% and 100%) to study the influence of SS dosage on weight changes behaviour of concrete incorporating coarse aggregate. It appears that the weight change for all specimens were increased. The increasing happens because of the expansive reaction products that filling up the pores of the concrete. The density of concrete specimens was higher due to the immersion into 1M NaCl solution and thus increasing the weight. Also, it is clear that SS has an optimal point of 100% replacement with respect to the weight changes concrete specimen. As SS replacement further increases to 10%, a declined weight change of concrete specimens is observed. The result shows that SS that made of 100% SS replacement level is comparable with natural aggregate. This also means no significant different in weight change for the all specimens. It occurs because concrete should be examined as three-phase materials, thereby coarse aggregate should be proportioned depending on the cement content and its surface area. SS aggregates generally exhibit a propensity to expand. This is because of the presence of free lime and magnesium oxides that have not reacted with the silicate structures and that can hydrate and expand in humid environments. This potentially expansive nature (volume changes of up to 10% or more attributable to the hydration of calcium and magnesium oxides) could cause difficulties with products containing SS and is one reason why SS aggregates are not suitable for use in Portland cement concrete (National Slag Association).

The physical properties of SS that have a higher percentage of void and higher water absorption than natural aggregates also can cause the increasing percentage weight change of the specimen. The higher percentages of weight change, the better the concrete resists against the sodium chloride attack. The chloride binding in OPC for all water-cement ratio from NaCl was intermixed and the specimens cured for 28, 56 and 90 days prior to testing. The number of bound chlorides increased with increasing curing time, although most of the binding happened before 28 days (Arya et al.,1990). All the concrete

specimens were rusted except the natural aggregate (0% SS) after 28 days immersed in 1M NaCl solution. The replacement of SS into mix design has given no significant weight change.

Table 1 Mix proportions of Concrete.

W/C	Mix	Cement (kg/m³)	Water (kg/m³)	Coarse aggregate (kg/m³) 10 mm and 20 mm		Sand (kg/m³)
				NA	SS	
	SS - 0%	390	225	1150	-	620
	SS -10%	390	225	1035	115	620
0.58	SS - 50%	390	225	575	575	620
	SS – 100%	390	225	-	1150	620
	SS - 0%	355	225	1175	-	635
	SS -10%	355	225	1057.5	117.5	635
0.64	SS - 50%	355	225	587.5	587.5	635
	SS – 100%	355	225	-	1175	635
	SS - 0%	325	225	1200	-	645
	SS -10%	325	225	1080	120	645
0.70	SS - 50%	325	225	600	600	645
	SS – 100%	325	225	-	1200	645

As mentioned above, another key parameter affecting due to expansion behaviour of concrete specimens is SS %. In this section, three different water-cement ratios with dosage fixed at 0, 10%, 50%, and 100% were adopted. For 0.58 w/c ratio, the higher expansion is 0% and the lowest expansion is 50% SS after 90 days immersed. The result shows the change and increase of expansion for all specimens is comparable. That means, the expansion of concrete specimens is no affected by replacement of SS. At 0.64 w/c ratio, the higher percentage expansion is 0% SS which the value is 0.408%, followed by 50% SS which the value is 0.405% then 0.400% percentage expansion for 10% SS and the lower percentage expansion is 100% SS which the value is 0.399%. After 28 days, all concrete specimens were rusted and breaking out due to sodium chloride except for 0% SS specimen. The lower percentage changes are the better of chloride resistant. At 0.7 w/c ratio, it shows that the percentage expansion for two proportions is similar to the 50% and 100% SS which increased due to time. The expansion for NA at 28-day is 0.169% and increased to 0.413% after immersion into 1M NaCl solution for 90 days. Lastly, the expansion for 10% SS for 28 days is 0.165% and increased to 0.408% for 90 days. It can be seen that all the concrete specimens have an increasing rate of expansion due to time after immersion into 1M NaCl solution for 90 days. This situation can be explained by increasing water-cement ratio that also can increase the concentration of sodium chloride solution. This will allow the chloride reacts with C3A in OPC, thus can cause the expansion increase of the specimen due to time. The lower percentage change is the better chloride resistant.

All the concrete specimens show the increasing of chloride depth change due to time. It is because the sodium chloride solution has a better concentration at 90-day immersion compared to 28-day immersion. The longer time also gives the opportunity to chloride reacts with C3A on concrete to penetrate the chloride diffusion. Table 2, also shows the lower percentage of chloride penetration depth is mostly for 100% SS replacement and the higher percentage of chloride penetration depth is NA for all concrete specimens. From this result, 100% SS is better chloride resistant compared to NA. All the specimens were rusted and corrosion occurs at SS aggregate after 28 days except for NA. Almost the 100% SS replacement is the lower percentage depth of chloride diffusion. NA concrete is the higher percentage depth of chloride diffusion. It means the lower percentage is the better chloride resistant.

Table 2 Weight Changes, Expansion and The Chloride Penetration Depth Changed of SS specimens with various w/c ratio.

W/C Ratio	SS (%)	Weight Changes (%)			Expansion (%)			Chloride Penetration Depth (%)		
		28 days	56 days	90 days	28 days	56 days	90 days	28 days	56 days	90 days
0.58	0	0.262	0.386	0.500	0.113	0.290	0.401	20.00	35.00	41.67
	10	0.272	0.376	0.488	0.103	0.299	0.391	25.00	31.67	38.33
	50	0.324	0.418	0.494	0.098	0.271	0.377	26.67	30.00	33.33
	100	0.285	0.395	0.504	0.095	0.291	0.385	18.33	25.00	28.33
0.64	0	0.273	0.368	0.483	0.100	0.279	0.408	30.00	33.33	43.33
	10	0.282	0.382	0.480	0.125	0.287	0.400	15.00	30.00	40.00
	50	0.271	0.401	0.486	0.104	0.282	0.405	20.00	25.00	28.33
	100	0.299	0.391	0.497	0.108	0.284	0.399	18.33	21.67	25.00
0.70	0	0.290	0.364	0.481	0.169	0.371	0.413	33.33	41.67	50.00
	10	0.287	0.360	0.475	0.165	0.341	0.408	31.67	40.00	46.67
	50	0.270	0.404	0.484	0.179	0.301	0.414	28.33	36.67	41.67
	100	0.277	0.378	0.490	0.182	0.303	0.403	26.67	33.33	38.33

3.2 The Effect of W/C Ratio

As shown in Figure 4 and Table 2, the overall w/c ratio of all specimens are identical, irrespective of SS % when immersed in 1M NaCl solution at 90 days. It can be seen that the weight of concrete specimens increases slowly with age. This is because of the relatively dense structure of concrete associated with very low w/c ratio, which did not exhibit enough free water for further hydration of binder at later ages. It is also shown that the weight decreased as the concrete grade decreased. However, w/c ratio has a strong effect on expansion, especially in the 0.70 ratios. For w/c ratio, the concrete with deformed shows a higher expansion property, compared with the low ratio. Differences observed in the depth of chloride penetration properties are attributed to different properties associated with w/c ratio. As shown in Table 2, the depth of chloride penetration is highest and it is almost two times higher than that of smooth 0.70 ratios. It can be seen that the lower w/c ratio of concrete would decrease the depth of chloride penetration. The low w/c ratio means the low of permeability of concrete. A concrete with low permeability improves resistance to chloride ion penetration and diffusion (U.S Department of Transportation, August 2000). The weight decreased but expansion increased when w/c ratio increased can be explained as in w/c ratio increased, the chloride may penetrate into concrete and react with C3A and cause the increasing of expansion and decreasing of the weight.
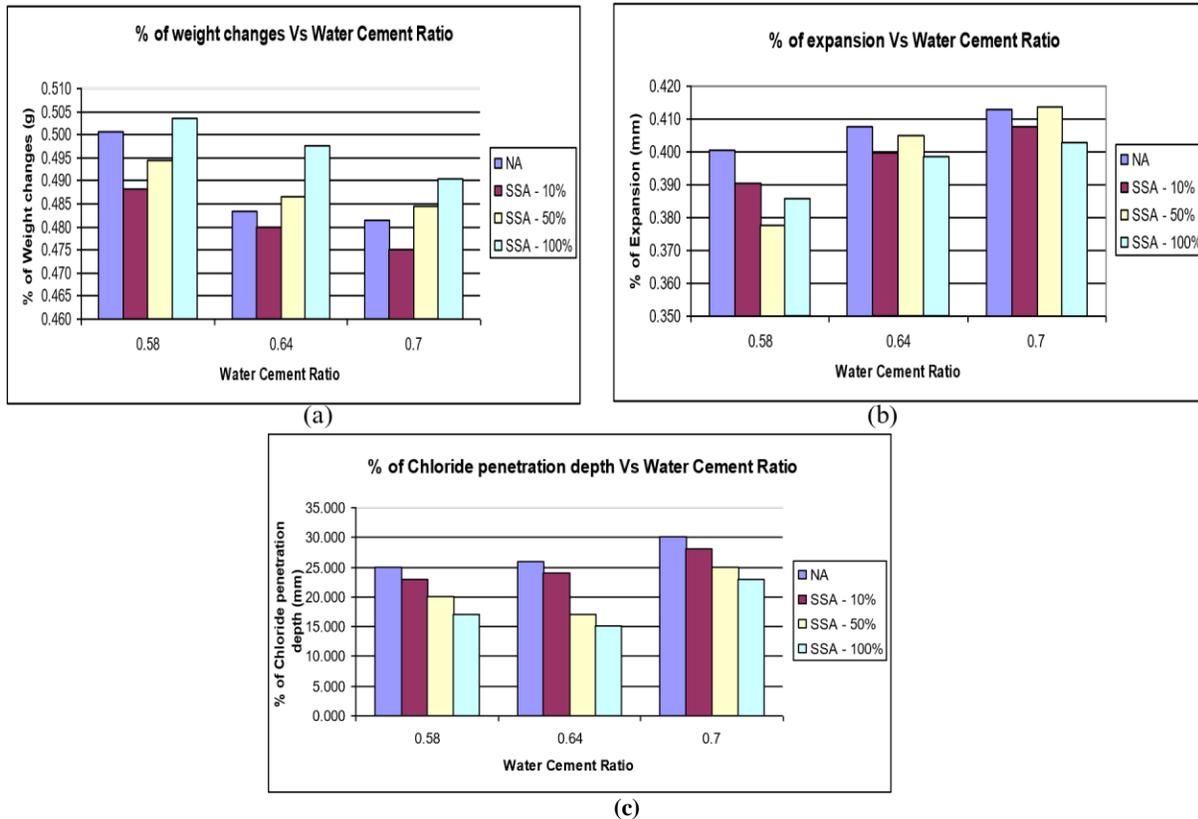
Figure 4 Concrete specimens made of various SS replacement level at various water cement ratio which is immersed 1M NaCl solution at 90 days. (a) Weight changes, (b) Expansion of dimension (c) Depth of chloride penetration

4.0 CONCLUSION

In this study, SS behaviour of concrete incorporating coarse aggregates was investigated. Three types of w/c ratio behaviour between these SS and matrix was also performed. Combined effect of SS and w/c ratio on the overall properties was analysed. With respect to performed tests their results have shown and compared in tables and figures and the following results are obtained:

- The concrete that uses 100% SS is better in chloride resistant compared to concrete without SS because from the result, the specimen with 100% SS have a lower chloride depth penetration compared to NA, 10% SS, and 50% SS. It shows the use of SS as coarse aggregates improves the chloride resistant of the concrete.
- This was explained by that at higher w/c there was more water to dilute the chlorides, and when this was taken into account the chloride binding was approximately independent of w/c (Tritthart, 1989b).
- The value of percentage expansion chloride penetration change increased when w/c ratio increased for all mix. This may be due to increased degree of hydration with increasing w/c.
- The chloride intrusion increased with increasing w/c as expected.
- The result for weight and dimension change is comparable with 100% NA, SS has not affected the weight and dimension change.
- The value of percentage weight change is decreased when w/c ratio increased for all mix.
- The low w/c ratio and a large amount of SS aggregate as coarse aggregate in concrete are better chloride resistant.

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