

Some Durability Aspects Of Mortar Incorporating Local Activated Water-Cooled Slag

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ABSTRACT

This paper aims to investigate the effectiveness of the mechanical activation of local water-cooled slag (WCS), to protect mortars exposed to aggressive environments. OPC mortar samples made with different contents of WCS (0, 20, 35 and 50%, by weight of OPC). WCS with various finenesses (0.5, 2.0 and 3.3 m²/g) were prepared, and mortar samples were exposed to different environments of sulphates, chlorides and combined solution of sulphates and chlorides. The examined mortar properties included the compressive strength, expansion, weight gain, and determination of chloride profile and penetration depth. 50 mm cubical specimens were used for determining the compressive strength at various ages of 8, 16, 26 and 52 weeks, while 25.4x25.4x285 mm prisms were utilized for measuring both the weight and length change regularly every two weeks through the period of one year. Two 75x150 mm cylinders were prepared from each mortar mix to establish chloride profile and depth of chloride penetration into the cover zone. The results showed that mechanical activation of the local slag had led to appreciable reduction in the degradation of OPC mortar. The expansion, weight gain and chloride penetration were significantly reduced due to the use of WCS in mortar. The environment containing sulphate ions only was the harshest on mortar samples regarding length and weight change.

Keywords

Slag; Activation; Expansion; Hydration; Chloride ingress

1. INTRODUCTION

Durability is very important for any construction material, because it directly affects the economics, serviceability, and maintenance of the structure. The durability of concrete depends on various factors such as exposure conditions, internal properties of the concrete, and the type and quantity of constituent materials. Because nearly all concrete deterioration processes are driven in some

manner by the ingress of water and water-borne agents, one way to minimize retrogression is to make the concrete less permeable. This densification is achieved by using lower water-cementitious materials ratio (w/b) and supplementary cementitious materials (SCMs) [1].

Blast-furnace slag is the non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, which develop in a molten condition simultaneously with iron in a blast furnace. Dependent upon the cooling method used, slag is categorized into three basic types, air-cooled (ACS), granulated water-cooled slag (WCS), and expanded slag. Air-cooled slag is the material resulting from solidification of molten blast-furnace slag under atmospheric conditions. Subsequent cooling may be accelerated by application of water to the solidified surface. Granulated slag is the glassy, granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water. Expanded slag is the light weight cellular material obtained by controlled processing of molten blast-furnace slag with water, sometimes with other agents, such as steam, or compressed air [2].

Slag hydraulic reaction is relatively slow, and the use of activator is beneficial. Typically, OPC is used as activator, as it provides gypsum and calcium hydroxide to the mix. However, in low OPC content mixes, additional alkali can be added. Slag activators are usually termed alkaline (sodium hydroxide, sodium carbonate, and sodium silicate) or sulphate (gypsum, hemihydrate, anhydrite, phosphogypsum, and sulfur in the slag) [3]. Mechanical activation by high-energy grinding is also suggested to improve the reactivity of the blended cement [4].

The effectiveness of water-cooled slag (WCS) on the various characteristics of concrete, such as rheology, compressive strength, freezing and thawing, permeation and shrinkage, has been extensively investigated and scrutinized by several authors [5-7]. Most of the literature has stated that the inclusion of WCS in concrete mixes had notably improved concrete characteristics, due to the pozzolanic reaction,

resulting in a denser concrete microstructure [7]. However, the use of local Egyptian slag in concrete is not extensive in construction industry due to its moderate reactivity index. Therefore, the present study is undertaken with the following objectives:

1. To study the possibility of adopting the mechanical activation technique for enhancing the performance of the local slag.
2. To investigate the impacts of water-cooled slag content and fineness on the rate of compressive strength loss, percent expansion, and percent weight gain of OPC mortars.
3. To assess the role of WCS content and fineness on the total chloride profile and penetration depth in mortar.

2. EXPERIMENTAL WORK

Clean siliceous natural sand complying with ASTM C33 was used. Local ordinary Portland cement (OPC) complying with BS 12 (1978) and ESS 373 (1991) was utilized throughout the work. Local water-cooled slag was also considered as a source of cement replacement material. The chemical analysis and surface area of both OPC and WCS are listed in Table 1. The water-cooled slag was produced by rapid quenching of slag in water. The water-cooled slag was oven dried at 105 °C for 24 hours to remove the moisture, which occurred during the granulation process. The grinding of WCS was performed using a laboratory ball mill with maximum capacity of 10 kg. The surface area of the slag was measured volumetrically from the adsorption of the nitrogen gas at the liquid nitrogen temperature (-195.8 °C) using a BET volumetric apparatus. The surface area of the produced slag samples were 0.5, 2.0 and 3.3 m²/g.

Table 1 Chemical analysis and surface areas of OPC and WCS.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	LOI	Surface area, m ² /g
OPC	21.51	6.01	2.54	66.3	1.5	0.62	0.21	1.81	2.6	0.37
WCS	44.05	13.78	1.73	36.2	0.3	0.6	0.15	2.07	0.2	0.5, 2 and 3.3

Seven mortar mixes made with w/b ratio of 0.55 and WCS content of 0, 20, 35 and 50%, (replaced by dry weight of OPC) were studied. Slag with finenesses of 0.5, 2.0 and 3.3 m²/g was used. Constant binder/sand ratio of 0.50 was used throughout the testing program.

The constituents of mortar mixes were mechanically mixed according to BS 5075 part 2 (1982). Three 50 mm cubical mortar specimens were prepared for the compressive strength measurements. Nine prismatic specimens of 25.4x25.4x285 mm from each mortar mix were prepared for both length and weight change measurements. Such specimens were attached with stainless steel gauge studs of 6 mm diameter, fixed throughout their axes, according to ASTM C490 (1983). Moreover, two cylinders of 75x150 mm from each mortar mix were prepared for determining the chloride profile and penetration depth.

After casting, all samples were covered with polyethylene sheet for 24 hours, and then stored in water tanks for 27 days prior to exposing to aggressive solutions. Mortar specimens prepared for compressive strength and both length and weight change measurements were fully submerged in their specified aggressive solutions containing either 10% sodium sulphate (Na₂SO₄) or 10% sodium sulphate (Na₂SO₄) + 5% sodium chloride (NaCl). Both upper and lower surfaces of cylindrical mortar specimens prepared for total chloride profile and penetration measurements were coated with epoxy to achieve unidirectional flow. Once the epoxy dried, the cylinders were fully submerged in solution containing 5% sodium chloride for an exposure period of 10 months. Meanwhile, three specimens from each mortar mixes were stored in water and used as control specimens.

The compressive strength of mortar specimens was recorded at ages of 8, 16, 26 and 52 weeks. The length of mortar specimens were regularly recorded every two weeks, according to ASTM C190 (1983), to monitor percent expansion. The percent weight gain was also recorded for all specimens prepared for length change measurements. On the other hand, each cylinder intended for chloride penetration was vertically cut into two halves. Both halves were sawn sprayed with 0.1 N silver nitrate solution indicator. The color of the sprayed surface changes due to the precipitation of white AgCl if the chloride ion was present. The depth of chloride penetration was considered as the average of six measurements (three on each side of the split sample). For all tests, triplicate specimens were used and the average of the results was considered.

To determine total chloride profile, the specimens were taken at various depths using a drill. The drilling processes were carried out at progressive depths up to 50 mm into the specimen from the surface. The dust produced was sieved through a 150 µm sieve to obtain a homogeneous sample. The amount of total chloride content according to BS 1881: part 124, 1989 was measured.

3. RESULTS AND DISCUSSION

3.1 Compressive strength

Figure 1 illustrates the compressive strength development of OPC and OPC-WCS specimens exposed to different environments. For specimens immersed in water, the compressive strength measured increased as a result of increasing the curing period. The compressive strength of the 20% WCS specimens remained higher than the corresponding control OPC specimens until the end of the exposure period. While, the compressive strength of the 35% and 50%

WCS specimens were lower than that of the control mortars for exposure period of about 24 weeks, after which they started to exceed the corresponding OPC mix.

At severe sulphate environments, it was found that the compressive strength for all mortar specimens increased up to 26 weeks and then decreased up to 52 weeks, see Figure 1.b. The reduction in the compressive strength at the end of exposure period reached about 11, 10, 7 and 6% for OPC, 20%WCS, 35%WCS and 50%WCS specimens, respectively, compared with the corresponding compressive strength at 26 weeks of exposure.

It can also be noted, from Figure 1.b that, the compressive strength of the 20% WCS specimens remained higher than that of the corresponding OPC specimens until the end of the exposure period. Whilst, for exposure period up to 24 weeks, the compressive strength of the 35% and 50% WCS specimens remained lower than that of the OPC specimens. After 24 weeks and up to 52 weeks, the compressive strength of all specimens made with WCS was higher than that of the corresponding OPC specimens.

The increase in the compressive strength of OPC and OPC-WCS mortars stored in water is attributed to the progress of normal hydration of cement and pozzolanic reaction of WCS. Whilst, the initial increase in the strength of the specimens stored in sodium sulphate solution is due to the formation of small volume of calcium sulpho-aluminate (ettringite) crystals which help to fill the pores [8]. Yet, at longer exposure periods, such crystals increase in volume and create internal tensile stresses causing a reduction in the compressive strength. Furthermore, it was found that sodium sulphate can damage the mortar, due to the formation of the anhydrous and hydrated forms of those salts which leads to excessive volume changes [8].

Figure 1.c shows the compressive strength of OPC and OPC-WCS mortar specimens immersed in 10% Na₂SO₄ + 5% NaCl solution. Similar trends as those found for the specimens immersed in 10 %Na₂SO₄ was noticed. However, the compressive strength of specimens immersed in 10% Na₂SO₄ + 5%

NaCl solution was higher than the corresponding samples immersed in 10% Na₂SO₄ solution. The slight increase in the compressive strength of the specimens stored in 10% Na₂SO₄ + 5% NaCl solution, when compared to that stored in 10% Na₂SO₄ solution may be attributed to the formation of calcium chloro-aluminate (Friedel's salt) as a product of the chemical reaction between the aluminate phase and chloride ions. This product fills the mortar pores reducing mortar porosity and hence increasing the compressive strength [8-10].

Figure 2 demonstrates the impact of WCS fineness on the compressive strength. As seen, for the various environments, the compressive strength of tested mortar specimens increased as the WCS fineness increases. This could be attributed to the surface area of the slag particles that is exposed for the pozzolanic reaction. The finer the slag particles, the larger the surface area for the calcium hydroxide to react with and hence a better pozzolanic reaction, and a higher compressive strength can be achieved.

Additionally, when the mortar specimens were immersed in 10% Na₂SO₄ + 5% NaCl solution, the compressive strength was reduced by about 21, 19, 15 and 19% for control OPC, 0.5 m²/g, 2.0 m²/g and 3.3 m²/g WCS finenesses respectively. Whilst, in case of 10% Na₂SO₄ solution, the compressive strength was reduced by 29, 26, 20 and 22% for control, 0.5 m²/g, 2.0 m²/g and 3.3 m²/g WCS finenesses respectively, when compared to the corresponding of that immersed in water. This could be attributed to the positive effect of the presence of chloride ions as discussed above.

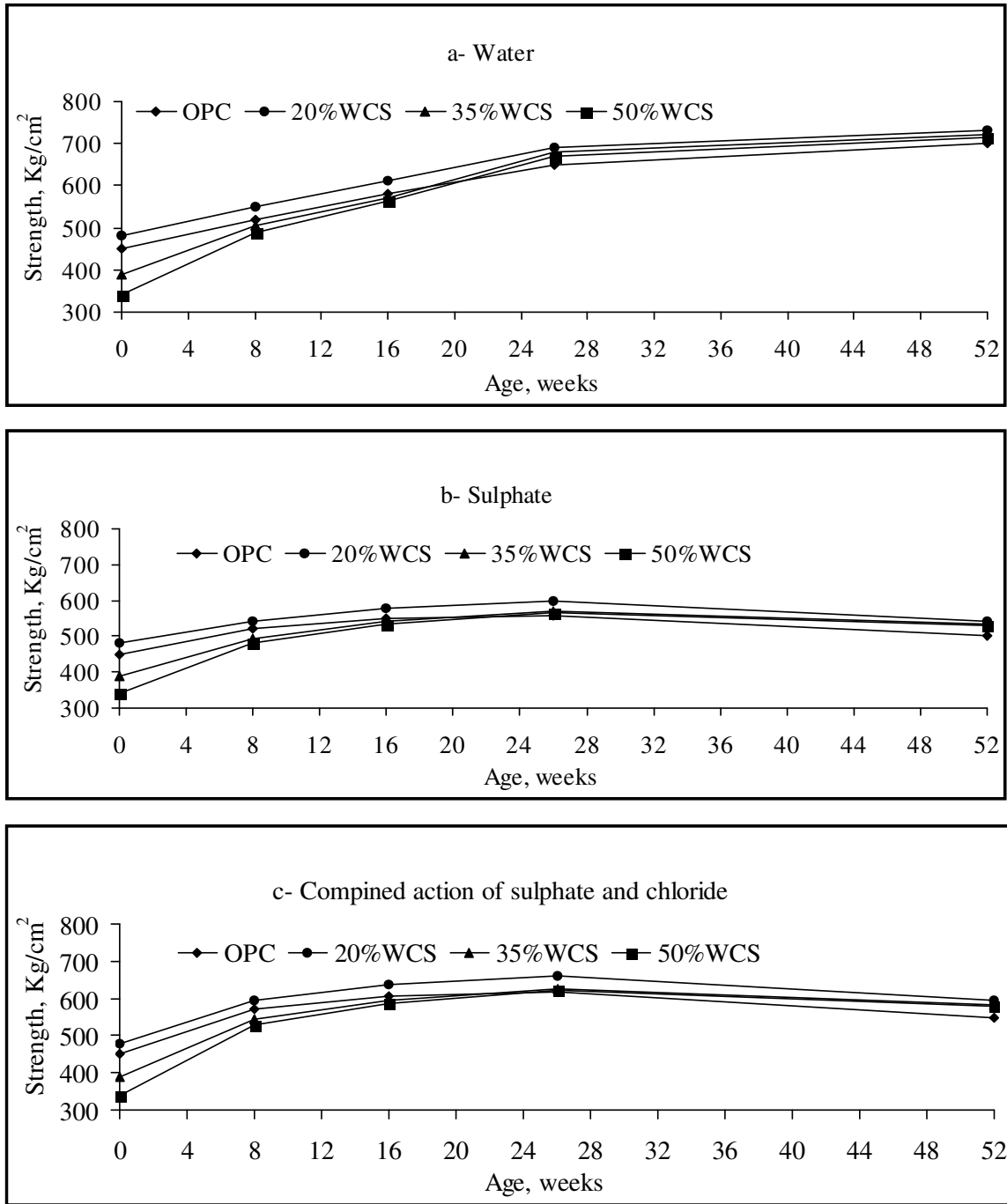


Figure 1: Strength of OPC and slag mortar specimens exposed to various conditions.

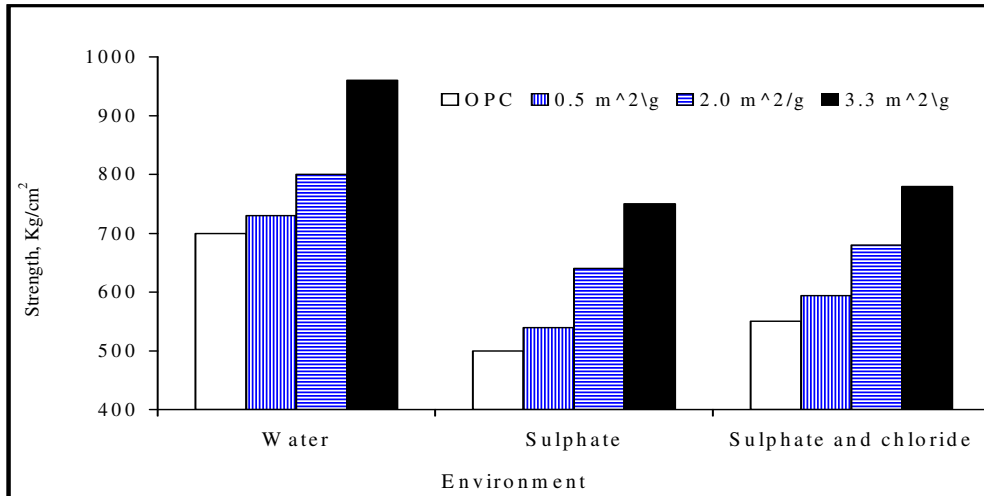


Figure 2: Strength of OPC mortar made with various finesses of WCS when exposed to various conditions.

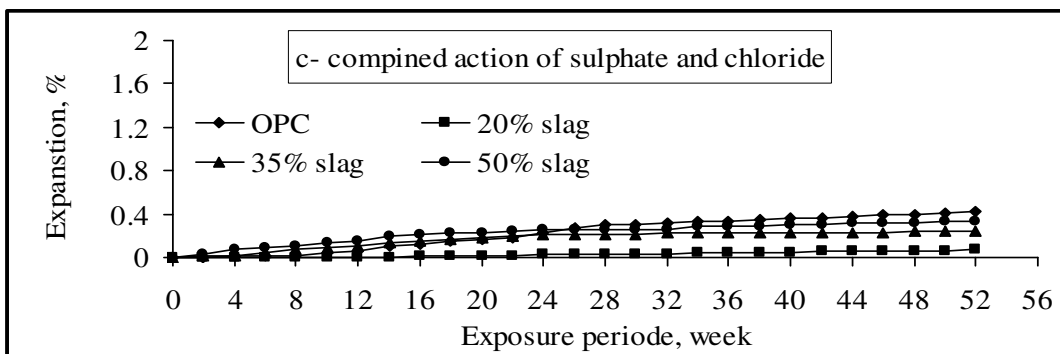
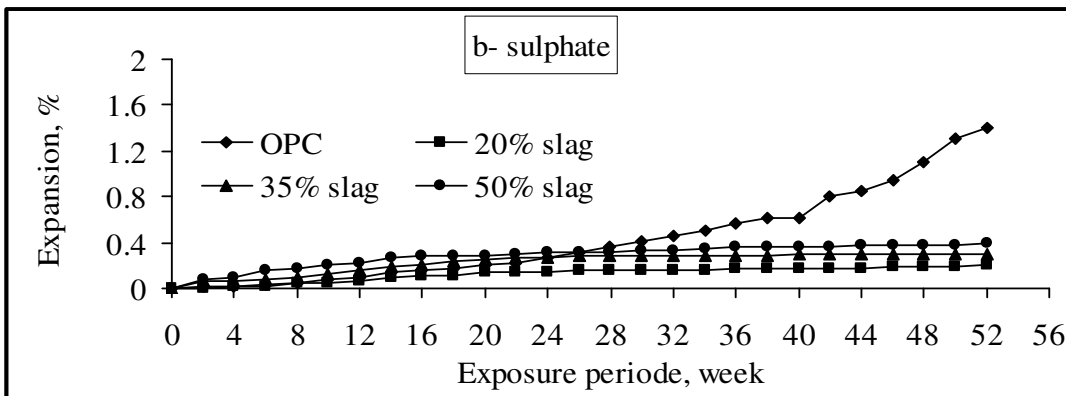
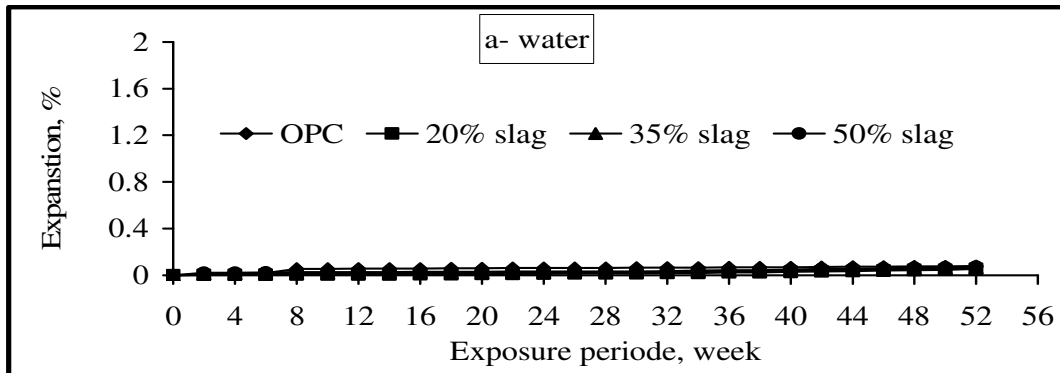


Figure 3: Expansion of OPC and slag mortars exposed to various conditions.

3.2 Length and weight change

The results of both length and weight change are demonstrated in Figures 3 and 4 respectively. It is obvious that, with water curing, the noted expansion for all studied mortars is negligible and complies with ASTM C1012 criteria (less than 0.1 %).

In environments containing sulphate ions, the expansion for all tested specimens remained less than 0.1% till a period of about 6 weeks. Then the expansion of the specimens containing 50% slag started to exceed the proposed ASTM C1012 limit. Whilst, the expansion for 35% and 20% slag specimens started to exceed the proposed ASTM C1012 limit after an exposure periods of about 8 and 14 weeks respectively. After 40 weeks of exposure, the percent expansion for OPC specimens started to increase very rapidly with time to reach about 1000, 450 and 325 times more than that of 20, 30 and 50% WCS specimens, by the end of exposure period (one year). This substantial increase in expansion of OPC mortar was associated with several cracks on the edges of the tested specimens, while no cracks were observed on OPC-Slag specimens.

Similar pattern of deterioration was observed for the specimens exposed to both chloride and sulphate (see Figure 3.c). Nonetheless, the unfavorable effect of combined sulphate and chloride ions seemed to be slightly lower than that of sulphate solution alone.

The resulted expansion of the specimens exposed to sulphate ions could be attributed to the formation of ettringite [8-10] as a result of the chemical reactions between sulphate ions

with aluminate phase of cement and Ca(OH)_2 , leading to an excessive expansion and consequently degradation of hardened cement paste (HCP). The noted reduction in expansion of WCS specimens when compared to the corresponding of OPC specimens might be attributed to the enhancement in the microstructure of HCP as a result of the inclusion of such pozzolanic material in the mix. This could reduce the amount of aggressive ions transported into its matrix. The inclusion of WCS in OPC mortar also led to a remarkable reduction in the amount of Ca(OH)_2 due to its consumption in the pozzolanic reaction.

On the other hand, the reduction in expansion measured for the specimens immersed in combined solution of chloride and sulphate ions was a consequence of the chemical reaction between chloride ions and the aluminate phase of cement, forming calcium chloro-aluminate (Friedel's salt) and hence reducing the amount of aluminate phase available to react with sulphate ions.

The above-mentioned chemical reactions resulted in the deposition of chemical reaction products in the pore structure of HCP, and hence increase its weight with time. Figure 4 shows the weight gain of OPC and slag mortars exposed to the considered solutions. As expected, for specimens immersed in water, the weight gain of OPC and WCS mortar specimens was negligible. The opposite was true when those specimens were stored in aggressive solutions containing either sulphate ions or combined action of chloride and sulphates, where, a remarkable increase in weight occurred with time, especially for OPC mortar.

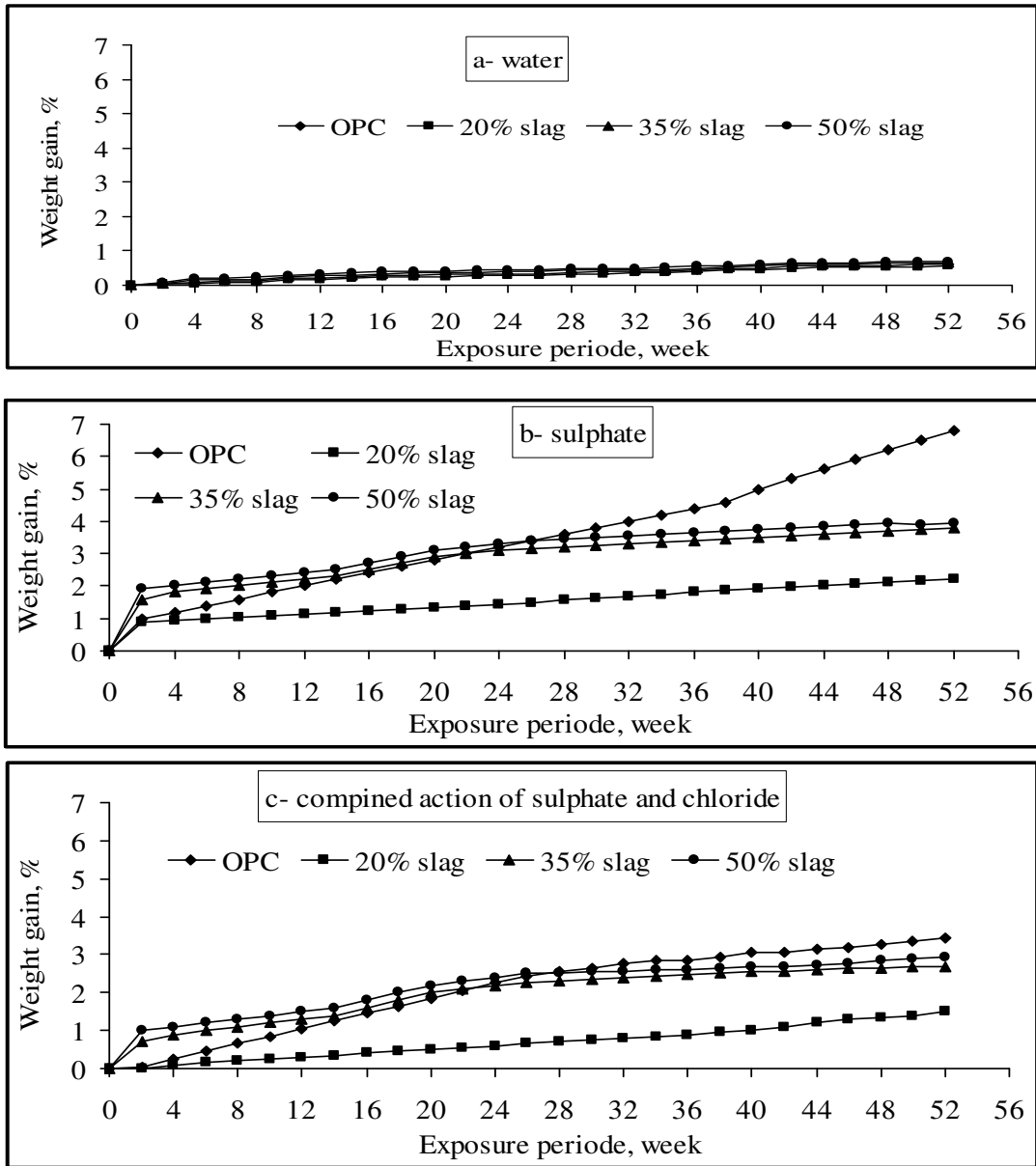


Figure 4: Weight gain of OPC and slag mortar specimens exposed to various conditions.

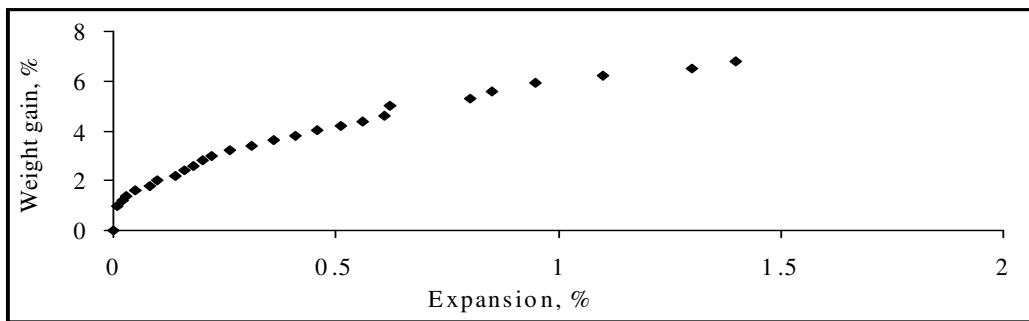


Figure 5: Relationship between expansion and weight gain of hardened cement paste.

The results of Figure 4.b also emphasized that the inclusion of 20% slag into OPC matrix by mass of OPC has caused a reasonable reduction in the weight gain. Whilst, at 35 and 50% slag replacement levels, weight gain increases up to 24 and 26 weeks respectively. After these periods, weight gain was reduced compared to that of pure OPC mortar specimens.

For specimens exposed to the combined action of chloride and sulphate ions, similar effects were observed as those found for the specimens exposed to sulphate ions only. However, it seemed that the presence of chloride ions could slow down the rate of degradation of HCP that exposed to sulphates.

Generally, these observations were in agreement with that obtained by length change measurements. As a result, an attempt was done to correlate the length and weight changes, as demonstrated in Figure 5. It is obvious that a clear correlation between percent expansion and weight gain of HCP is present.

Figure 6 demonstrates the influence of WCS fineness on the percent expansion of OPC and OPC-WCS mortar specimens immersed in water, 10% Na₂SO₄ and 10% Na₂SO₄ + 5% NaCl solution. The expansion of mortars was significantly reduced with increasing fineness of WCS. In case of specimens immersed in water, the amount of reduction in expansion reached about 32, 87 and 99%, of the corresponding OPC mortar, for 0.5, 2.0, and 3.3 m²/g WCS fineness, respectively. For specimens submerged in 10% Na₂SO₄ solution, the same amount of reduction reached about 85, 96 and 99%, respectively. For specimens immersed in 10% Na₂SO₄ + 5% NaCl solution, the reduction was about 82, 95 and 99%, correspondingly.

Figure 7 shows the amount of reduction in weight for specimens stored in the tested environments. In water, the gain in weight reached about 8, 67 and 84%, when 0.5, 2.0

and 3.3 m²/g fineness of WCS were adopted, respectively, compared to OPC mortar. For specimens immersed in 10%Na₂SO₄ solution, the amount of reduction in weight was about 68, 84 and 91%, respectively. While specimens kept in 10% Na₂SO₄ + 5% NaCl solution, showed a reduction in weight of about 56, 82 and 97%, for different WCS finesses correspondingly.

3.3 Chloride profile and penetration

The results obtained by chloride penetration test for the different mortars made with various slag contents are shown in Figure 8. At 20, 35 and 50% slag replacement levels, the depth of chloride penetration was reasonably lowered compared to the corresponding OPC mix. The amount of reduction in chloride penetration reached about 55, 33 and 22%, when 20, 35 and 50% slag replacement levels were adopted, respectively. It is also obvious from Figure 8 that, increasing the slag replacement level, increases the depth of chloride penetration. This may be attributed to the limited quality of the WCS produced from the local materials.

The above conclusions can also be drawn from Figure 9, which demonstrates the impact of WCS fineness on chloride penetration of mortar specimens. Chloride penetration is significantly reduced with increasing the finenesses of slag. The reduction in chloride penetration reaches about 55, 78 and 89%, when 0.5, 2.0 and 3.3 m²/g finenesses of WCS were used, respectively, compared to the OPC mortar.

Figure 10 demonstrates the total chloride profile of OPC mortar made with different contents of WCS. It is clear that using WCS reduced total chloride content at all depths. However, the use of 20% replacement level appeared to be the best ratio in all cases

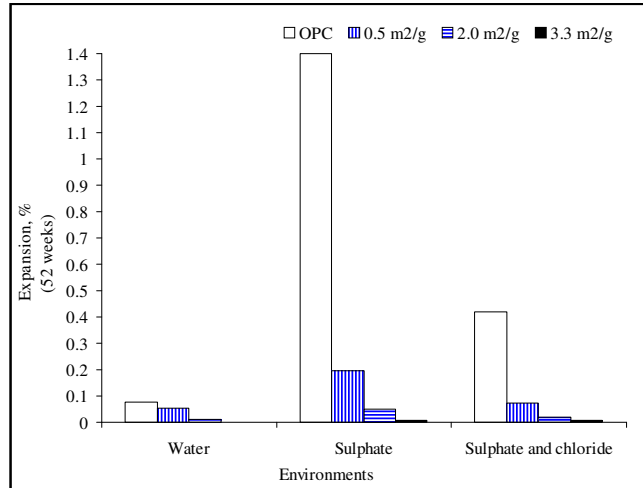


Figure 6: Expansion of OPC mortar made with different finenesses of 20% WCS.

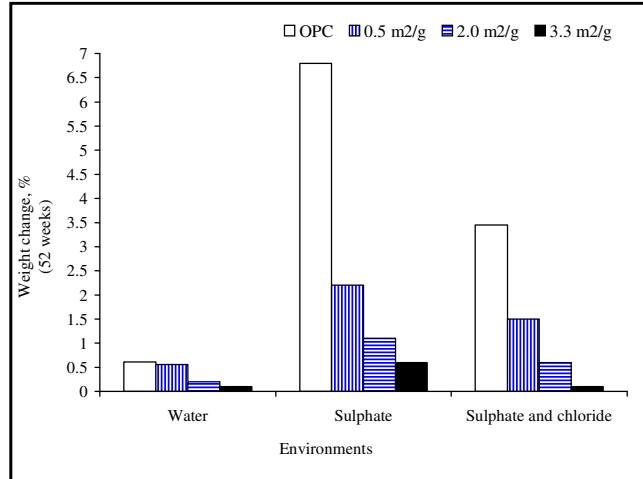


Figure 7: Weight gain of OPC mortar made with different finenesses of 20% WCS.

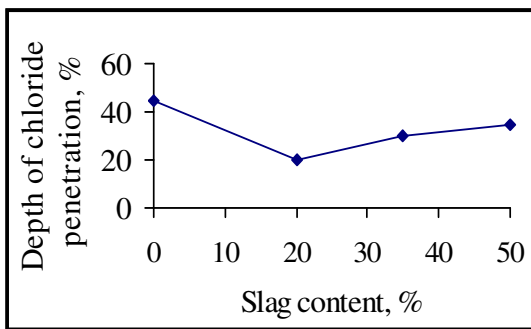


Figure 8: Chloride penetration of OPC mortar made with different contents of slag.

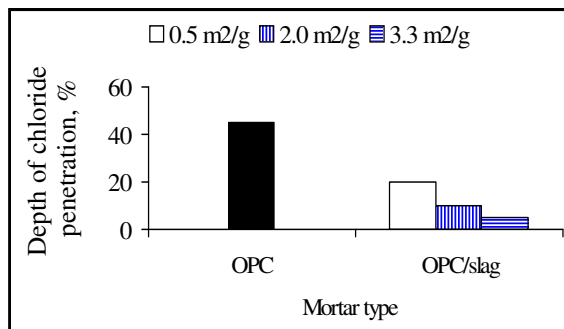


Figure 9: Chloride penetration of OPC mortar made with different finenesses of slag.

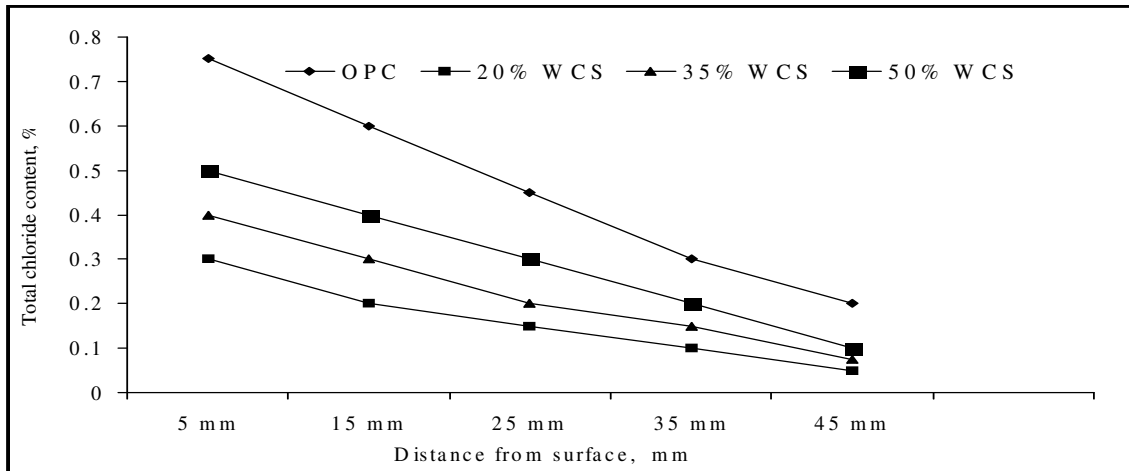


Figure 10: Total chloride profile of OPC mortar made with different contents of WCS.

4. CONCLUSIONS

According to the experimental work carried out in this investigation, the main conclusions can be summarized as follow:

1. Slag can be mechanically activated through vigorous grinding. Research results showed that finer Slag had better effect, than coarser slag, when used in mortar samples stored in sever Sulphate, chloride, and both sulphate and chloride environments. Improved compressive strength and resistance to aggressive environments was observed.
2. In sulphate and in chloride environments, the inclusion of activated Water Cooled Slag (WCS) as a partial replacement of OPC, with 20, 35 and 50%, has a notable beneficial effect on mortar's compressive strength, percent expansion, weight gain and resistance to chloride penetration.
3. The fiercest effect on hardened OPC and OPC-WCS mortars, regarding length and weight change, was produced when mortars were exposed to sulphate ions.
4. Strong correlations between the expansion and weight gain of mortar samples was found for the tested samples.

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