

GGBFS Based Geopolymer Mortars Immersed in Sodium and Magnesium Sulfate Solutions and Sea Water

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Abstract - Geopolymers have been found to possess similar and even advantageous properties compared to normal cement with the possibility of substantial reduction in carbon dioxide emission. The present research focused on the durability effects on GGBFS based geopolymer mortar specimens specifically in the areas of exposure to sodium and magnesium sulfate solution and sea water with varying ratios of 0.25, 1.5, and 2.5 of sodium silicate to sodium hydroxide as alkaline activators. Three concentrations of sodium and magnesium sulfate solutions were made, which consisted of 3, 5, and 7 percent of sodium and magnesium for which the specimens were immersed for six months. For specimens immersed in sodium and magnesium sulfate solutions, the general observation was that the compressive strength decreased after 6 months. The most drastic reduction of compressive strength occurred when sodium silicate to sodium hydroxide ratio was 2.5, while the lowest change observed at 0.25. The densities of the mortar specimens was not affected by sea water and sulfate attack. Likewise, the visual appearance of the mortar specimens were similar when compared to the un-immersed specimens, however the most severe change in physical appearance was observed with the specimens immersed in magnesium sulfate with signs of deterioration.

Keywords— *geopolymer; sodium silicate; sodium hydroxide; sulfate exposure; sea water exposure;*

1.0 INTRODUCTION

Cement, the mostly widely used material of modern structures today, is reaching record levels in production and consumption throughout the world. The global cement production is estimated to be 4.4 billion metric tons by 2020 [1]. Although beneficial in the advancement of civilization, cement production has environment effects that are of concern, specifically, carbon dioxide emission. For one ton of cement produced, approximately one ton of carbon dioxide is released to the atmosphere, from which half comes from the burning of lime

while the other half comes from the fossil fuels used in the kiln for energy purposes and the energy used in terms of transportation and delivery [2, 3]. Hence, if by 2020 the global cement production reaches 4.4 billion metric tons, than that would mean a proportionate 4.4 billion metric tons of carbon dioxide emission from the cement industry alone.

In addition to the environmental problems, cement concrete have significant durability concerns that can arise in the lifetime of the structure, requiring repair/renovation cost in the billions yearly. For example, in the United States, which is one of the largest markets that produce and built concrete structures, the overall cost associated with repair, renovation, and prevention of durability problems were estimated to be in the range of 18-21 billion dollars in 2006 alone [4]. The durability problems that can arise are plenty including fire induced effects and effects on concrete/rebars from water or sulfate sources for structures near or in bodies of water. For instances, when the concrete structure is exposed to external sulfate attack, the calcium-alumino-hydrate of the hardened cement paste can react with calcium and alumino sulfates, from external sources, to form ettringite which cause expansion and cracking leading to further problems with corrosion in the steel rebars [5, 6]. In addition to this, calcium-hydrogen can react with sulfates to form gypsum which again can lead to expansion and cracking [7]. These conditions can be somewhat limited in the case of exposure to sea water, where the high concentration of chlorides in the sea water inhibit in the cement producing Chloroaluminate compounds, thus lessening expansion possibilities due to less quantity of C_3A to produce ettringite under sulfate attack [8], however the chlorides from the sea water can cause severe corrosion problems for the rebars if exposed.

The environmental and durability concerns of cement production and use especially in the twenty-first century has been determined not to be sustainable for a long time, hence the need to look for innovative materials that may address these concerns. Geopolymers are one of these innovative materials that may be able to replace or significantly reduce the use and production of cement.

Geopolymers were first defined by Dr. Joseph Davidovits [9] to describe a reaction of aluminosilicate source material and highly alkali solutions yielding a binder product similar to cement. The materials employed are typically high temperature naturally occurring materials like metakaolin, volcano ash, and pozzolanic materials [3, 10]. Within the last couple decades, research have looked at using aluminosilicate containing byproducts material like fly ash and ground granular blast furnace slag [11]. Synthetically made material has also been the subject of research into geopolymers [12]. Generally, any material with high concentrations of amorphous aluminum and siliceous present can be used as base material for geopolymers, whether from natural deposits or by-products [2, 13-17.] The technology is relatively new and has gained vast interest from researchers all over in the world, which has lead to a 200% increase in research topics related to geopolymers in the last twenty years considering only two source journals [18]. Geopolymers have been found to possess similar and even advantageous properties compared to normal cement. Some of these properties include fast reaction and strength gain, high resistance to heat, freezing-thawing resistance, low shrinkage properties, and lower permeability [19].

Although research into geopolymers is extensive, research into durability aspects of geopolymers have garnered interest only recently [20], which in order to transition to real application in construction, durability issues like effects of sulfate, and sea water need to be addressed. These concerns have been the subject of few investigations into geopolymers [20.], and thus will be the focus of this research.

2.0 MATERIALS AND METHODOLOGY

Previous research has looked at using ground granular blast furnace slag (GGBS) as partial replacement for ordinary cement, where replacement percentages typically range from 30 to 85% [21]. Typical benefits of using GGBFS partially with ordinary cement include; increased strength, higher sulfate and ASR attack resistance, lower emission of CO₂, lower permeability, and increased workability [21]. However, in this research the focus was to use GGBFS to completely replace ordinary cements, while serving as the aluminosilicate source material needed for geopolymer activation.

2.1 Materials

The composition of the GGBFS is provided in table 1. The material was acquired from UAE via Al-Rashid Cement Company. The provided material was ready made fine particles with a fineness of 406 m²/kg and a specific gravity of 2.86. Calcium, Silicon, and Aluminum oxides account for about 91 percent of the chemical composition of the material, while magnesium and ferric oxides are the other compounds with more than 1 percent.

2.1.1 Alkaline Activators

The alkaline activators used were a combination of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) at different ratios. The Na₂SiO₃ to NaOH ratios considered were of 0.25, 1.5, and 2.5. The concentration of the sodium hydroxide used was 8 M, which was made by dissolving the solid NaOH provided by Sigma into distilled water. Likewise,

the sodium silicate solution was manufactured dissolving solid particles of Na₂SiO₃ into distilled water using heat to yield a solution that consisted of 10.2% Na₂O, 29.6% SiO₂, and 60.2% H₂O.

Table 1. Chemical composition of GGBFS

Chemical Composition	Symbol	GGBFS
Silicon Dioxide	SiO ₂	33.78
Aluminum Oxide	Al ₂ O ₃	13.97
Ferric Oxide	Fe ₂ O ₃	1.44
Calcium Oxide	CaO	42.85
Magnesium Oxide	MgO	5.24
Potassium Oxide	K ₂ O	0.40
Sodium Oxide	Na ₂ O	0.10
Sulphur Trioxide	SO ₃	0.22
Chloride	Cl	0.018
SulphideSulphur	S ⁻²	0.74
Manganese Oxide	Mn ₂ O ₃	0.14

2.1.2 Fine Aggregates

Silica sand mixed with beach sand served as the fine aggregates for our mortars. Due to sitting in laboratory conditions for an extended period of time, the sand needed to be washed first and cleaned to dissipate any unwarranted particles, which the sand was dried afterwards in the oven for 24 hours. The particle size dispersion consisted of 10% of 2.36 mm retained sand particles, 40% of 1.18 mm, 30% of 0.60 mm, 15% of 0.30, 5% of 0.15 mm. The ratio of sand to GGBFS was held constant at 2.75.

2.2 Methodology

The sodium silicate and sodium hydroxide solutions with the specified ratios were mixed one day before use. To make the geopolymer mortar specimens, first the sand and the GGBFS were mixed for a period of 4 minutes. Once mixed, water to bring the fine aggregates into saturated surface dry condition and the alkaline activator solution made of the premixed sodium silicate and sodium hydroxide plus an additional 2% by mass of superplasticizers were poured onto the mixture of sand and GGBFS, which was further mixed for an additional 4 minutes. The ratio of the alkaline activators to GGBFS was held constant at 0.40 throughout. The mixing was made using a Hobart Mixer. Once ready, the mix was cast into 50 mm cubic specimens. The specimens were then vibrated for 20 seconds using a vibration table, and then smooth surface with trowel and covered with plastic bags. The specimens were held in room temperature for one hour before placement in oven in dry condition for 24 hours at a curing temperature of 60°C. After 24 hours, the specimens were measured and were either tested for compressive strength or held in room temperature until specified experiment. For each specified experiment, three different mixtures were tested corresponding to three ratios of sodium silicate to sodium hydroxides. Those ratios are 0.25, 1.50 and 2.5 of Na₂SiO₃ to NaOH corresponding to for identification purposes M1, M2 and M3, respectively.

2.2.1 Compressive Strength

The compressive strength was used as a benchmark for the research parameters. The average compressive strength values were reported out of three samples per test.

2.2.2 Sulfate Resistance

In order to investigate the sulfate resistance of GGBFS geopolymers, the mortars cured at 60°C for 24 hours were treated with different concentrations of sodium and magnesium sulfate solutions (Na₂SO₄ and MgSO₄). Six plastic containers were prepared to contain solutions of 3%, 5%, and 7% of sodium and magnesium sulfate in solution to immerse the cubic specimens. After 6 months of exposure, the specimens were investigated with three samples for each concentration levels. The compressive strength, density measurements, and physical appearance were the parameters investigated and compared with the non-immersed mortar specimen measurements at seven days after curing. The specimens were tested in dry condition via as soon as the specimens were taken out of the solution media they're allowed to sit for five days, after which measurements for density and compressive strength were conducted. The sodium and magnesium sulfate solutions were prepared by dissolving amount of solids needed to have the desired concentration of sulfate with 900 ml of distilled water per liter of solution and then diluted further to get to 1 liter solution. The ratio of volume of solution to volume of cube specimens was kept constant at four to one, meaning for one 50 mm cubic specimen (volume 125 mL) 500 mL of solution was needed. In order to keep the concentrations constant and prevent loss to evaporation, solutions were changed every month and sealed from air and kept in room temperature around 23°C.

2.2.3 Sea Water

The sea water immersion followed similar procedure to sulfate resistance. The specimens are immersed into the sea water mediate obtained from the coast of the Red Sea in Jeddah, KSA. The specimens were than taken out of the solution after six months and allowed to sit for five days before test measurements.

3. RESULTS AND DISCUSSION

3.1 Density

The mortar specimen densities before and after exposure to sea water, and different percentages of sodium and magnesium sulfate solutions are presented in Tables 2 and 3. The densities increased for specimens after exposure to the specified medium for six months. For sea water exposure, the densities of the specimens before immersion are 2385 kg/m³, 2247 kg/m³, and 2262 kg/m³ for M1, M2, and M3, respectively. After immersion, the densities become 2413 kg/m³, 2268 kg/m³, and 2278 kg/m³ for M1, M2, and M3, respectively, which resulted in less than 1 percent increase for all three mixture types. The results indicated that sea water exposure had little or no effect on the density of the GGBFS based geopolymer mortar specimens.

Table 2. Densities before exposure to sea water, and concentrations of sodium and magnesium sulfate solutions.

Mix Type	Sea Water (kg/m ³)	Na ₂ SO ₄			MgSO ₄		
		3% Na (kg/m ³)	5% Na (kg/m ³)	7% Na (kg/m ³)	3% Mg (kg/m ³)	5% Mg (kg/m ³)	7% Mg (kg/m ³)
M1	2385	2314	2345	2299	2400	2380	2409
M2	2247	2343	2331	2332	2304	2269	2255
M3	2262	2322	2242	2345	2236	2257	2209

Table 3. Densities after exposure to sea water, and concentrations of sodium and magnesium sulfate solutions.

Mix Type	Sea Water (kg/m ³)	Na ₂ SO ₄			MgSO ₄		
		3% Na (kg/m ³)	5% Na (kg/m ³)	7% Na (kg/m ³)	3% Mg (kg/m ³)	5% Mg (kg/m ³)	7% Mg (kg/m ³)
M1	2413	2329	2364	2317	2420	2402	2423
M2	2268	2361	2348	2340	2329	2286	2261
M3	2278	2333	2253	2348	2250	2271	2217

Similar observations were found for the mortars immersed in the sodium and magnesium sulfate solutions. The densities of all mortar specimens increased after immersion of 6 months. No significant difference of densities was observed between the different concentrations of sodium and magnesium sulfates. For instances, the density before immersion in 3% Na was 2314 kg/m³, 2343 kg/m³, and 2322 kg/m³ for M1, M2, and M3 in that order, after immersion a relative increase to 2329 kg/m³, 2361 kg/m³, and 2333 kg/m³ for M1, M2, and M3, respectively, resulting in less than 1 percent difference of density for each mixture type after approximately six months of immersion (table 4). Likewise, the densities before immersion in 3% Mg, was 2400 kg/m³, 2304 kg/m³, and 2236 kg/m³ and after immersion they become 2420 kg/m³, 2329 kg/m³, and 2250 kg/m³ for M1, M2, and M3, respectively, and again all changes were less than 1 percent of the original measurements.

Table 4. Density loss after exposure to sea water, and concentrations of sodium and magnesium sulfate solutions.

Mix Type	Sea Water (kg/m ³)	Na ₂ SO ₄			MgSO ₄		
		3% Na (kg/m ³)	5% Na (kg/m ³)	7% Na (kg/m ³)	3% Mg (kg/m ³)	5% Mg (kg/m ³)	7% Mg (kg/m ³)
M1	1.15	0.65	0.77	0.79	0.87	0.93	0.59
M2	0.96	0.76	0.73	0.36	1.10	0.78	0.24
M3	0.71	0.51	0.48	0.11	0.61	0.62	0.34

Regardless of whether it was sodium or magnesium or whether the sulfate solution concentration was 3% or 5% or even 7%, the densities of the mortar specimens did not vary much within 1 percent of the initial values. The increased densities of the specimens were probably due to increased mass from absorbed solution left in the specimen after they were taken out and dried in room temperature for 5 days before measurements. Furthermore, the low disparities between the initial and post immersion densities of sodium and magnesium sulfate and the different percentages, indicate that the mortar specimens are not affected by sulfate attack. Hence, it is believed that the geopolymer mortar specimens tested in this research are durable and have sufficient

resistance to sulfate attack. This further indicated a lack of ettringite and gypsum formation, and hence a lack of expandability in the GGBFS based geopolymer mortars. In Addition, there was no observable effect from sodium silicate to sodium hydroxide ratio on the densities of the mortars before or after immersion in the treatment medium.

3.2 Visual Appearance

3.2.1 Sea Water Exposure

Figure 1 shows the comparison of the physical appearance between un-immersed and sea water immersed specimens after exposure to the specified medium for six months. As can be seen, the physical surface of the specimens exposed to sea water did not change much with respect to the original unexposed samples. From close inspection of the specimen, no visual signs of surface deterioration, erosion, and cracks or spalling was detected, which indicated no volume change occurred from expansion due to formation of ettringite and gypsum.



A) Un-immersed B) Sea Water immersed

Figure 1) Specimens immersed in sea water after 6 months before drying in room temperature.

3.2.2 Sodium and Magnesium Sulfate Exposure

Figures 2 and 3 show specimens after immersion in sodium and magnesium sulfate solutions before and after drying. After six months of immersion in the sodium and magnesium sulfate solutions, it was observed that the specimens visual appearance were somewhat similar when compared to the un-immersed specimens. However, for some specimens, deterioration and wear down was observed. When compared with original un-immersed condition, the specimens exposed to sodium sulfate solutions showed the least comparable change. The only difference that can be noticed in figure 2 is the lost of smoothness on the edges of the sodium exposed specimens in addition to more pores, which was similar for all concentrations of sodium. The roughness or lack of smoothness on the exterior boundaries of the specimens can be due to the compaction of the specimens and not necessarily from the immersion treatment.

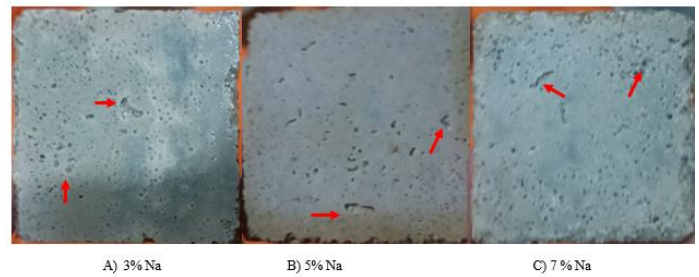


Figure 2) Specimens immersed in Sodium sulfate solutions of A) 3% Na, B) 5% Na, and C) 7% Na after 6 months before drying in room temperature.

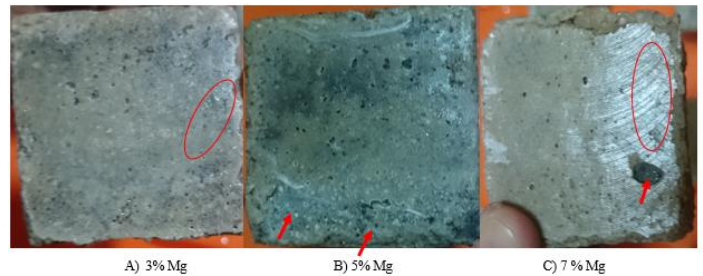


Figure 3) Specimens immersed in Magnesium sulfate solutions of A) 3% Mg, B) 5% Mg, and C) 7% Mg after 6 months before drying in room temperature.

As can be seen from figure 3, the specimens immersed in the magnesium sulfate have similar appearances with each other. Part A shows a typical specimen that was exposed to 3% $MgSO_4$ right after being taken out of the solution; no sign of deterioration is seen, except little white spots, whereas for part b those white spots are hardly there, with layer of surface missing at the base of the specimen indicated with the arrows. Part C with exposure to 7% magnesium sulfate had the most drastic appearance with a very glossy texture to the right and small pore below that. Compare that with the dry condition after 5 days from figure 4, where the glossy appearance was no longer present. Part A shows the white spots clearer (*erosion at the base right should be ignored because picture was taken after compression tests which lead to the erosion in the picture indicated with the red arrow*). As for part B, the same deterioration at the base can be seen more clearly now after allowing the specimen to dry, however notice the small white spots which was not as visible in the wet condition. These white spots are believed to be caused by the precipitation of the magnesium dissolved in the solution.

In all, the general trend observed was that as the magnesium sulfate concentration increased so did the level of deterioration, where 7% $MgSO_4$ had the most noticeable changes. Figure 5, provides a clearly picture of this deterioration of the specimens as evidence by the fallen particles on the sides of the specimens. In all when compared to the original un-immersed specimens of figure 1(A), it is clear that the magnesium sulfate solution caused the most drastic deterioration and erosion of the specimens when compared to sodium sulfate exposure damage.



Figure 4) Specimens immersed in magnesium sulfate solutions of A) 3% Mg, B) 5% Mg, and C) 7% Mg after 6 months after drying for 5 days in room temperature.

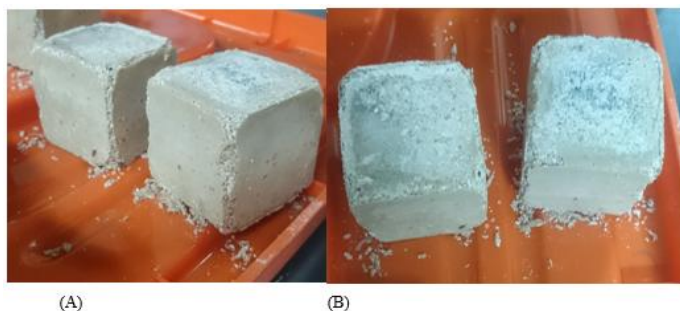


Figure 5) Specimens immersed in Magnesium sulfate solution with a concentration of 7% Mg after 6 months showing fallen particles of specimens.

3.3 Compressive strength before exposure to sea water and sulfate solutions

In order to determine the durability effects and the effects from Na_2SiO_3 to NaOH ratio on the mortar specimens after exposure to sea water and sulfate solutions, the specimens were tested for compressive strength after 7 days at a curing regime of 60°C for 24 hours. It was concluded that for the control sample, as the Na_2SiO_3 to NaOH ratio increased from 0.25 to 1.5 and 2.5, the compressive strength increased proportionally. The control mortar specimen compressive strength after 7 days was found to be 28.8 MPa, 42.6 MPa, and 47.3 MPa for M1, M2, and M3, respectively. The strength increase from M1 to M2 was approximately 50 percent, whereas the compressive increase from M2 to M3 was only 11 percent. This indicated that higher sodium silicate to sodium hydroxide content improved the compressive strength of the mortars before exposure to any external attacks. The observation of increased compressive strength due to increasing sodium silicate to sodium hydroxide content can be attributed to the fast polymerization that occurs in geopolymers after curing regime [13, 22-23]. In fact, MehrzadYadollahi and RamazannDemirboga [24] found that the compressive strength increased rapidly up to 7 days, continuing to increase albeit at a slower rate until 28 days was reached. They also observed that compressive strength gain ceased to increase after 28 days regardless of the curing regime. The findings for this research and the research by MehrzadYadollahi and RamazannDemirboga are in agreement with the previous research by [23], even though different composite materials were used in the researches, which suggested this behavior to be a universal feature of geopolymer mechanism.

3.4 Compressive strength after exposure to sea water and sulfate solutions

After six months of immersion in sea water and sulfate solutions of different percentages of sodium and magnesium, the mortars were tested for compressive strength after allowing the specimens to sit in room temperature to dry for 5 days. The results are presented in tables 5-9.

3.4.1 Sea Water Immersion

For specimens immersed in sea water, the results yielded lower compressive strength compared to the compressive strength before immersion. The compressive strengths of the specimens immersed in sea water are 26.8 MPa, 35.2 MPa, and 25.90 MPa for M1, M2, and M3 respectively. When compared to the compressive strength after 7 days, the compressive strength decreased after immersion treatment by 7%, 17%, and 45% for M1, M2, and M3, correspondingly (table 5). The findings are in distinct contrast to research by Ahmed A. Amer et al [25], which found the GGBFS based geopolymer mortar paste specimen gradually increased in compressive strength until six months of immersion, similar to other findings [24]. Ahmed A. Amer et al [25], concluded that this was due to continued activation forming more C-S-H.

Table 5. Compressive strength of un-immersed and sea water immersed for 6 months.

MIX TYPE	Un-immersed 7th Day Compressive Strength (MPa)	Sea water Compressive Strength (MPa)	Percent Change (%)
M1	28.8	26.83	6.83
M2	42.6	35.20	17.37
M3	47.3	25.90	45.24

3.4.2 Sodium and Magnesium Sulfate

For specimens immersed in sodium and magnesium sulfate solutions, the general trend observed was that the compressive strength decreased after six months of immersion. However, the difference in compressive strength before and after was not drastic, in fact on some specimens, an increase in strength was noticed. For example, with a concentration of sodium of 3 percent, the compressive strength was found to be 30.4 MPa, 36.3 MPa, and 31.3 MPa, when compared to non-immersed 7 day compressive strength, which is an increase of 6 percent for M1, and a decrease of 17 percent, and 51 percent for M2 and M3, respectively (Tables 6-7). Whereas a decrease for all mixture types was observed when the concentration of sodium was 5%, resulting in a decrease of compressive strength of 14 percent for M1, and M2, and a decrease of 64 percent for M3. However, lower decrease was observed when the sodium concentration was at 7 %, which resulted in a decrease of 5 percent, 0.12 percent, and 28 percent for M1, M2, and M3, correspondingly.

Table 6. Compressive strength of sodium sulfate immersed for 6 months.

MIX TYPE	3% Na Compressive Strength (MPa)	5% Na Compressive Strength (MPa)	7% Na Compressive Strength (MPa)
M1	30.43	24.48	27.30
M2	36.33	37.68	42.55
M3	31.13	28.78	34.25

Table 7: Compressive strength change from 7th day un-immersed to after 6 months of exposure to sodium sulfate.

MIX TYPE	3% Na Compressive Strength change (%)	5% Na Compressive Strength change (%)	7% Na Compressive Strength change (%)
M1	5.64	-15.02	-5.21
M2	-14.73	-11.56	-0.12
M3	-34.20	-39.16	-27.59

A similar trend was observed when the sulfate solution consisted of magnesium at 3, 5, and 7 percent concentrations (Tables 8-9). For 3 percent magnesium sulfate solution, the compressive strength decreased for mixtures M2, and M3 by 17 and 39 percent, whereas for mixture M1 the compressive strength did not change after immersion. These trends can be seen in figures 6 and 7, which shows the compressive strengths of the specimens after immersion to sea water, sodium and magnesium sulfate solutions and the un-immersed 7th day compressive strength of our control sample.

Table 8. Compressive strength of magnesium sulfate immersed specimens.

MIX TYPE	3% Mg Compressive Strength (MPa)	5% Mg Compressive Strength (MPa)	7% Mg Compressive Strength (MPa)
M1	28.88	27.28	29.53
M2	35.33	26.98	23.98
M3	28.63	22.13	22.03

Table 9: Compressive strength change from 7th day un-immersed to after 6 months of exposure to magnesium sulfate.

MIX TYPE	3% Mg Compressive Strength change (%)	5% Mg Compressive Strength change (%)	7% Mg Compressive Strength change (%)
M1	0.26	-5.30	2.52
M2	-17.08	-36.68	-43.72
M3	-39.48	-53.22	-53.44

As can be seen in figures 6-7, the largest divergence occurs for M3 for sodium silicate to sodium hydroxide ratio of 2.5, followed closely by M2. Generally as the sodium silicate to sodium hydroxide increased the compressive strength also increased for our control sample, however that behavior was not observed in the specimens immersed in both sodium and magnesium sulfate solutions. This difference in behavior can possibly be attributed to deterioration of the specimens from the sulfate attack.

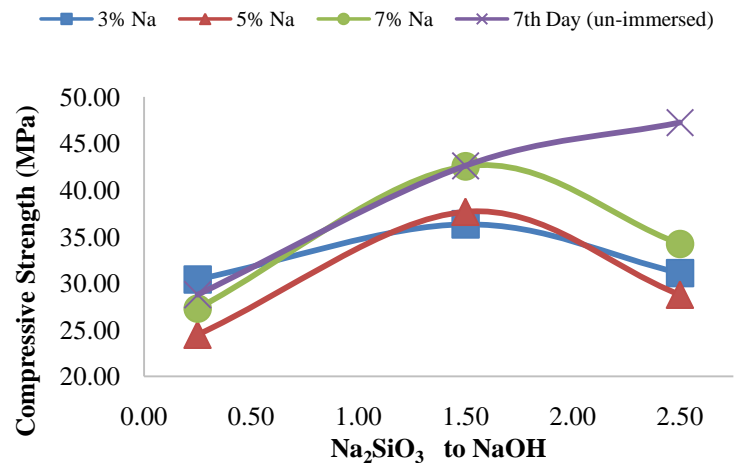


Figure 6) Compressive strength comparison between un-immersed and sodium sulfate immersed specimens in terms of sodium silicate to sodium hydroxide ratio.

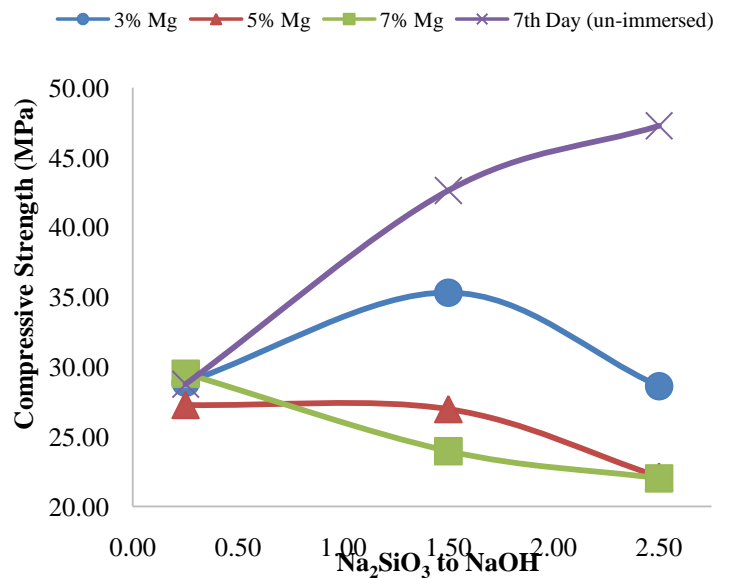


Figure 7) Compressive strength comparison between un-immersed and magnesium sulfate immersed specimens in terms of sodium silicate to sodium hydroxide ratio.

Overall, the compressive strength decreased or did not change much for most specimens regardless of the chemical and percentile difference of sodium and magnesium sulfate solutions. S.W. Wallah [5] found similar results, where the compressive strength only changed slightly when exposed to 5% sodium sulfate solution when compared to the early compressive strength of the non-immersed specimens. However, in contrast, Dontallo[26] found an increase in strength after 90 days immersion in a 4.4% Na₂SO₄ solution for both the control sample of sulfate resistant Type II Portland cement and hybrid cement binder, which consisted of 80% by dry mass fly ash and 20% by mass PC clinker. Fernandez-Jimenez et al [27] found the compressive strength increased over time regardless of the base material used for the cement paste and the immersion treatment. According to Dontallo [26], the compressive strength increase, even in the tested ordinary Portland cement, can be attributed to dissolution and growth of new ettringite crystals in the pore structure causing densification of the microstructure in a process called "Ostwald Ripening," where by small crystals with high surface energy grow and reduce the actual surface area. The discrepancy of the present research and the others can be explained by whether or not ettringite and gypsum are present or formed after the immersion of the specimens. Technically, geopolymers are less susceptible to sulfate attack due to the different mechanism and products formed by the geopolymerisation process [13]. However, this does not guarantee the geopolymer based mortars to be free from the formation of ettringites and gypsum, which comes via calcium presences from the source material or the aggregates used to make the specimens which leads to the eventual change of compressive strength [13, 24, 26].

4.0 CONCLUSIONS

The present research on durability effects on GGBFS based geopolymer mortar specimens increases research knowledge on these innovative materials; specifically in the areas of exposure to sea water and sulfate solutions with varying ratios of the activation solution of sodium silicate and sodium hydroxide. Hence, with the completion of the research, the following are some of the conclusions that was reached.

1. The density of the mortar specimens stayed constant and was not affected by sea water and sulfate attack. For all measurements, the densities changed less than 1 percent when immersed in sea water and sulfate solutions.
2. The physical surface of the specimens exposed to sea water did not change much with respect to the original unexposed samples.
3. After six months of immersion in the sodium and magnesium sulfate solutions, it was observed that the specimens visual appearance were somewhat similar when compared to the un-immersed specimens. However, for some specimens, deterioration and wear down was observed. In all, when compared to the original un-immersed specimens, it was clear that the magnesium sulfate solution caused the most drastic change with signs of deterioration and erosion.
4. The control mortar specimen compressive strength after 7 days was found to be 28.8 MPa, 42.6 MPa, and 47.3 MPa for M1, M2, and M3, respectively. The strength increase from M1 to M2 was approximately 50 percent, where as the compressive strength increase from M2 to M3 was only 11 percent. This indicated that higher sodium silicate to sodium

hydroxide content improved the compressive strength of the mortars before exposure to any external attacks.

5. For specimens immersed in sea water, the compressive strength was lower when compared to the compressive strength before immersion. The compressive strength decreased after immersion treatment by 7%, 17%, and 45% for M1, M2, and M3, correspondingly.

6. For specimens immersed in sodium and magnesium sulfate solutions, the general trend observed was that the compressive strength mostly decreased with some specimens not changing more than 1 percent after six months of immersion. For concentration of sodium of 3 percent the compressive strength when compared to un-immersed 7 day specimens, increased by 6 percent for M1, and decreased by 17 percent, and 51 percent for M2 and M3, respectively. While at sodium concentration of 5% for sodium sulfate solution, the compressive strength decreased 14 percent for M1, and M2, and 64 percent for M3, and at 7% a decrease of 5 percent, 0.12 percent, and 28 percent was observed for M1, M2, and M3, respectively. A similar trend was observed when the sulfate solution consisted of magnesium at 3, 5, and 7 percent concentrations.

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