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Effects of Different Types of Sulphates and Concentrations on Steel

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ABSTRACT

Steel which is indispensable in infrastructures, transportation and manufacturing has a major drawback which is its susceptibility to deterioration (corrosion) that causes economic damage. Some structural failures cannot be unconnected to steel deterioration. Different factors cause deterioration of steel and steel structures but less attention has been given to the sulphate attack based on surrounding environment as one of the factors. In this work, the effects of different types of sulphates and different concentrations of sulphate solutions on the physical properties of steel over a period of time were considered. The sulphates include Calcium sulphate ($CaSO_4$), Ammonium sulphate [$(NH_4)_2SO_4$], Sodium sulphate (Na_2SO_4) and Magnesium sulphate ($MgSO_4.H_2O$) with concentrations of 1%, 3% and 5%. Weight loss analysis and physical observation were adopted to ascertain the deterioration of steel samples. Results show a progressive increase in weight loss for all the samples in the different solutions as the duration of immersion increases. With the exception of ammonium sulphate, the weight loss reduces with increasing sulphate concentration. Ammonium sulphate solution has a more significant effect on the steel samples than the other sulphate solutions. The deterioration also reflected in the colour and physical appearance of the steel samples. Hence sulphate causes deterioration in steel, therefore, appropriate precautions and prevention should be applied in constructions involving steel in a sulphate-rich environment.

KEYWORDS: *steel, deterioration, sulphate attack, calcium sulphate, ammonium sulphate, Sodium sulphate, magnesium sulphate*

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1. INTRODUCTION

Steel which is one of the world's most important engineering and construction material is an alloy of iron and other elements, primarily carbon that is widely used in various applications because of its high tensile strength and low cost. The base metal for steel is iron, the carbon content of steel is between 0.002% - 2.1% by weight, although these values vary depending on the alloying element. Steels are widely used in the construction of roads, railways, buildings and other common application. Large modern structures such as stadiums, telecommunication mast, skyscrapers, bridges and so on are supported by a steel skeleton, also most concrete structures in use today employ steel rebar as reinforcements. Steel is also used in variety of other construction materials such as bolt nuts and screws. Some other common application of steel includes steel pipe for pipelines offshore construction and so on.

Steel which is indispensable in infrastructures, transportation and manufacturing has a major drawback which is its susceptibility to corrosion that causes economic damage. Deterioration of steel (corrosion) has been a major problem in the construction processes and industries or for steel pipes and piles. Across all industrial sectors, the inferred costs of metal corrosion have been estimated to range between 2% and 3% of gross domestic product (GDP) in developed countries (Enning and Garrelfs, 2014)

Different factors cause deterioration of steel and steel structures but less attention has been given to the sulphate attack as one of the factors. Hence unmindful exposure of steel to sulphate attacks exists. The knowledge of the types of sulphate together with the actual concentrations of the sulphate that result to negative effects becomes necessary.

Sulphate is a polyatomic anion with the empirical formula $SO^{2-}{}_4$ (Lewis, 1916). Sulphates are salts of sulphuric acid. There are different types of sulphate salts in aqueous solution that attack the steel structures and reinforcements; some of these sulphates includes calcium sulphate, magnesium sulphate, potassium sulphate, sodium sulphate, ammonium sulphates and so on. These salts of sulphates alter the physical properties and behavior of the steel when they come in contact with the steel itself. This interaction is termed "Sulphate Attack". It is also the effect of sulphates on steel and the consequent deterioration of the steel over a period of time, affecting its strength and appearance.

Some structural failures cannot be unconnected to steel deterioration. In steel structures this corrosion alters the behavior and properties of the steel structures and failure or collapse becomes imminent. This deterioration also affects bolted connection, weakens the bolts and hence causes failure at the joint which also leads to collapse of the steel structures. Reinforced concrete structures are not left out in this menace. Sulphates attack the concrete which spalls and breaks off, exposing the steel rebar to the same attack. Methods of determining the rate of corrosion of steel embedded in concrete is quite different from that of steel in soil medium or steel in stand-alone as could be seen from the works of some researchers although the weight loss analysis was adopted by all the researchers (Trivedi et al., 2016, Gezawa et al., 2015, Corral-Higuera et al., 2011).

The sources of the sulphate attack may differ, for example in a reinforced concrete, the attack can be in two main forms, either internal or external sulphate sources, but for steel structures, the sulphate attack is mostly of external sources. Internal sources of sulphate to the steel occurs in a situation where the sulphate ions are incorporated in the mixing and the casting of the concrete either as hydraulic cement, aggregate or sulphate-contained admixtures or the use of sulphate dissolved water in the mixing, casting and curing of the reinforced concrete. External sulphate sources are mostly due to the interaction and penetration of the sulphates in solution to the steel. The external sources of the sulphate attack are more common and are usually as a result of high sulphate soil (sulphate-rich soil) and groundwater or can be as result of atmospheric or industrial pollution. These external sources can introduce the sulphate to the steel in the following ways: the soil may contain sulphate salts in excess which may be natural nor incorporated by the use of sulphate-rich fertilizers, Also, sulphates dissolve in groundwater which is transported to foundation of structures by capillary action mostly on the foundation of structures like buildings, earth retaining walls, pile foundations, piers, overhead bridges, underground structures and storage tanks and so on. Also, other external sources of sulphate to the steel are through sulphate dissolved fluids such as sea waters, industrial wastes, water treatment plant wastes and so on. Sea water pose a greater source of external sulphate attack since sea water contains lots of dissolved salts in them, including salts of sulphates. However, there are still other sources of sulphate attacks like use of sulphate-contained paints and finishes.

2. Materials And Methods

2.1. Materials

The following materials were used in this work:

- Salt of sulphates: These sulphate salts are a white powdery substances which were used in the preparation of the sulphate solutions. They include
  - A. Calcium Sulphate ($CaSO_4$): The anhydrous form of calcium sulphate was purchased with molar mass of 136.14g/mol, and a percentage purity of 96%. It is whitish and powdery in nature.
  - B. Magnesium Sulphate ($MgSO_4.H_20$): The monohydrate form of the magnesium sulphate was purchased, with a molar mass of 138.28g/mol and a percentage purity of 90%. The magnesium sulphate is crystalline (granular) in nature and whitish in colour.
  - C. Sodium Sulphate (Na_2SO_4): The anhydrous form of sodium sulphate was used in the experiment, with a molar mass of 142.04g/mol and a percentage purity of 99%. Sodium sulphate (anhydrous) is whitish in colour and powdery in nature
  - D. Ammonium Sulphate [$(NH_4)_2SO_4$]: The anhydrous form of ammonium sulphate was used, with a molar mass of 132.14g/mol and a percentage purity of 99% (minimum assay). This sulphate salt is in form of a whitish crystals (granules)
- Distilled water: Distilled water is the water that has had many impurities removed though distillation. This distilled water is efficient for preparations of sulphate solutions to ensure a pure aqueous solution free of impurities. Twenty (20) litres of this distilled water was used in preparing the sulphate solutions of different sulphate salts and different concentrations of the sulphates.
- Steel samples: Structural steel section and 8mm thick mild steel reinforcement bar were used.

2.2. Methods

The following methods were adopted:

2.2.1. Preparation of the sulphate solutions

The sulphate solutions of calcium sulphate, magnesium sulphate, sodium sulphate and ammonium sulphates to a concentration of 1%, 3% and 5% for each of the sulphate salt for a volume of 600ml were prepared using percentage by weight method. The prepared different solutions were poured into transparent airtight containers.

2.2.1. Preparation of the steel sample

The steel samples were cut to their appropriate sizes so they can fit into the airtight containers housing the prepared sulphate solutions comfortably. The structural steel plate was cut into a rectangle of size 40mm x 20mm. A 3mm diameter hole was drilled on the sample for passing the rope used for suspending the sample in the sulphate solution. The 8mm thick mild steel was cut to a size of 40mm x 8mm.The samples were cleaned (using pickling method), rinsed with alcohol and dried to make them free from impurities that may affect the results. A total of 60 samples of the mild steel of size 40mm x 8mm and a total of 60 samples of steel plate of size 40mm x 20mm were prepared.

2.2.3. Weight loss analysis

This was used in determining the rate of corrosion. The samples were weighed on the analytical 4-digit electronic weighing balance to obtain their initial weight. For each sulphate solution, the samples were immersed for a period of 7days after which they were removed from the solution, washed with alcohol, brushed to scrub away the corrosion products, dried and reweighed. This procedure and activities on the seventh day was repeated on the 14^{th} day, 21^{st} day, 28^{th} day and the 35^{th} day for other samples.

2.2.4. Physical observation of samples

During the preparation of solutions and weight loss analysis, physical observations of the solution and the samples were made.

3. Results and Discussions

3.1. Results

The results of the experimental investigations are presented on **Table1 to 12.** The results of the physical observation of solution are as stated. The salt of calcium sulphate ($CaSO_4$) is partially soluble in water, as some of the solute particles can be seen from the transparent air-tight container. Magnesium sulphate, Ammonium sulphate and Sodium sulphate are very soluble in water because a very clear solution was obtained after the preparation. The colour of the samples changed to brownish red and the appearance looked rusty after immersion. The solutions that were crystal clear before immersion turned to brownish colour and blackish brown.

3.2. Discussions

The weight loss analysis was the method adopted in estimating the rate of deterioration (corrosion) of the steel samples. This method is simple with no sophisticated instrument required. A direct measurement is obtained with no theoretical assumption or approximations. A close look at the tables shows the difference between the initial weight before immersion in solution and the final weight on removal from solution. The difference gives the weight loss of the sample and it signifies that deterioration has occurred. The tables show a progressive increase in weight loss for all the samples in the different solutions as the duration of immersion increases. Surprisingly, as the concentration percentage of the sulphate solution increased, the weight loss of 95% of the samples reduced. This occurred in all the sulphate solutions except that of ammonium. Ammonium sulphate solution has a more significant effect on the steel sample than the other sulphate solutions. The rate of attack of the sulphate solutions on both the 8mm thick mild steel reinforcement bars and structural steel plate are similar because the weight loss values are within close range.

4. Conclusion

A. Steel samples were subject to different concentrations (1%, 3% & 5%) of sulphates namely: Calcium sulphate ($CaSO_4$), Ammonium sulphate [$(NH_4)_2SO_4$], Sodium sulphate ($NaSO_4$) and Magnesium sulphate ($MgSO_4.H_2O$), to determine their effects on steel over a period of time.

B. Weight loss analysis and physical observation were adopted to ascertain the deterioration of steel samples.

C. There is a progressive increase in weight loss for all the samples in the different solutions as the duration of immersion increases.

D. As the concentration percentage of the sulphate solution increased, the weight loss of 95% of the samples reduced. This occurred in all the sulphate solutions except that of ammonium.

E. The deterioration also reflected in the colour and physical appearance of the steel samples.

F. Ammonium sulphate solution has a more significant effect on the steel samples than the other sulphate solutions.

G. The rate of attack of the sulphate solutions on both the 8mm thick mild steel reinforcement bars and structural steel plate are similar because the weight loss values are within close range.

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Table1. Initial weight, final weight and the weight loss for Calcium sulphate solution 1% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	16.0190	16.0082	0.0208	10.6862	10.6654	0.007
Day 14	15.7196	15.6895	0.0071	12.3237	12.3166	0.0254
Day 21	15.4085	15.3666	0.0306	11.2952	11.2646	0.0383
Day 28	15.1433	15.0891	0.0435	11.5809	11.5374	0.0509
Day 35	15.4298	15.3685	0.0788	11.0485	10.9697	0.0567

Table2. Initial weight, final weight and the weight loss for Calcium sulphate solution 3% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	16.1515	16.1445	0.0095	11.1598	11.1503	0.0108
Day 14	15.5501	15.5247	0.0214	11.3038	11.2824	0.0175
Day 21	15.8302	15.7919	0.0379	12.8388	12.8009	0.0281
Day 28	14.8100	14.7591	0.0362	11.2572	11.2210	0.0574
Day 35	14.9363	14.8796	0.0692	11.4344	11.3652	0.0307

Table3. Initial weight, final weight and the weight loss for Calcium sulphate solution 5% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	14.9628	14.9520	0.0108	11.0006	10.8900	0.0116
Day 14	15.2050	15.1875	0.0175	11.3830	11.3614	0.0246
Day 21	15.6838	15.6557	0.0281	11.2895	11.2632	0.0263
Day 28	15.6598	15.6024	0.0574	11.7809	11.7255	0.0554
Day 35	15.8887	18.8580	0.0307	11.6714	11.6270	0.0444

Table4. Initial weight, final weight and the weight loss for Magnesium sulphate solution 1% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	15.7083	15.7017	0.0071	11.8716	11.5051	0.3665
Day 14	15.6875	15.6587	0.0288	11.0225	10.9973	0.0252
Day 21	15.6006	15.5535	0.0471	11.5189	11.5009	0.0180
Day 28	15.1726	15.1122	0.0604	10.9377	10.8835	0.0542
Day 35	14.9979	14.9241	0.0738	11.1830	11.1106	0.0724

Table5. Initial weight, final weight and the weight loss for Magnesium sulphate solution 3% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	14.9905	14.9819	0.0086	10.9926	10.9767	0.0159
Day 14	15.6954	15.6733	0.0221	11.2588	11.1608	0.0980
Day 21	15.9720	15.9376	0.0344	11.1842	11.1037	0.0805
Day 28	15.6761	15.6169	0.0592	12.3371	12.2934	0.0437
Day 35	15.9124	15.8536	0.0588	10.6844	10.6278	0.0566

Table6. Initial weight, final weight and the weight loss for Magnesium sulphate solution 5% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	15.8230	15.8124	0.0102	10.2786	10.2674	0.0112
Day 14	14.8391	14.5199	0.0192	10.8584	10.8382	0.0202
Day 21	15.2800	15.2505	0.0295	11.0228	10.9951	0.0277
Day 28	15.0071	14.9559	0.0512	11.2462	11.1990	0.0472
Day 35	15.7942	15.7394	0.0548	11.4892	11.4361	0.0531

Table7. Initial weight, final weight and the weight loss for Sodium sulphate solution 1% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	14.7148	14.6943	0.0205	11.0715	11.0665	0.0050
Day 14	15.2985	15.1235	0.1750	11.9904	11.9669	0.0235
Day 21	14.9565	14.9009	0.0556	11.2245	11.1920	0.0325
Day 28	15.5001	15.2653	0.2348	11.4103	11.3620	0.0483
Day 35	15.1286	15.0044	0.1242	11.5337	11.4750	0.0587

Table8. Initial weight, final weight and the weight loss for Sodium sulphate solution 3% concentration

DURATION	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	14.9652	14.9641	0.0011	11.4856	11.4839	0.0017
Day 14	14.8668	14.8551	0.0117	11.6703	11.6593	0.0110
Day 21	15.7093	15.6856	0.0237	11.4240	11.3815	0.0425
Day 28	15.0650	15.0221	0.0429	11.1833	11.1592	0.0241
Day 35	15.7856	15.7430	0.0426	10.1650	10.1357	0.0293

Table9. Initial weight, final weight and the weight loss for Sodium sulphate solution 5% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	15.3788	15.3758	0.0030	11.6595	11.6484	0.0111
Day 14	14.9740	14.9645	0.0095	11.6890	11.6826	0.0064
Day 21	15.5526	15.5348	0.0178	10.7082	10.6925	0.0157
Day 28	15.7303	15.6933	0.0370	10.4505	10.4308	0.0197
Day 35	15.7696	15.7247	0.0449	10.3621	10.3384	0.0237

Table10. Initial weight, final weight and the weight loss for Ammonium sulphate solution 1% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	14.7853	14.7555	0.0298	10.7806	10.6627	0.1179
Day 14	14.9867	14.9363	0.0504	10.7195	10.5882	0.1313
Day 21	15.3173	15.2158	0.1015	11.1869	11.1656	0.0213
Day 28	15.7160	15.5975	0.1185	11.1102	11.0729	0.0373
Day 35	15.8890	15.7726	0.1164	11.2953	11.0968	0.1985

Table11. Initial weight, final weight and the weight loss for Ammonium sulphate solution 3% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	15.0403	15.0171	0.0232	11.4052	11.3869	0.0183
Day 14	15.5020	15.4548	0.0472	11.0740	11.0491	0.0249
Day 21	15.1384	15.0939	0.0445	11.5683	11.4145	0.1538
Day 28	15.2892	15.1495	0.1397	11.5991	11.3881	0.2110
Day 35	15.9264	15.8335	0.0929	11.5919	11.2942	0.2977

Table12. Initial weight, final weight and the weight loss for Ammonium sulphate solution 5% concentration

	8MM THICK MILD STEEL			STRUCTURAL STEEL SECTION		
DURATION	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]	INITIAL WEIGHT [g]	FINAL WEIGHT [g]	WEIGHT LOSS [g]
Day 7	15.4927	15.4644	0.0283	10.5665	10.5475	0.0190
Day 14	15.1248	15.0796	0.0452	11.7548	11.7205	0.0343
Day 21	15.2612	15.2099	0.0513	12.7173	12.6456	0.0717
Day 28	15.6924	15.5553	0.1371	11.4377	11.2727	0.1650
Day 35	14.8268	14.6683	0.1585	11.4482	11.2220	0.2260

Figure1. Deteriorated/ corroded structural steel and steel sections in sulphate solutions characterized by colored solution