

An Investigation on Corrosivity of Road Salt and Alternatives on Steel

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ABSTRACT

Road salts are commonly applied for controlling snow and ice on the roads for safe and efficient operation of transportation systems. The application of rock salts, mostly used deicer, induces infrastructure problems and corrosion is a major one. Transportation agencies of cold countries spend millions of dollars annually fixing infrastructure, more specially corrosion related problems associated with the rock salts. Researchers and transportation stakeholders are concerned about the corrosion on the roadway infrastructures and are working to mitigate them in diverse ways. This study conducts laboratory experiments and determines the corrosivity of seven corrosion resistant road salts developed by Starstech, a South Korean manufacturer, comparing with traditional rock salt on steel rebar. The corrosion resistant salts along with rock salt were dissolved in deionized water separately for preparing brine solution. Steel rebar was submerged in each of brine solution for observing corrosivity. Change in color and weight of rebar at different durations were observed and reported. The outcome of this research is reported based on physical observations and change in weight of rebar after each cycle of submergence in different brine solutions. The formation of protective layer on the steel rebar for each of corrosion resistant brine solution was obvious from the visual observation. The loss in weight of rebar submerged in brine produced from traditional rock salt was higher than alternative salts. The outcome of alternative salts is promising as corrosion resistant deicer and may be suitable option for using in cold countries.

INTRODUCTION

The application of road salts during winter in cold climate regions is a common practice for transportation systems to work effectively and safely. Around 60 million tonnes of road salt are reportedly used annually around the world, with the US using the most at over 20 million tonnes. Canadian provinces consume approximately five million tonnes of road salts at each year (Tenneti, 2022). A substantial amount of road salt is used in China (600,000 tonnes), Norway (320,000 tonnes), Sweden (210,000 tonnes), Denmark (55,000 tonnes) and other cold regions. The rate of rock salt application in Canada is higher than US or any other countries in the cold world. The annual consumption rate of salt in Canada is 6 tonnes/km of the road (Rødland et al., 2020). In this paper, the single term deicing will be used as a replacement of de-icing and anti-icing for ease of reading.

Transportation agencies of different cold climatic zones generally use chloride-based road salts like sodium chloride (NaCl), calcium chloride (CaCl_2), and magnesium chloride (MgCl_2) as deicers (Wang et al., 2019; Shi et al., 2009). Sodium chloride, among the chloride-based salts, is extensively applied in different cold countries for controlling snow and ice (Li et al., 2019).

NaCl is largely used as a deicer and is spread on the roads or other transportation facilities in the form of dry rock salt and solution of salt and water (namely as brine). The solid or brine may be used alone, in combination of salt and brine (pre-wetted), or mixed with sand (Sutter, 2014). When applied, the brine solution immediately begins to function. The solid salt grains are broken down by the moving vehicles on the road and these grains create brine solutions by drawing out moisture from the ice formation. This mechanism lowers the freezing point and facilitates in melting the accumulated snow, ice, or frost from the pavement surface. These deicers also provide a debonding layer between accumulated snow, ice or frost and top of the underlying surface for easy removal (National Winter Service Research Group & Institute of Highway Engineers, n.d.). The public safety on all forms of transportation in winter is ensured by using salts as deicing materials on roads (more specifically, highways) as well as parking lots, walkways, and driveways (National Winter Service Research Group & Institute of Highway Engineers, n.d.; Toronto and Region Conservation Authority, 2022).

Road Salt and their Impacts

The major advantage of the application of rock salts is the enhancement of the road safety (Environment and Climate Change Canada, 2015) through the melting of snow and ice at a temperature lower than freezing point of water (Perera et al., 2013). Regaining frictional resistance of pavement surface, increasing vehicle maneuverability, speed, and roadway capacity attributes to road safety due to the melting ice and snow. According to a comparative study of salted and unsalted roads, winter accidents may be reduced by up to 88.3% and a reduction in crash related cost by 10% (Dindorf & Fortin, 2014). Snow and ice control along with other maintenance measures mitigate winter hazards and this requires a multi-billion-dollar investment each year in many cold regional countries. However, the applied road salts pose some detrimental effects on the roadway and surrounding infrastructures (Fay et al., 2013).

Corrosion is a major infrastructural problem induced by the application of road salts in winter road maintenance. Automobiles moving on the snowy roads are corroded from the electrochemical oxidation of metals being in contact with solution of chloride ions from the deicers and moisture from the snow or ice (Casey et al., 2014). The wind transports salt dust, generated from the rubbing action of the moving vehicles and pavement surface, at the surrounding area of roads. These dusts corrode the metal surface at the adjacent area, even on the metals at 15 m away from the road (Krejslova & Geiplova, 2011). In the presence of air and moisture, any concrete structure exposed to rock salts (more especially, chloride ions) corrode the reinforcing steel (Portland Cement Association, n.d.). Concrete fractures are propagated by the initial corrosion of the steel, which also causes scaling, paste disintegration, an increase in

permeability, a drop in compressive strength, and a loss of material weight (Shi et al., 2013; Xie et al., 2015). The presence of chloride ions in road salts is also a primary cause of the corrosion of bridges, roadways (concrete roads), parking lots, walkways (Shi et al., 2010, 2013, 2014) and other structures constructed with any corrosion prone metal. The damage in asphalt pavement due to deicers is caused by a variety of processes, including chemical reactions, emulsions and the development of additional stress inside the asphalt (Shi et al, 2009).

Transportation agencies spend millions of dollars annually fixing infrastructure problems caused by snow and ice. An economic analysis by Vitaliano (1992) revealed that using deicers induces corrosion cost for infrastructures and automobiles. Each year it is estimated that a cost of at least \$615 is added per ton of salt used for roadway infrastructure and \$113 per ton of salt for vehicle infrastructure. The installation of corrosion resistant features in newly constructed bridges and repairing of old ones in the snowy states in USA require an investment in the range of \$250-\$650 million per year (Transportation Research Board, 1991). Dindorf and Fortin (2014) analysed the cost estimates of different damages associated with the usage of road salts in seven studies conducted from 1976 to 2010. This study reported that the cost per ton of salt application ranged \$30-\$113 for vehicle corrosion, and \$600-\$615 for additional road maintenance. The overall damage cost per ton of salt application was \$3,341 including \$1,460 as maximum cost for infrastructure damage. The study of Heinz et al. (2008) enumerated the damage cost of applied rock salts to be 15 times more than the materials and their application cost.

Alternative Deicers and their Performance

The reduction in corrosion from the deicers is essential for transportation agencies to ensure minimum infrastructure damages. Researchers and practitioners in cold countries are adding corrosion inhibitors or additives to road salts to reduce corrosion related consequences (Xie et al., 2015). The acetate-based products being comparatively less corrosive than rock salt have gained attention of different agencies in recent time. The commonly used acetate-based products are Potassium Acetate (KAc), Sodium Acetate (NaAc), and Calcium Magnesium Acetate (CMA) (Western Transportation Institute, 2017). Different laboratory studies have found better corrosion resistivity of CMA (Xie et al., 2015), KAc and NaAc (Shi et al., 2009) to metals (i.e., steel, cast iron, aluminum, and galvanized steel) than rock salts. These acetates are applicable at a higher temperature than chloride-based salts and need to apply at 50% higher rate. Acetates can corrode the galvanized steel and emulsify asphalt mixture (Du et al., 2019).

Different authorities, involved in snow and ice control, have been adopting agro-based deicers due to their resistivity to corrosion and environmental impacts (Muthumani et al., 2015). Agro-based products, derived from the processing of beet juice, molasses, corn, and/or cane barley, are utilized alone or in mixing with other road salts. These additives provide corrosion resistivity by the coverage of the metal surface and the decrease of corrosion initiating ions (Nazari et al., 2017). These products also perform better in reducing freezing point of water and the blending of these with regular salts is less corrosive to metals (Muthumani & Shi, 2017). The application of agro-based chemicals in snow and ice control requires high cost and brings about an increase in biological or chemical oxygen demand problems (Du et al., 2019).

Glycols (include glycol, glycerol, and glycerin) are non-chloride deicers and effectively work at low temperature ranges. Sodium formate and potassium formate are also effective at the same temperature range (20°F to 15°F) of glycols. Both are non-chloride deicers and are used generally at airports. Numerous glycols designed for usage on highways are currently available on the market. Glycols are found to be corrosion resistive to metal surfaces. On the contrary, these deicers have adverse effects on concrete and are costlier than NaCl (Western Transportation Institute, 2017). Based on the study of Dindorf and Fortin (2014), neither sodium nor potassium formate cause steel to corrode and Nazari et al. (2019) found

sodium formate to serve as a corrosion inhibitor in ice and snow control. Researchers observed the initiation of corrosion on plain steel and galvanized steel by potassium formate (Xie et al., 2015). Succinates, currently served as new additives in NaCl, exhibited satisfactory performance as corrosion inhibitor. These are not produced in massive amount at this moment (Fay & Akin, 2018).

Researchers have been working to find out suitable alternatives of traditional rock salt to minimize environmental and infrastructure damages. The alternatives (agro-based products, acetates, glycols, formats, succinates) discussed above are found to perform effectively in deicing and to exhibit resistance to corrosion on different metals. Each alternative product that is available usually incurs an added complication compared to road salt, these include higher costs, adverse impacts on concrete and asphalt, and corrosivity consistency on metals. It is essential to evaluate the viability of newly developed road deicers and corrosion-inhibitors in the laboratory and field level at different conditions.

OBJECTIVE

Advanced Road & Transportation Engineering Lab (ARTEL) at Carleton University in Ottawa has recently initiated a multi-year research project with a South Korea based company, Starstech, to evaluate viability of various corrosion resistive deicing chemicals they have developed. The overall goal of this research project is to obtain a better understanding of corrosion resistive alternative de-icing materials supplied by Starstech. The objective for this testing procedure includes:

- I. Determining the corrosion effects of solid deicing materials on steel used in roadway infrastructure.
- II. Comparing the corrosivity of newly produced alternative deicing materials to road salt.

MATERIALS AND EXPERIMENTAL DESIGN

The corrosivity of deicing products were performed at Carleton University's Engineering Laboratory. All the tests had identical test conditions including temperature, humidity, and light exposure. Laboratory experiment conducted in this current study is based on the visual observation of changes in color and measurement of the weight loss of rebar due to deicers' effects. The schematic diagram of the entire procedures is presented in Figure 1.

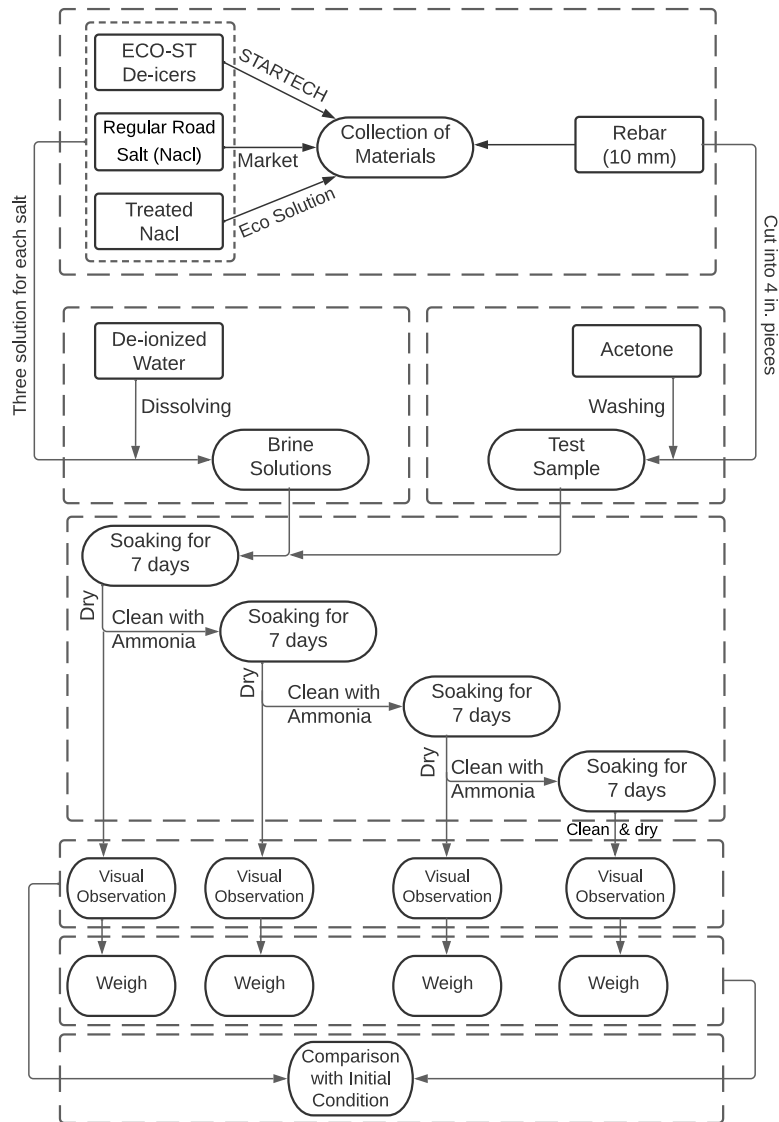


Figure 1: Experimental procedure and flow chart

Starstech provided six variants of environment friendly deicing salt. Eco Solutions, a local Ontario company, provided their alternative deicer Organic Melt (sodium chloride treated with their FUSION liquid). Sifto Safestep road salt (NaCl) was collected from open market of Ottawa for comparative analysis with the provided alternative de-icers. Uncoated rebars of 10 mm in diameter, acetone, deionized water, diammonium hydrogen citrate with other necessary utensils for this experiment were also purchased from the market.

Brine solution for each of the deicers were prepared by dissolving the solid material into deionized water. Every deicer, 3.0% of total weight, was dissolved into deionized water in a three-litre batch for making brine solution. Each brine solution for all samples were split into three mason jars, each containing 750 mL of the solution with 22.5 gm of deicing salt. The water solution of 3.0% mass percentage was inspired from the testing document “EM502-1 Performance Assessment on Deicing Chemicals – Test method for Corrosion effect on Steel” (Ministry of Environment, 2014). Brine solutions of different deicers were designated from A-H and labelled on the body of the jars. The designations with their respective deicers are presented in Table 1.

Table 1: Designation of brine solutions

Deicer	A – ECOST	B – ECOST 0.5% Starfish Extract	C – ECOST 1% Starfish Extract	D – ECOST 1.5% Starfish Extract	E – ECOST 2% Starfish Extract	F – ECOST 2.5% Starfish Extract	G-Eco	NaCl
Brine	A	B	C	D	E	F	G	H

Standard 10 mm steel rebar, collected from the market, was cut into four in pieces. A total number of 24 pieces, resulting from three samples for each type of deicer, were prepared. These pieces of testing rebars were cleaned with acetone to remove impurities. The cleaned rebars were stored in a closed environment to prevent the occurrence of rust on the surface of rebars until the time of testing.

The initial rebar samples were weighed and submerged in different labelled (A1-H1) jars, as shown in Figure 2, for the duration of seven days. The letters 'A-H' represents the brine solution and '1' indicates test set. Three tests were run at the same time to ensure the parameters around each test to be identical. These labels remained the same for all the experiments till the end.

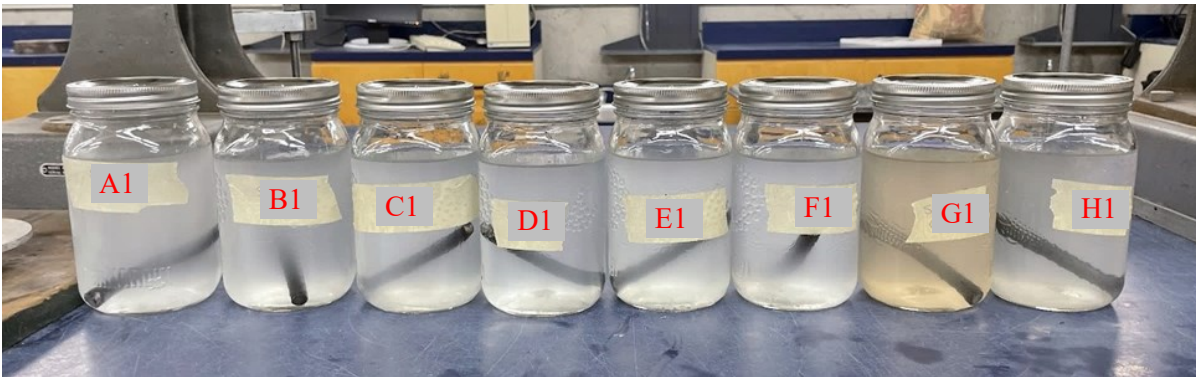


Figure 2: Initial rebars submerged in their respective brine solution (Jars are labelled from A to H)

Test samples were removed from the brine solution after a week of soaking. They were allowed to dry for 24 hours and then weighed and recorded. The dried rebar samples were cleaned using ammonia to remove any additional impurities. The cleaned samples were weighed again and returned to their respective brine solution for another week, this was done to expand prolong the exposure to the brine materials and observe the differences that accumulated over extended time intervals. Removing from the brine, drying, weighing, and cleaning the rebars were continued for another three weeks. After the final week, the rebar materials were soaked for 30 minutes in a solution consisting of 20% diammonium hydrogen citrate aqueous solution as per KS M 8403. This was repeated until the presence of corrosion on the rebar sample was gone.

After the complete removal of corrosion, the samples were washed with deionized water and patted dry with a paper towel. The patted dry samples were placed in an oven at 80° C to make fully dried weighed to the nearest 0.0001g. The data for this experiment was collected and stored using Microsoft excel. The sheet included the start date of the test, the initial weight of rebar material, the percentage of deicing materials for each solution, the cleaned and dried rebar weight after each week.

RESULTS AND DISCUSSION

This study has obtained qualitative and quantitative measurement of the formation of corrosion on the rebar surface exposed to brine solution. The qualitative data include the images of color changes

in the rebar samples as well as a quantitative set of data to determine the loss of rebar weight throughout the accumulation and removal of the corrosion. A total of three testing events were conducted for this research. Each event contained one sample for each of the testing materials resulting in eight samples per event and a total of 24 samples for all the tests.

The corrosion formation (based on visual observation of change in color) on the rebars from the initial stage to each of one, two, three and four weeks of submergence in eight brine solutions are presented in Figure 3. Figure 3 represents one sample of each category. The initial condition for eight different events shows the rebar samples in the size of 4 in cleaned with acetone. No existence of corrosion on any sample of rebar surface is noticeable in figure at initial condition. This was to ensure that all the samples had the same starting point when it came to the possibility of corrosion forming. The samples were then submerged as seen in Figure 2 and left like this for a week.

The second row of Figure 3 shows the transition of initial samples after being submerged one week in their respective brine solutions and drying for 24 hours. It was seen from the initial glance that Eco Solutions Organic Melt (Solution G) and road salt (Solution H) produced a very orange tint in the water. There was little to no indication of corrosion or buildup forming on any of the samples at the wet condition after being removed from the brine solutions. The start of corrosion at air dried condition can be seen to form on the metal for G and H solutions as shown in Figure. This is unlike their counterparts of E-COST solutions (A-F) where these brines produced a white tint and a coating of a white substance started to cover the rebar samples. There is seen to be a little corrosion, a very small extent compared to samples G and H, start to form near the ends of the rebar samples C, D, E, and F.

The third row in Figure 3 presents dried rebar samples after being soaked in their brine solution for a two-week period. Few changes are observable in a direct comparison of these rebars to one-week rebars in Figure 3. The potential corrosion seen previously on samples C, D and E has mostly disappeared. A small amount of corrosion is found on the bottom of sample F in Figure 3. The accumulation of residue on the rebar appears to be less white and dense on the metal, despite the fact that it is still present. The corrosion accumulated on samples G and H has increased significantly at this stage.

The fourth and fifth row in Figure 3 are the great pictorial representation on how much more corrosion is being formed on the metals submerged in brine solutions for three- and four-week periods. All the Starstech test samples show the formation of a white layer on the metals. It is believed that the white layer was a protective coating that developed to protect the metal from chloride ion action. Another thought was that it was a variation of white rust – a less dangerous version of corrosion. Further tests would need to be run on the metals to see what this buildup consists of. It was observed that some Starstech samples developed small amounts of orange corrosion near the edges after one week of being submerged however, it seems that this corrosion is not displayed after the second week. It might have taken some time for Starstech technology of capturing the chloride ions from the brine solution to take affect, however more testing would need to be completed to confirm this speculation. It is noted that sample B and F show high amounts of the white buildup.

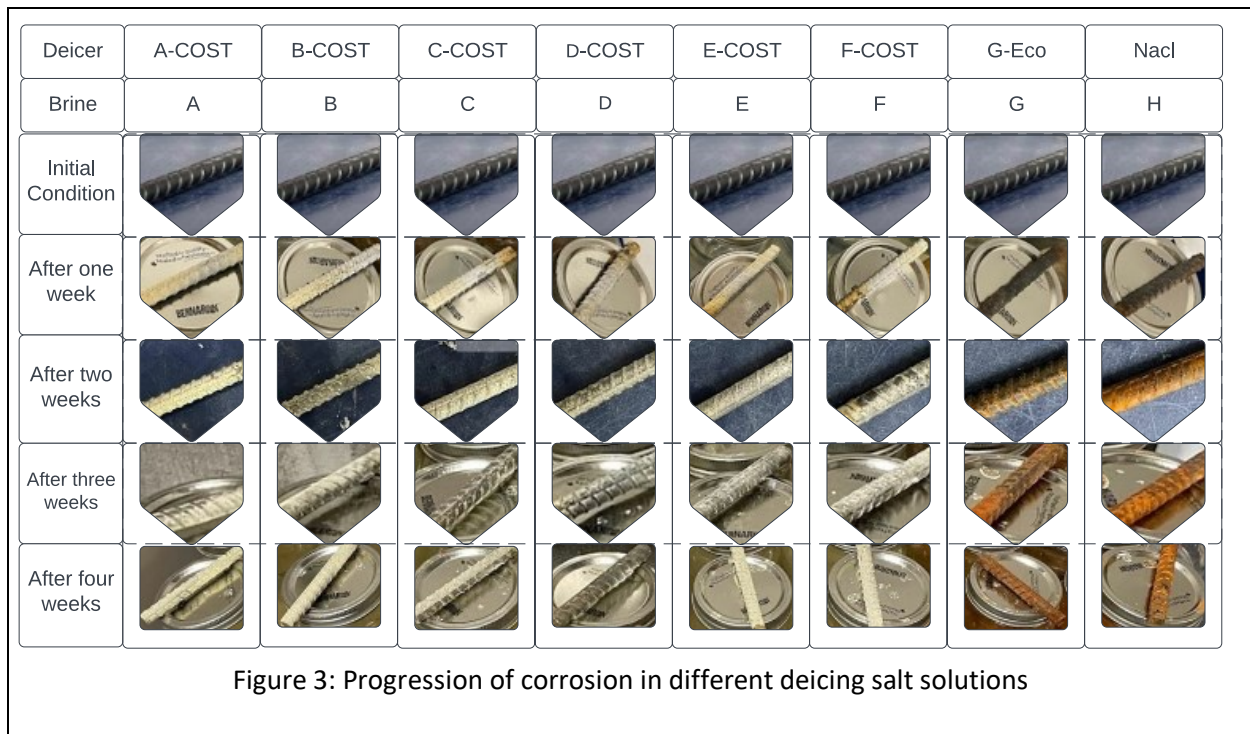


Figure 4 represents three tested samples of each category at the end of four-week period after the submergence in their respective solutions. The presence of corrosion layer on the three samples soaked in G and H solutions is clearly visible. The formation of coating on the rebars submerged in every ECOST samples is seen in the images. Other rebars submerged in ECOST solutions. Figure 11 shows all the tested samples when they are dried after the 4-week duration of being submerged in the brine solution. The corrosion comparison is blatant, and it is seen that ECOST does a great job of preventing the aspect of orange corrosion on steel rebar in comparison to other deicing materials.



The following figures show the comparison of one sample for each deicing material and a controlled sample which was kept in ideal conditions to prevent any accumulation of rust or buildup.



Figure 5: ECOST Samples A1(left) and B1 (right) in comparison to the control rebar sample.



Figure 6: ECOST Samples C1(left) and D1 (right) in comparison to the control rebar sample.



Figure 7: ECOST Samples E1(left) and F1 (right) in comparison to the control rebar sample.



Figure 8: Samples G1 (Left) and H1 (right) in comparison to the control rebar sample.

Observing Figures 5-8 it is evident how the ECOST alternative deicers had a far different reaction to the rebar samples than the Organic Melt and the Road Salt. The ECOST samples all had relatively the same final result, a white residue buildup on the outside of the metal, it is still unknown what this buildup is; it could be white rust but highly unlikely as the sample is carbon steel and not galvanized. Without

further research it will remain unknown. Figure 15 shows how the Organic Melt and Road Salt affected the rebar samples, the results are what one would expect. A thick rust coat has formed uniformly around the steel sample with very little of the original steel able to be seen, this is a much more drastic result compared to all the other samples. After the soaking in brine solutions, the rebar samples were submerged in diammonium hydrogen citrate to remove any corrosion or buildup that accumulated on the metals. This can be seen in Figure 9.



Figure 9: All samples from experiment 1 submerged in diammonium hydrogen citrate.

After the corrosion was removed, the samples were then dried in an oven at 80 C to ensure all the liquid was removed and the samples were weighed. The final weights of the samples were compared to their initial weights. Figure 10 shows a comparison between two of the samples, one after it was treated with diammonium hydrogen citrate and one before it was.



Figure 10: A comparison between the washed sample from experiment 1 (front row) and the unwashed samples from experiment 3 (back row)

The percentage loss of weight of steel material submerging in different brine solutions for a four-week periods is presented in Figure 11. This presented data outline a great representation for how much corrosion affected each sample. The figure shows that rebars submerged in both A1 and F2 solutions experienced the lowest percent change in weight of 0.07%. Road salt sample, H3, is found to experience the highest change in weight with 0.35%. The three rebars soaked in solutions of alternative deicing (G1, G2, G3) lose weight about 0.28%, 0.24% and 0.29%.

Average weight loss of steel rebar submerged in all ECOST samples, A-F, are 0.074%, 0.099%, 0.110%, 0.087%, 0.088% and 0.081%, respectively. The average weight loss of the three samples soaked in H solution is 0.2433% and this is highest one. This loss of weight of rebar for H solution is above 3 times with ECOST solutions. About 0.2117% average loss of weight of rebars for treated NaCl available in Ontario market is observable. All the ECOST solutions introduces the lowest amount of weight loss.

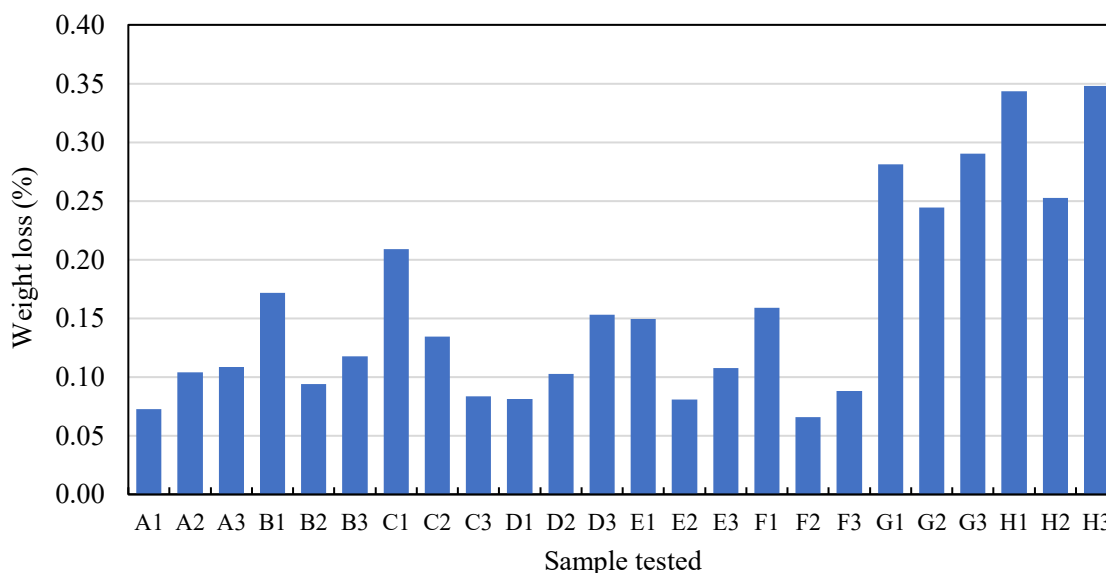


Figure 11: Weight loss for each rebar sample

From the qualitative and quantitative evidence that was shown in the figures previously, it is evident that ECOST is the highly favorable deicer corrosivity perspective. The qualitative and quantitative observations show very little to no corrosion taking place on the rebar samples when their counterpart of the local Ontario deicer and regular road salt shown significant formations of corrosion from the first week and consistently growing. This is backed by the evidence in the weight loss that occurred from the initial date of the tests to after all of the residues and corrosion was washed off the samples.

FINAL REMARKS

The corrosivity of the newly produced six deicers by Starstech, regular salts and treated salt available in local market in Ontario is qualitatively and quantitatively analysed in laboratory. Brine solution for each salt was prepared and steel rebars were submerged in solutions up to four weeks period. The change in color of each sample was observed at each consecutive week was observed. This study also reports about the loss of weight after four-week periods. From the experiments the following conclusions can be drawn:

- The change in color on the rebar surface shows the regular road salt (NaCl) to experience the highest amount of corrosion.

- All ECOST solutions exhibited the most promising results with the formation of coating on the steel surface and least loss of weight.
- A slight qualitative and quantitative improvement in case of Eco Solutions Organic Melt de-icer is observable in comparison with regular road salt.

The results from this data show a promising future for the alternative de-icers in terms of corrosivity. All the outcomes of ECOST are similar and may be viable in field application. Further investigation can be carried out for the feasibility of using these de-icing ECOST in field conditions.

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AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: Dr. Kamal Hossain developed the project proposal and supervised research. Lawlor designed and conducted the experiments, analyzed the data, and prepared the draft manuscript. Rana and Hossain reviewed the paper. All authors reviewed the results and approved the final findings of this study.

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