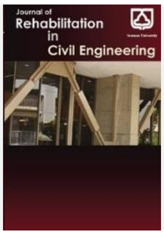

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Compressive Strength of Recycled Green Concrete Affected by Chloride and Sulfate Exposures

Md. Roknuzzaman [1]; **Md. Mahabub Rahman** [2,*]

1. Associate Professor, Department of Civil Engineering, Hajee Mohammad Danesh Science and Technology University, Bangladesh
2. Lecturer, Department of Civil Engineering, Hajee Mohammad Danesh Science and Technology University, Bangladesh

* Corresponding author: *mmr.civil@hstu.ac.bd*

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ABSTRACT

The use of recycled aggregate to make concrete is a viable option to minimize demolition waste load in landfills and to preserve the natural resources of aggregates. Several studies reveal the potential of recycled aggregates, which can be re-used in concrete, resulting in green concrete with acceptable strength parameters. However, the performance of green concrete under adverse exposure conditions is yet to be evaluated on a larger scale. The present study investigates the compressive strength of green concrete under chloride and sulfate exposure. C-20-grade concrete specimens are prepared using recycled coarse aggregates derived from demolished concrete blocks from an 8-year-old highway culvert. After 28 days of regular water curing, the specimens are subjected to chloride and sulfate environments by immersing them in chloride and sulfate solutions. Compressive strength tests are conducted after 28 days, 56 days, 84 days, and 112 days of immersion. The results are compared with normal concrete of the same composition. Green concrete is found to be more susceptible to salt attacks than regular concrete. Sulfate exposures happen to be more damaging compared to chloride exposures. A maximum of 36.73% loss of compressive strength is encountered for 112 days of immersion of specimen in 10% Na_2SO_4 solution. The study recommends that caution should be taken while using recycled concrete in chloride and sulfate-prone environments.

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1. Introduction

Management of construction and demolition waste, commonly termed as CDW is a major concern in recent days as it occupies a major portion of landfills. More than 10 million tons of CDW are reported to be generated annually worldwide [1,2]. Most of the generated CDW ends in landfills creating a huge load on limited landfill spaces. Concrete is a major portion of CDW that comes from demolished concrete structures. Concrete used in buildings and roadways may eventually be damaged at a stage of its lifetime. Now-a-days it is a common practice to demolish and replace the older low-rise structures with new high-rise construction to make efficient use of limited land space which results in concrete waste. Recycling of concrete part from CDW has drawn attention to the researchers as it has economic and environmental benefits. One easiest way to reuse demolished concrete is making recycled aggregates from them. The demolished concrete goes through a process that the materials crush down into small size coarse aggregate so that it can use farther in building or any other project. In present days, different types of additives are being introduced in normal concrete to improve its performance and to make efficient use of byproducts. Many of such replacements are found to be effective. For instance, replacement of conventional cement with ferrocement gives better performance in retrofitting and concreting works in terms of structural performance and cost [3–5]. More ductile concrete was obtained by using geopolymer and FRP bars in concrete [6]. A popular term “green concrete” is introduced to the concrete produced with one or more recycled materials as its ingredients [7]. Several waste materials have the potential to be used in green concrete. In some earlier studies potential of waste tire, textile fibers, and rubbers were investigated to improve quality of concrete as well as geotechnical materials and positive outcomes were reported [8–10]. Almost five times increase in impact resistance of concrete was claimed by using waste tire and silica fume [11]. The suitability of using recycled coarse aggregates to produce green concrete is presented in several studies. Studies revealed that concrete with sufficient strength can be obtained using recycled aggregate as a partial replacement of natural aggregates. It was reported that, only 3 MPa strength loss when natural aggregates were replaced by recycled aggregates[12]. However, some other studies recommended that the replacement of natural aggregates should be limited to 25-30% in order to get concrete without compromising its ceiling strengths [7,13]. However, performance of recycled concrete depends on several factors such as the amount of attached old mortar, configuration of original parent concrete mix, type of parent aggregate, residual cementing property etc. [14–17]. Although the green concrete performs good in terms of their fresh and hardened properties, their durability assessment still needs attention. A poor concrete durability at higher water cement ratio was reported in a study [18]. A durability assessment of recycled concrete based on water penetration and porosity suggested that water cement ratio should be reduced by 0.1 point to get recycled concrete with 100% recycled aggregates of similar quality as compared to regular concrete [19]. In many cases, concrete may be exposed to chemical environments containing various types of salts. Cement based mortar and concrete are susceptible to deterioration by chloride and sulfate ions present in its exposure. Chloride attack is primarily responsible for corrosion in reinforcing bars and about 40% of structural failure is due to corrosion in reinforcement [20]. In cold areas, deicing agents like sodium chloride may accelerate the process of frost deterioration which may in turn result in surface scaling and low strength and stiffness in concrete [21–23]. Chloride attack is characterized by salt expansion as well as calcium leaching from cement mortar [24]. Chloride attack may lead to the formation of Friedel's salt in the following process [24,25]:

$$2NaCl + Ca(OH)_2 + 3CaO.Al_2O_3 + 10H_2O \rightarrow 3CaO.Al_2O_3.CaCl_2.10H_2O + 2Na^+ + 2OH^- \quad (1)$$

$$12CaO.7Al_2O_3 + 9Ca(OH)_2 + 7CaCl_2 + 61H_2O \rightarrow 7(3CaO.Al_2O_3.CaCl_2.10H_2O) \quad (2)$$

On the other hand, sulphate attack is governed by expansion that results in cracking or softening of outer layers [26]. Sulphate attack leads to the formation of ettringite which eventually results in expansion and disruption of cement paste. An earlier study confirmed that when sodium sulphate reacts with hardened cement paste, ettringite and gypsum may be produced resulting in a loss of integrity of the mortar [27]. Following reactions are involved in the process,

$$Ca(OH)_2 + Na_2SO_4 + 2H_2O \rightarrow CaSO_4.2H_2O + 2NaOH \quad (3)$$

$$3CaO.Al_2O_3 + 3(CaSO_4.2H_2O) + 26H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O \quad (4)$$

In several studies, strength and durability of concrete was found to be decreased when it was submerged into chloride and sulfate solutions [20,28,29]. As chloride and sulphate attack are proved to be damaging for regular concrete, it may be more destructive for green concrete. The use of recycled green concrete is being promoted in many countries to save their natural resources and to protect the environment. If such concrete is to be used in chloride and sulfate prone environments like coastal regions, the precise impact of salt exposure on such concrete must be investigated. The present study is considered to investigate the effect of chloride and sulphate exposure on compressive strength of green concrete. Discarded concrete blocks collected from demotion site is broken to prepare recycled aggregates and concrete specimens are prepared with them. Compressive strength tests are carried on the specimens after subjecting them to chloride and sulfate solutions for some regular intervals. Loss of strength and strength gaining patterns are discussed in the results and discussion section.

2. Materials and methods

2.1. Materials

2.2.1. Recycled aggregate

Discarded concrete blocks (parent concrete) were collected from a demolished highway culvert located at Dinajpur, Bangladesh. The parent concrete made of stone aggregate was 5 years old and demolished due to extension of road width. The collected blocks were broken manually by hammers to obtain standard aggregate size fractions. The procedure was similar to that commonly used for making brick aggregate from whole size bricks. Maximum size of aggregate was kept at 25 mm. Standard sieves were used to separate and arrange aggregates of different sizes ranging from 9.5 mm to 25 mm. Figure 1 shows the source of parent concrete and the process of obtaining recycled aggregate from it. ASTM C33/C33M-18 and ASTM C136/C136M-19 were followed to maintain similar gradation of aggregates in green concrete and normal concrete [30,31]. Water absorption and specific gravity of aggregates re determined following ASTM C128-15 [32]. Bulk density were worked out by adopting ASTM C29/C29M-17a standard procedure [33]. The properties of recycled aggregates as well as natural stone aggregates are presented in Table 1.

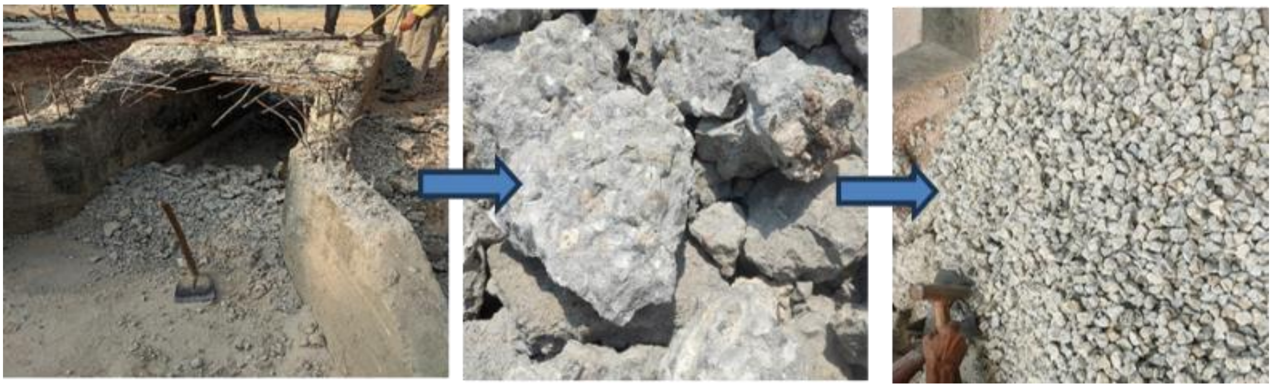


Fig. 1. Collection of parent concrete and making of recycled aggregate.

Table 1. Properties of concreting ingredients.

Ingredient	Description	Source	Properties
Coarse aggregate	Recycled coarse aggregate	5 years old culvert demolished for road widening	Size: 9.5 – 25 mm Fineness modulus: 6.55 Specific gravity: 2.31 Water absorption: 6.5% Bulk density: 1360 kg/m^3
	Natural stone aggregate (for normal concrete)	Local	Size: 9.5 – 25 mm Fineness modulus: 7.73 Specific gravity: 2.68 Water absorption: 2% Bulk density: 1610 kg/m^3
Fine Aggregate	Sand	Local	Fineness modulus: 2.45 Specific gravity: 2.65 Water absorption: 2%
Cement	Ordinary Portland cement CEM-1, 52.5 N	Local market	Normal consistency: 25.5% Initial setting time: 110 minutes Final setting time: 305 minutes Compressive strength: 25.7 MPa(3-days), 39.2 MPa (7-days), and 49.5 MPa (28 days)
Water	Potable water	Tap	-

2.2.2. Concrete ingredients

Other concreting materials such as fine aggregates and binder were collected from local sources. The properties of all concerting ingredients are shown in Table 1. For creating artificial chloride and sulphate exposure, sodium chloride, magnesium chloride, sodium sulphate and magnesium sulphate solutions were used. 10% solutions of each salt were prepared using anhydrous salt powder and distilled water.

2.2. Mix proportioning

A study carried on concrete mix design with recycled aggregate by different method revealed that the method proposed by American Concrete Institute (ACI) suited best for designing mixes of green concrete with recycled aggregates [34]. In the present study, standard procedures recommended by American Concrete Institute in ACI 211.1-91 and ACI 214R-11 were adopted for designing concrete mix of grade C-20 [35,36]. As the recycled aggregate has lower density than natural aggregates, its quantity (in terms of weight) is lower in the mix design. Since the water cement ratio was kept the same for both cases, quantity of cement and water remained same. Table 2 shows the proportions of ingredients in the designed concrete mix.

Table 2. Proportioning of concrete mix.

Design parameters	Mix type	Unit content (kg/m^3)			
		Water	**Cement**	**Coarse Aggregate**	**Fine aggregate**
Grade: C-20 Specified strength = 20 MPa Required average strength = 27 MPa Design slump = 75-100 mm Water cement ratio = 0.58	Green concrete	193	334	966	722
	Normal concrete	193	334	1143	700

2.3. Saline exposure

Standard cylindrical concrete specimens of diameter 100 mm and height 200 mm were cast and cured for 28 days in normal water. After the regular curing the specimens were immersed in the solutions of sodium chloride, magnesium chloride, sodium sulphate and magnesium sulphate. The concentration of each solution was kept as 10% (w/w).

2.4. Testing of concrete specimens

ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens was followed for this test was followed for determining compressive strength of the specimens [37].

For checking performance under prolonged curing, an interval of 28 days was chosen. The tests were conducted before immersion of specimens in salt solutions, after 28 days, 56 days, 84 days and 112 days of immersion. To compare the findings, normal concrete specimens were also subjected to similar exposure and tested. For each condition, 6 cylindrical specimens were tested and the average value of compressive strength was reported. Figure 2 shows some instances of the experimental program.

Fig. 2. Compressive strength test.

3. Results and discussions

It is evident that, use of recycled aggregate results in a reduction in compressive strength [38]. The compressive strength of concrete specimens after different periods of immersion is shown in Figure 3 and Figure 4.

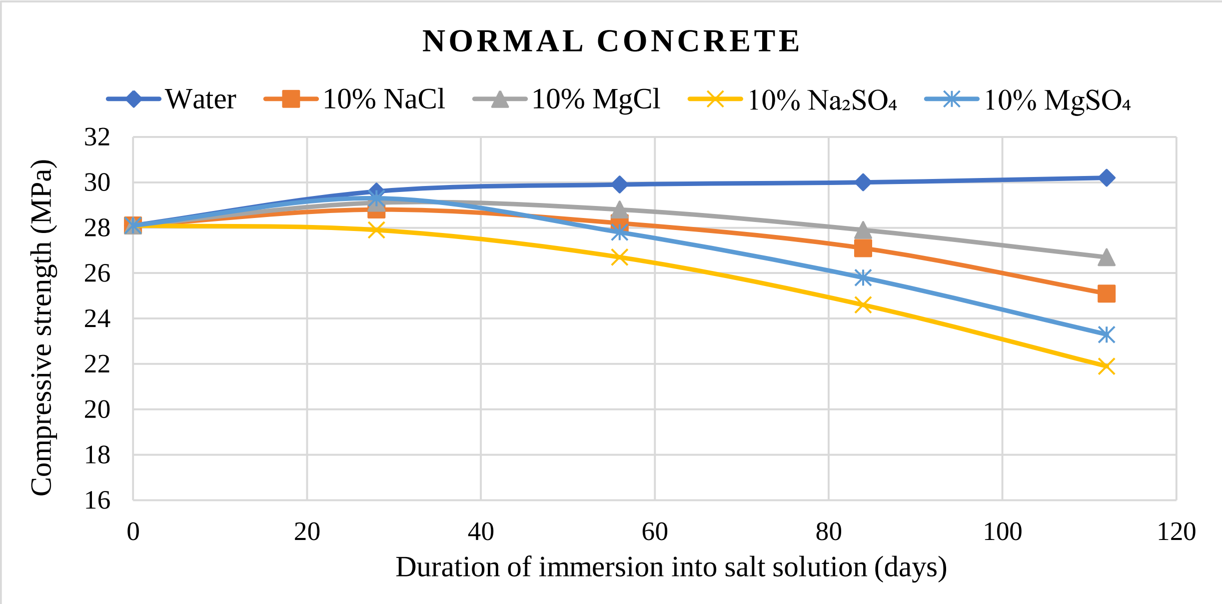


Fig. 3. Compressive strength of normal concrete specimens after different period of immersion into salt solutions.

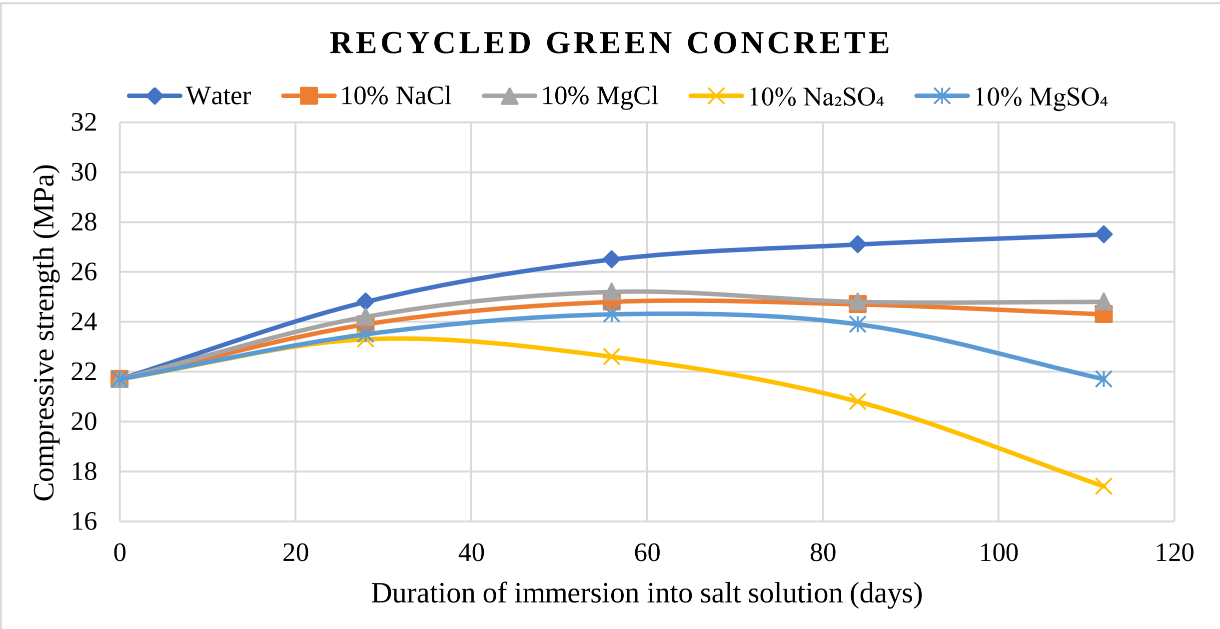


Fig. 4. Compressive strength of recycled green concrete specimens after different period of immersion into salt solutions.

As expected, compressive strength of green concrete as well as normal concrete was found to be increased with time when they were immersed into water. For the C-20 grade concrete mix, specified compressive strength f_c' is 20 MPa and required average compressive strength f_{cr}' is 27 MPa after 28 days of water curing [36]. The normal concrete mix could meet the requirement, but the green concrete could not satisfy the required average compressive strength f_{cr}'. The 28-days strength for green concrete (21.7 MPa) was about 20% below the requirement. An important observation was made here that, unlike normal concrete, green concrete was found to keep gaining strength at a significant rate after 28 days of regular curing which is shown in Figure 5.

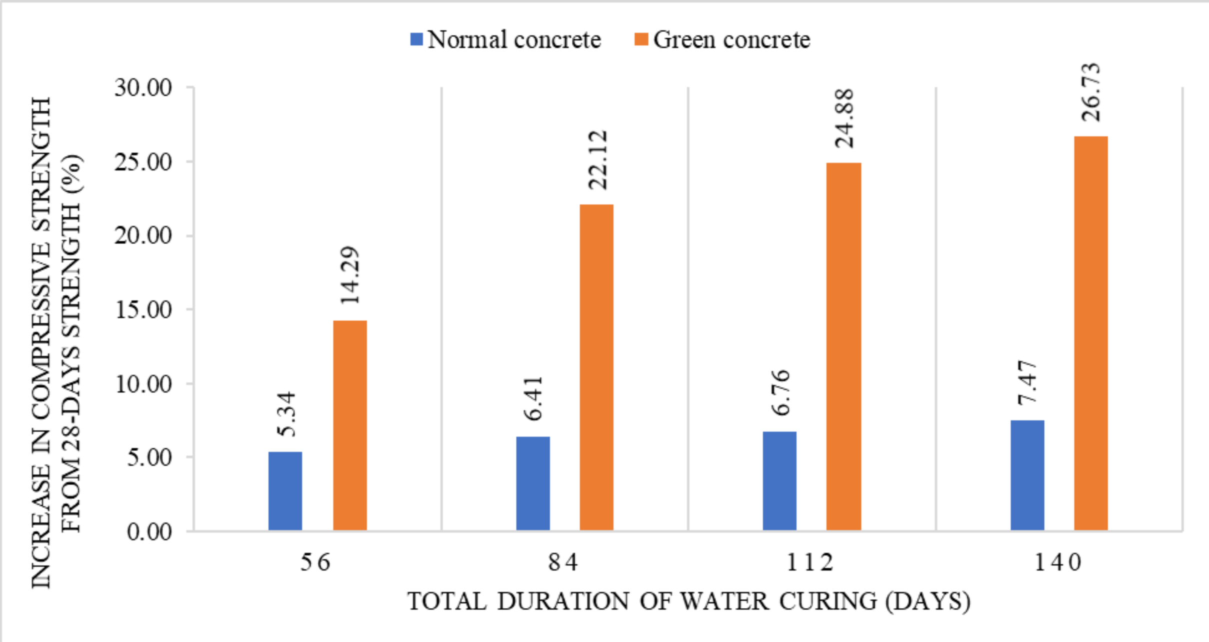
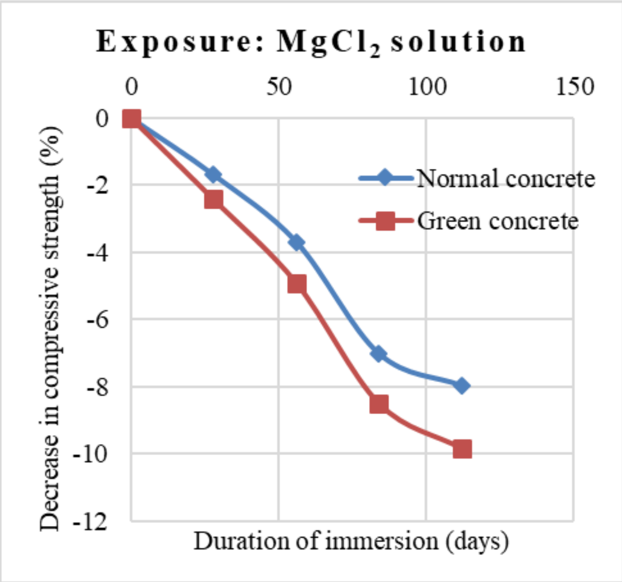


Fig. 5. Attainment of compressive strength with time in water curing.

This indicates the requirement of additional curing to gain sufficient strength for green concrete. For an additional water curing of 28 days, a 14% increase in compressive strength was observed for green concrete which was only 5% for normal concrete. Moreover, 56 days additional curing increased the compressive strength by 22% and this time it could meet the average strength requirement. Increased strength in prolonged curing after using higher portion of recycled aggregate was reported in another study [39]. 18 MPa increase in compressive strength from 28 days to 56 days was presented in that research where 80% recycled aggregates were used. Use of early strength gaining admixtures might be helpful in the cases of green concrete made with recycled aggregates.

On the other hand, when salt solutions were used as immersion media, strength was found to be reduced with time for all the cases. Figure 6 and Figure 7 show the effect of chloride and sulfate exposure on reducing compressive strength in the concrete specimens. Compressive strength was found to be reduced alarmingly when the specimens were exposed to saline environment. Chloride exposure, however, had less impact on strength than sulfate exposure.

Among the four different exposure conditions tested, sodium sulfate exposure was identified to be the most damaging that reduced the compressive strength of green concrete by 36.73% (decreased from 27.5 MPa to 17.4 MPa) in 112 days. At this point its compressive strength was found to be 13% below the specified strength (20 MPa) and 35% below the required average strength (27 MPa) for C-20 grade concrete. Green concrete tested here contains recycled aggregates that had old residual mortar attached to them. Earlier studies showed that among different salts, sodium sulfate has more potential to react with old mortar [16,40,41]. This might be the reason for the more aggressive behavior of sodium sulphate. 18% loss of compressive strength in 60 days and 40% loss in 18 months by sulfate attack was reported previously for normal concrete [42,43].



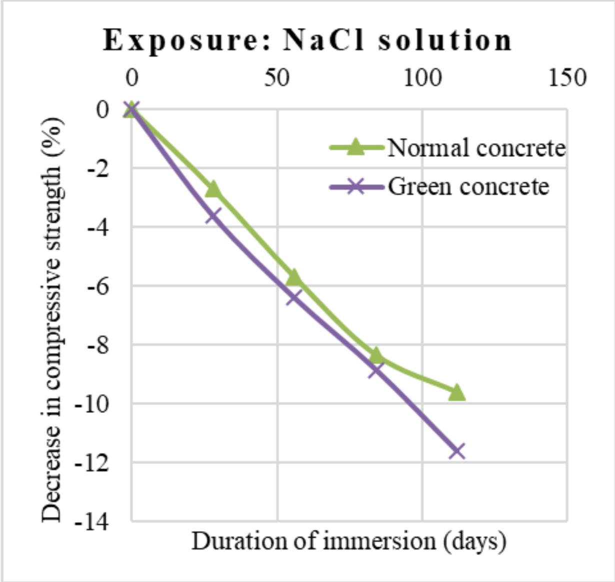
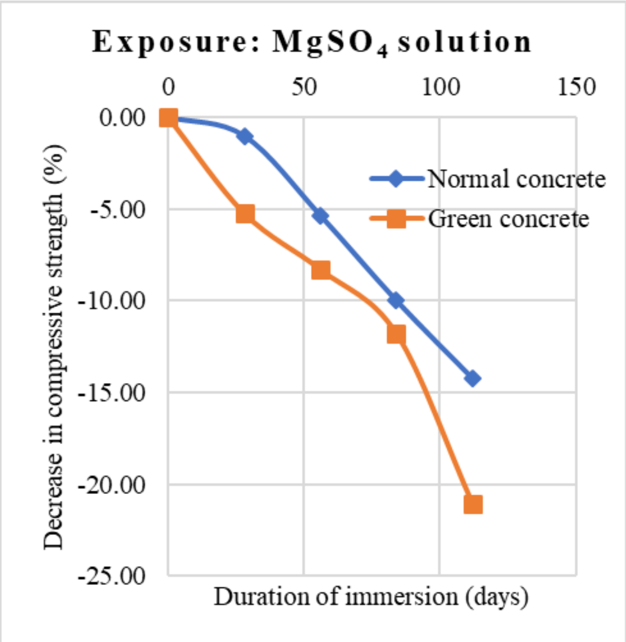


Figure 6. Reduction of compressive strength in chloride exposure



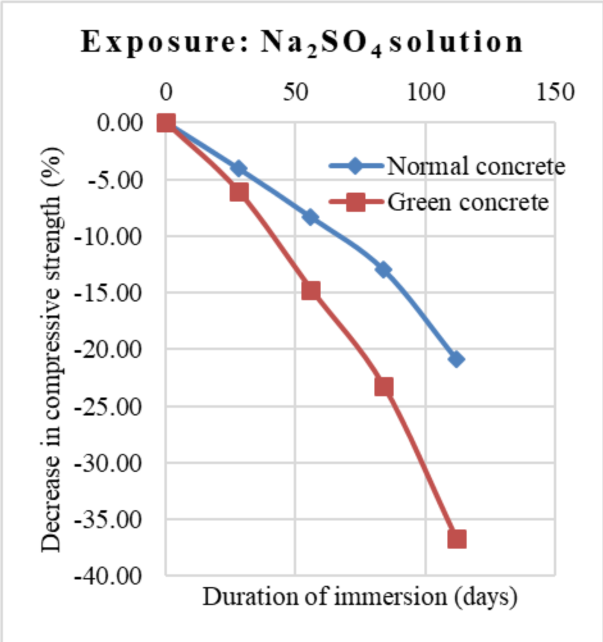


Fig. 7. Reduction of compressive strength in sulfate exposure.

4. Conclusions

The study revealed that the performance of green concrete is not good in chloride and sulphate prone environment as it shows more degradation of properties compared to normal concrete. Compressive strength was mostly affected by sulphate action resulting in a 36.73% loss of strength when exposed to 10% sodium sulphate for 112 days. The effect of magnesium sulphate was somewhat less than that of sodium sulphate, but significant property degradation was observed for magnesium sulfate, as well. Use of sulphate resistant cement is recommended for such exposure; however, further studies should be made to confirm it. The effect of chloride attack was less prominent; however, it may result in a 10% reduction in compressive strength and thus is should also be dealt with caution. The present study considered compressive strength only and observations were made for 112 days. Longer exposure may create severe damage in concrete and corrosion of steel are also expected to be problems which are not reflected in this study. Further investigations are necessary, giving emphasis on durability parameters and impact on reinforcement.

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