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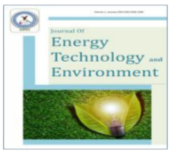

Concreting with Chloride Contaminated Aggregates: Effect on Compressive Strength and Concrete – Rebar Bond Strength

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Abstract

This study investigates the effect of chloride contaminated aggregate on the compressive and concrete rebar-bond strength of concrete. The coarse aggregates were contaminated by immersing them in a sodium chloride (NaCl) solution for a specified period of time. Two NaCl solutions were used - 10mg/L and 40mg/L. The aggregates were contaminated by soaking them in the NaCl solutions for 7 days, and thereafter left to dry under air for 3 days. Three concrete mixes were utilized for the study – C0, C10 and C40. C10 and C40 mixes were prepared with coarse aggregates contaminated with NaCl solutions of 10mg/L and 40mg/L respectively; while the C0 mix, which was the control mix, was prepared with uncontaminated coarse aggregates. A mix ratio of 1:1.5:3.53 was employed, to prepare concrete cubes which were cured under water for various periods up to 56 days. Compressive strength and pull-out tests were carried out on the cured concrete samples. The results revealed that the concrete mixes containing chloride contaminated aggregates had higher early strengths (at 3 and 7 days) than the control mix. However, at later ages of 28 days and beyond, the trend reversed with the compressive strength of the control mix becoming greater than that of the concrete mixes containing chloride contaminated aggregates. The results of the pull-out test showed a decline in the rebar-bond strength as the concentration of the NaCl solution used in contaminating the coarse aggregates increased. This study therefore shows that the effect of the use of chloride contaminated aggregates on the compressive strength of concrete worsens with the concrete age and reduces the concrete-rebar bond strength, and thus should be avoided at all cost.

1. Introduction

Reinforced concrete is a composite material comprising of steel and concrete that has been widely used over the last decades. The steel component often regarded as rebar, provides the tensile strength; while the concrete component, which has a high alkalinity (pH ranging from 12.5 to 13.5), provides protection to the steel reinforcement in the form of a physical barrier. This physical barrier is provided by the formation of a thin passive film around the steel reinforcement [1]. Reinforced concrete is used for the construction of most civil infrastructures such as bridges, wharves, tunnels or harbour structures, offshore platforms, dams and a wide range of buildings (private and public). Due to the wide range of use, reinforced concrete structures are subjected to a variety of exposure conditions such as marine, industrial or other severe environments, and are often expected to last with little maintenance for long periods of time, often 100 years or more [2].

Marine environment is one of the most aggressive and complex environments that a concrete structure can be exposed to [3]. It influences concrete structures through various physical, chemical, mechanical and biological processes, which cause deterioration of the concrete microstructure. On an average, seawater contains 3.5-4% of dissolved salts, mainly sodium chloride [3,4].

One of the main causes of corrosion of steel in concrete is the exposure of the concrete to chloride ions [5]. Chlorides may enter into concrete through two main routes – external (in the form of admixtures, de-icing salts, and via the penetration of seawater) or internal (via the use of chloride contaminated materials such as aggregates and water) [6,7]. When these chlorides enter into concrete, some of them are bound either physically by the calcium silicate hydrate (C-S-H) phase or chemically by the alumina-ferric oxide-mono sulphate (AFm) phase; while some remain as free chlorides in the pore solution. It is the free chlorides that are responsible for the breakdown of the protective thin passive film surrounding the steel [8]. Over time, the steel reinforcement becomes exposed and undergoes corrosion, and according to Bastidas-Arteaga *et al*. [9], this can affect the load carrying capacity of the structure by the loss of steel reinforcement section and the loss of the concrete-steel bond. This is considered as one of today’s most prevalent form of premature concrete deterioration worldwide and cost billions of dollars a year in infrastructure repair and replacement [10].

The Niger-Delta region of Nigeria has a coastline of over 1,000 km and is predominantly covered by saline seawater. Due to the salty nature of the waters along this region, it is difficult to find natural water that will be totally free of salt concentrates. In fact, most of the fine/coarse aggregates obtained from this region contain trace amounts of salt as well. Several studies e.g. [11–18] have looked at the effect of chlorides on the mechanical and microstructural properties of concrete. However, most of these studies were focused on the effect of using seawater or salt water as mixing water or for curing of the concrete; and not on using chloride contaminated aggregates that is also a potential route through which chlorides can enter into the concrete. This study investigated the effect these contaminated aggregates will have on some concrete properties such as strength and bond between concrete and steel reinforcement.

2. Methodology

2.1 Materials

Cement:

The cement used for this study was Portland cement of grade 42.5. It was obtained from a local vendor in Benin City in Edo State, Nigeria. The physical and chemical properties of the cement are shown in Tables 1 and 2 respectively.

Table 1: Physical properties of the cement

Property	Value
Specific gravity	3.15
Specific surface area (cm^2/g)	3540
Normal consistency	33mm
Setting times	
Initial	85 mins
Final	240 mins

Table 2**:** Chemical properties of the cement

Property	Value
Lime (CaO), %	60.87
Alumina (Al_2O_3), %	5.36
Soluble silica (SiO_2), %	20.55
Iron oxide (Fe_2O_3), %	4.00
Magnesia (MgO), %	0.74
Sulphuric Anhydride (SO_3), %	1.83
Insoluble Residue, %	2.93
Chloride (Cl_2), %	0.02
Al_2O_3/Fe_2O_3	1.34

Aggregates:

The fine aggregate used for the study was obtained from Uhunmobo, Uhunmode L.G.A, in Edo State, Nigeria. Sieve analysis conducted showed that the fine aggregate conformed to Zone II with a maximum aggregate size of 4.75mm sieve. The fine aggregate was free from clay, silt and organic impurities and conformed to the requirements of BS 882:1992 [19]. The coarse aggregate used was uncrushed granite obtained from Ofosu quarry in Ondo State. The sieve analysis carried out showed that it is of 20mm maximum size. Both the coarse and fine aggregates were dried prior to use. The aggregates were tested for their physical properties such as gradation, fineness modulus, specific gravity and bulk modulus. These are shown in Table 3.

Table 3: Properties of aggregates

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.60	2.74
Bulk density (g/cm^3)	1.52	1.61
Zone	II	N/A
Maximum size of aggregate	5mm	20mm
Fineness modulus	2.74	7.17
Aggregate Impact Value (%)	N/A	25.21

Water:

Clean potable water as obtained from the Civil Engineering laboratory of University of Benin, was used for mixing the concrete. The water was free from all forms of impurities and organic matter. It conforms to BS EN 1008:2002 [20] requirements.

Salt (NaCl):

Industrial salt was used for the study. It was purchased from a local chemical vendor in Benin City, Edo State.

Preparation of chloride contaminated aggregates:

The coarse aggregates were immersed in two sodium chloride solutions of different concentrations of 10mg/L and 40mg/L respectively. These concentrations were selected to represent typical chloride concentrations of the Niger Delta marine environments. The 10mg/L and 40mg/L salt solutions were prepared by dissolving 10mg and 40mg respectively of the industrial salt in 1 litre of distilled water. Thereafter, the coarse aggregates were immersed in the salt solutions. The resulting mixture of the coarse aggregate and the salt water was then left for 7 days to soak. There is no definite time given in the literature for the soaking period. It can vary from 1 day to 7 days [21]. The duration depends on how long it takes for the aggregates to reach saturation, and in this study, it was taken as 7 days. After soaking for 7 days, the coarse aggregates were removed from the salt solution and left to dry under air for 3 days, to ensure that all the surface water on the aggregate's surface is dried off.

Steel reinforcement:

The steel reinforcement bar used for the experiment was 12mm diameter high yield steel. The bars have two longitudinal ribs and rows of alternately inclined transverse ribs on both sides of the bars as shown in Figure 1.

Figure 1: Picture of 12mm diameter steel reinforcing bar

2.2. Concrete mix

Three concrete mixes were used for the study – C0, C10 and C40. C0 denotes the control mix, which does not contain any chloride contaminated aggregate. C10 denotes the concrete mix prepared with coarse aggregates contaminated with a 10mg/L sodium chloride solution, while C40 denotes the concrete mix prepared with coarse aggregates contaminated with 40mg/L sodium chloride solution. A mix design was prepared with target strength of 30MPa at 28 days. The mix ratios of the various constituents are shown in Table 4.

Table 4: Mix proportions of the starting materials

				Salt solution for contamination of aggregates		
Mix ID	w/c	Cement	Fine Aggregates	Control (0mg/L)	10mg/L	40mg/L
C0	0.51	1	1.5	3.53	-	-
C10	0.51	1	1.5	-	3.53	-
C40	0.51	1	1.5	-	-	3.53

The various constituents (cement, water and aggregates) were weighed separately and placed in the concrete mixer. After mixing, the concrete was placed into 100 mm cube moulds. The moulds were covered with thin polythene sheets and left to cure in the laboratory for at least 24 hrs, after which the cubes were demoulded and taken to the curing room.

Due to the fact that some of the concrete cubes were prepared with salt-contaminated coarse aggregates, they had to be cured separately so as not to contaminate the control concrete cubes (i.e. the C0 mix) in the curing bath. Curing was done for a period up to 56 days.

2.3. Test methods

Compressive strength:

Compressive strength was determined on triplicate samples of the mixes in Table 4, at specific ages of 3, 7, 28 and 56 days. At the test age, the concrete cubes were brought out from their respective curing environment, surface dried (as applicable), and weighed before testing. The compressive strength was carried out following the procedure in BS EN 12390-3:2019 [22], and was calculated using the expression below:

$$P = \frac{F}{A} \qquad (1)$$

where:

P compressive strength in MPa

F failure load in kN

A cross sectional area in mm^2

Pull-out test:

The pull-out test was carried out following the method adopted by Ogirigbo and Iyawe [23]. After 28 days of curing, samples for the pull-out test were brought out from the curing room for testing. Testing was done using a tensile machine. The concrete sample was placed in a concrete bracket (as shown in Figure 2a. The concrete bracket was made with steel plates of thickness of 10mm, four threaded rods each 500mm long and 12mm in diameter, and four bolts. The concrete bracket enabled the tensile machine to have adequate grip on the concrete sample, and ensured effective pulling of the rebar out of the concrete.

Thereafter, a tensile force was applied onto the rebar by pulling it upwards. The force at which cracks appeared on the concrete, at the region around the rebar, was recorded as the bond strength of the concrete-rebar bond. The bond strength was calculated using the equation shown as follows:

$$\tau = \frac{P}{\pi d l} \tag{2}$$

where:

τ	bond strength in MPa
P	failure bond load in kN
d	diameter of embedded steel reinforcement in mm
l	length of embedded steel reinforcement in mm

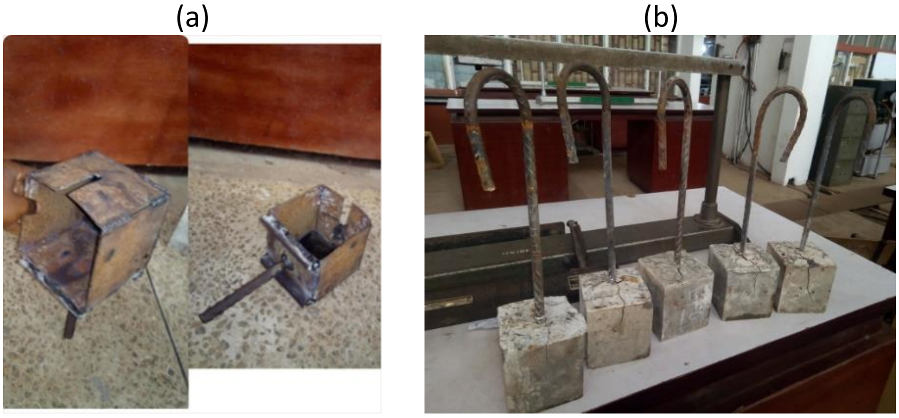

Figure 2: (a) Concrete bracket for holding concrete cubes (b) concrete cubes after testing showing cracks at interface between concrete and rebar

3. Results and Discussion

3.1. Compressive strength

Figure 3 shows the compressive strength development of all the concrete mixes at 3, 7, 28 and 56 days. The compressive strength was seen to increase with age for all the mixes; however, the rate of increase was not the same for all the mixes. The concrete mixes containing chloride contaminated aggregates had very high early strengths, as compared to the control concrete. For instance, as early as 3 days, the concrete mix containing coarse aggregates that were contaminated with 40mg/L sodium chloride solution, had already gained more than 60% of its target strength of 30MPa. For the C10 mix, the strength at 3 days was about 17Mpa, while that of the control mix (C0) was about 15MPa. The early increase in the strength of the concrete mixes containing chloride contaminated aggregates can be attributed to the accelerating effect of chlorides on the hydration mechanism, thereby resulting in early strength gains [24]. Similar findings were reported by [13,17,25]. From the figure, it can be seen that the C40 mixes had higher early strength than the C10 mixes. This is because the C40 mix probably had higher chloride contents than the C10 mix, which would have contributed significantly to its high early strength. This is in agreement with the study of Junjie *et* *al.* [18], and can be attributed to the combined effects of the increased Cl^- and Na^+ ions on the strength development. The strength at the age of 7 days had similar trend as that of 3 days, in that the concrete mixes containing chloride contaminated coarse aggregates had higher strengths than the control mix. For example, the 7-day strength of the C40 mix was about 27% greater than that of the control mix. However, as the age of the concrete samples approached 28 days and beyond, a reversal was observed in the strength results. The strength of the control mix became higher than that of the concrete mixes containing chloride contaminated coarse aggregates. This is similar to what was observed by Wegian [17], and can be attributed to salt crystallization forming in the microstructure, which can affect the strength gain.

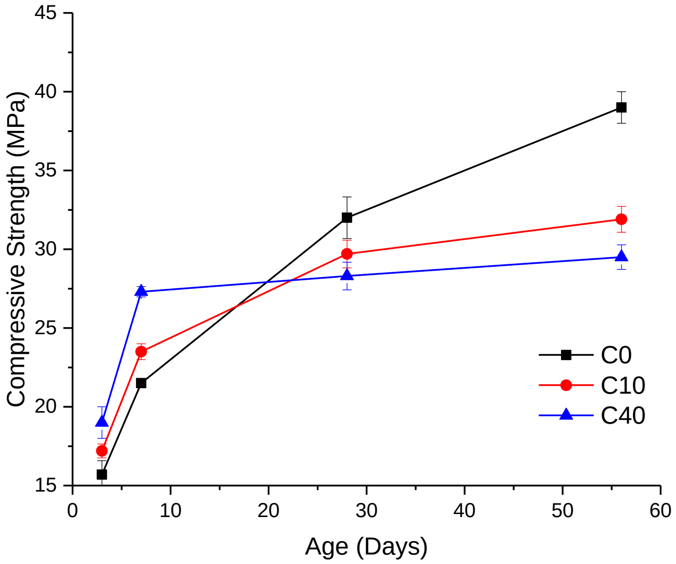

Figure 3: Compressive strength development for the various mixes

Strength deterioration ratios (SDR) were computed for all the concretes mixes at age of 28 and 56 days. The SDR was taken as the ratio of the strength loss of the concrete samples containing salt contaminated aggregates relative to the strength of those without salt contaminated aggregates [26]. The computed SDRs for 28 and 56 days strength are shown in Table 5. From the table, the SDR can be seen to increase with age and with the concentration of the sodium chloride solutions used in preparing the chloride contaminated aggregates. At the age of 56 days, there was a decrease of 24.4% in the strength of the concrete mix containing coarse aggregates contaminated with a 40mg/L sodium chloride solution.

Table 5: Computed strength deterioration ratios for the water and acid treated RCA concrete

Mix ID	28 day SDR	56 day SDR
C10	7.2%	11.6%
C40	18.2%	24.4%

3.2. Bond strength

Figure 4 shows the results of the bond strength of the various concrete mixes, which was obtained from the pull-out test conducted on 28-day old samples. The lowest bond strength was recorded in the C40 mix, which contained coarse aggregates that were contaminated with 40mg/L sodium chloride solution; while the highest bond strength was recorded in the C0 mix, which did not contain any chloride contaminated aggregates. The bond strength of the C10 mix was about 19.6% lower than that of the control mix (C0 mix); whereas, that of the C40 mix was about 22% lower than that of the control mix. This is in agreement with the study by Jaśniok *et al*. [27], and can be attributed to the presence of chlorides in the salt contaminated aggregates, which is bound to have initiated some form of localised rebar corrosion, thereby resulting in the low bond strength observed in the concrete mixes containing these aggregates.

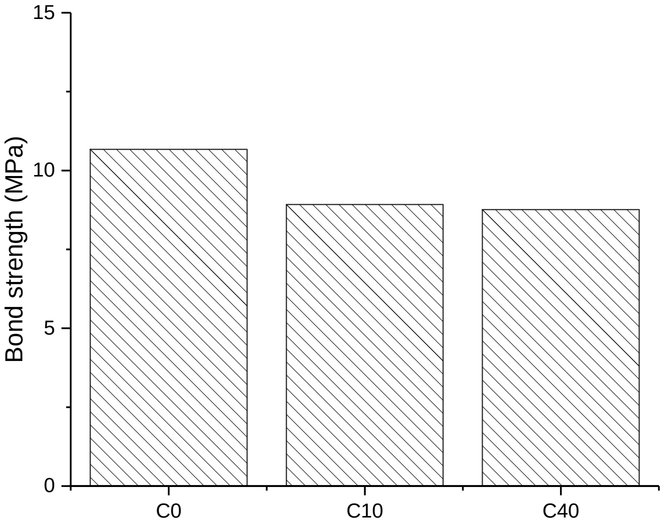

Figure 4: Bond strength for the various mixes

4. Conclusion

This study investigated the effect of using chloride contaminated aggregates on the compressive strength and bond strength of concrete. From the results obtained, the following conclusions have been drawn:

1. The use of chloride contaminated aggregates causes an initial increase in the compressive strength but later on decreases, and this can be attributed to salt crystallization forming in the microstructure, which can affect the strength gain
2. The use of chloride contaminated aggregates results in a decrease in the concrete-rebar bond strength

Overall, the findings of the study show that using chloride contaminated aggregates can be detrimental to concrete, especially reinforced concrete. Hence, if chloride contaminated aggregates are to be used, it will be suited for plain concrete works and the concrete mix should be designed in view of the later reduction in strength that will be caused by the presence of the chlorides.

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