EFFECT OF CHLORIDE CORROSION ON THE COMPRESSIVE STRENGTH OF CONCRETE

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ABSTRACT

This paper reports the findings of an investigation into the behaviour of the compressive strength of concrete under the attack of chlorides corrosion. The corrosive action of chlorides on concrete was simulated by immersing concrete grade 30 cubes in 0%, 5%, 10%, 15% and 20% concentrations of hydrochloric acid for a total of 84 days, after previously ascertaining the compressive strength at 28 days of casting and curing. The compressive strength of the concrete after immersion in the acid was assessed at the ends of 28 days, 56 days and 84 days of immersion periods. It was observed during the immersion period that the concrete cubes turned greenish with a weak mortar surround. Except for the zero percentage concentration of the acid, a reduction in the compressive strength of the concrete immersed in the various concentrations of the acid was observed. The extent of compressive strength reduction depends on the concentration of the acid and the duration of immersion period. However, the degree of compressive strength reduction is neither directly proportional to the concentration of the acid nor directly proportional to the duration of immersion period.

KEYWORDS: Compressive strength, Chloride, Corrosion, Concrete, Structures.

SIGNIFICANCE

The Study has exposed the danger posed by chlorides to concrete structures serving in chloride-rich environment, and solutions to this danger have been proffered

1. INTRODUCTION

Concrete is a versatile construction material extensively employed in the construction of the majority of civil engineering and building structures. In some structures where the use of concrete may not be extensive, the use of concrete material cannot completely be ignored. Infact the use of concrete material, no matter how minute it may be, in the construction of civil engineering and building structures can hardly be avoided.

Concrete is a construction material resulting from the intimate mixing of cement, fine and coarse aggregates and water. Admixtures, if desired, may be added to modify one or more properties of the concrete in the fresh or hardened states. The requisite quantities of materials for a given grade of concrete are usually obtained from a mix design for the concrete grade. The constituent materials when properly batched and thoroughly mixed sets through the process of hydration and hardens into a concrete mass capable of resisting compressive stresses. The extent to which a given concrete resists the compressive stresses to which it is subjected depends largely on its compressive strength. The compressive strength of the concrete in turn depends on the quality of the concrete.

Many factors exist that could affect the quality of concrete. These include the type of cement, the type and nature of aggregates, the quality of water, and the batching, mixing, placing, compaction and curing procedures. Others are climatic conditions, the presence of organic matters in the aggregates, and the presence of aggressive chemicals and/or aggressive chemicals initiating agents in the concrete environment. Aggressive chemical initiators, such as chlorides, degrades the concrete through the formation of aggressive chemicals that eventually corrodes the concrete. Corrosion can be defined as the spontaneous or gradual deterioration of materials and structures due to the chemical or electrochemical reaction in a given environment. The focus of the study reported in this paper is on the behaviour of the compressive strength of concrete attacked by hydrochloric acid which is a corrosive chemical that results when chlorides and water in the soil react under suitable conditions.

2. LITERATURE REVIEW

The durability and functionality of structures are of primary importance to owners, designers, and contractors; and the durability of structures is an important structural requirement for both safety and economic reasons[Musa, 1992]. Of the many known processes that can adversely affect the durability of concrete structures is subjection to chemical aggression with the resultant corrosive effects that eventually deteriorates the structure[Musa, 1992].

Chlorides have been, as far back as the 17th century, identified as corrosive agents in reinforced concrete; but it should, however, be stressed that emphasis was placed more on the reinforcement corrosion rather than the concrete corrosion. Lack of adequate knowledge on the adverse effects of chlorides on concrete, probably, encouraged the deliberate use of chlorides as admixtures and de-icing agents in concrete constructions[Regourd et al, 1980; Simm and Fookes, 1989]. As the years rolled by, the subject of chlorides related corrosion, though still more related to reinforcement, was being better understood. From the 1930s there was a growing interest in the corrosion of concrete by chlorides[Biczak, 1967]; and there was a growing concern against the use of chlorides as additives in reinforced concrete[Regourd et al, 1980; Simm and Fookes, 1989]. For instance, [SEG, 1990] recommended that strict limits on chloride levels in concrete be set. In 1977, amendment was issued to CP110 in which the use of chlorides as admixture in concrete was prohibited and maximum chloride levels in cement of 0.3% and 0.06% by weight were specified for the ordinary Portland cement and sulphate resisting Portland cement, respectively [[Regourd et al, 1980, Simm and Fookes, 1989]. In the same year, the American Concrete Institute (ACI) issued a guide to durable concrete in which a maximum chloride level in cement of 0.1% by weight was specified for reinforced concrete in moist environment and exposed to chlorides[[Regourd et al, 1980, Simm and Fookes, 1989].

The nature of chloride ions and their concentrations govern the types of deleterious chemical reactions occurring in structural concrete exposed to the salt solution. Strong solutions of sodium, potassium, calcium and magnesium chlorides react with the $Ca(OH)_2$ present in the Portland cement paste, and even gradually destroy calcium silicate hydrate[Klieger, 1980]. Chlorides that are detrimental to concrete include aluminum chloride, ammonium chloride, iron chloride, mercury chloride, manganese chloride, zinc chloride, etc.[Ludwig, 1980]. For instance, Mohan and Rai (1980) concluded that chlorides of ammonium are highly aggressive to concrete and cause very serious deterioration without significant amount of visual cracks. From a comparative study of the corrosive effects of chlorides and nitrates on concrete, it was concluded that the corrosive effects of chlorides and nitrates are similar, however, at higher concentrations, and longer immersion periods, the chlorides are more corrosive to concrete than nitrates (Mtallib and Akpan, 2005)

It has been observed[Musa, 1992] that most of the researchers on the problem of chlorides corrosion in concrete have concentrated more on the compounds and radicals of chloride salts, while paying less attention to the hydrochloric acid formed from the compounds and radicals of chlorides in the presence of water. It has been made very clear[Musa, 1992] that completely dry salts of chlorides are harmless to concrete; the salts of chlorides become harmful to the concrete only in the presence of water. The formation of hydrochloric acid from the chloride salts in the presence of water under suitable conditions has been demonstrated[Liptrot, 1974; George et al, 1979]. It is the hydrochloric acid formed from the reaction of chlorides and water, under suitable conditions, that is actually responsible for the corrosion of the concrete.

Mechanisms of Chlorides Corrosion

Under the action of inorganic acid, the CaO content of the cement is transformed into soluble compound of $CaCl_2$. This compound is dissolved or scoured at a rate that depends on its solubility. So, intense reactions and loss of calcium hydroxide result in the formation of large amounts of chlorides and the corresponding chloroaluminate. In summation, the process of concrete corrosion by the action of chlorides through hydrochloric acid involves the formation of highly soluble calcium chloride hydrate ($CaC1_2.2H_20$), and a poorly soluble calcium chloroaluminate hydrate ($3CaO.A1_20_3.CaC1_2.10H_20$) which is responsible for the softening of the concrete and weakening its bonds[Musa, 1992]. The reaction process can be represented by the following chemical equations.

$$2HCl + Ca(OH)_2 \text{ --------------------------------> } CaCl_2.H_20 \text{ ……………………………} \quad (1)$$
Calcium chloride hydrate

$$3CaO,A_21_3{+}CaC1_2,2H_20{+}8H_20 \text{ --------------> } 3CaO,Al_20_3.CaC1_2.10H_2O \text{ ………} \quad (2)$$
Calcium chloroaluminate hydrate

3. EXPERIMENTAL PROCEDURE

Mixed design was carried out for concrete of grade 30 using the procedure for the design of normal concrete mixes [DoE, 1975]. The constituent materials were batched by weight, mixed thoroughly, and cast into

150mmx150mmx150mm cube moulds, and compacted mechanically to the required density. A total of fifty-one (51) concrete cubes were cast. Six (6) of them were used to determine the initial compressive strength of the concrete at the end of 28 days of casting and curing; while the balance of forty-five (45) concrete cubes were used to assess the final compressive strength of the concrete immersed in the different acid concentrations at the ends of the various immersion periods. The concrete cubes were placed in a curing room and covered with sacks that were kept moisted for 21 days. The concrete cubes were air-dried in the laboratory for 7 days to ensure that there were no pore-water pressure in the concrete during testing.

At the end of 28 days of casting and curing, six cubes were randomly selected and tested for the compressive strength attained. The acid-water ratios by volume required for the various concentrations of the acid were calculated. the acid and water required for the concentrations were mixed into 35cm^3 plastic bowls. The concrete cubes were immersed in the different concentrations of the hydrochloric acid. During immersion it was observed that the cubes were coated with a greenish-coloured gel, and the surfaces of the concrete cubes also felt soft when touched. Three cubes were removed from each of the concentrations of the acid medium at the end of 28 days, 56 days, and 84 days of immersion periods, and tested for the compressive strength retained by the concrete.

4. PRESENTATION AND DISCUSSIONS OF RESULTS

The strength values at the end of each of the three periods of immersion in the five different concentrations of the acid and the calculated percentage changes in the compressive strength values between that of before and after immersion of the concrete cubes in the acid are presented in table 1 and plotted in figure 1.

Table 1: Results on grade 30 concrete immersed in hydrochloric acid (HCI)

Compressive strength at 28 days before immersion in the acid is 35.36Nmm^{-2}					
Comp. Strength Before Immersion (Nmm^{-2})	**Immersion Period (days)**	**Acid Conc. (%)**	**Comp. Strength After Immersion (Nmm^{-2})**	**Change in comp. Strength (%)**	
				Increase	**Decrease**
		0	37.04		
		5	27.11		23.33
35.36	28	10	24.59	4.75	30.46
		15	21.63		38.83
		20	15.70		55.60
		0	40.30		
		5	22.81		35.49
35.36	56	10	21.03	13.97	40.53
		15	18.81		46.80
		20	15.60		55.18
		0	41.33		
		5	20.15		43.01
35.36	84	10	17.63	16.88	50.14
		15	15.12		57.24
		20	11.70		66.91

The strength value of the concrete at the end of 28 days of casting and curing (i.e. before immersion in the acid) is 35.36Nmm^{-2}. While there exist a steady increase in the compressive strength of the concrete in the zero percentage concentration of the acid, there is a decrease in the compressive strength of the concrete in all other concentrations of the acid.

For the zero percentage concentration of the acid, the compressive strength of the concrete increased throughout the period of immersion. The compressive strength value increased to 37.04Nmm^{-2} (+4.75%) at the end of 28 days of immersion, 40.30Nmm^{-2} (+13.97%) at the end of 56 days of immersion, and 41.33Nmm^{-2} (+16.88%) at the end of 84 days of immersion. Since zero percentage concentration of the acid actually represent water without the acid, it is not surprising that the compressive strength increased in value during the immersion period since the compressive strength of concrete cured in water increases with age.

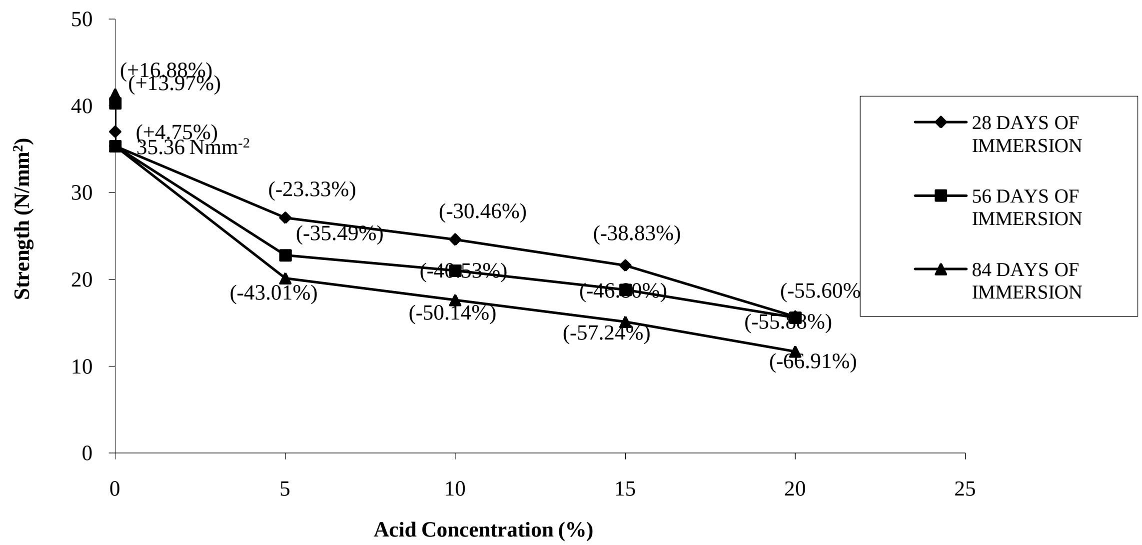

FIG. 1: GRADE 30 CONCRETE IN HCL

In the 5% concentration of the acid, the compressive strength decreased from 35.36Nmm^{-2} to 27.11Nmm^{-2} (-23.33%), 22.81Nmm^{-2} (-35.49%), and 20.15 (-43.01%) at the ends of 28 days, 56 days, and 84 days of immersion, respectively. It can be observed that the reduction in the compressive strength between the 28 days and 56 days of immersion periods is greater than that of between the 56 days and 84 days of immersion periods. This is due to the fact that while the acid concentration could still be strong at the end of 28 days of immersion, the concentration could have been highly reduced at the end of 56 days of immersion with the result that the action of the acid becomes milder between 56 days and 84 days of immersion.

For 10% concentration of the acid, the compressive strength reduction in the concrete are from 35.36Nmm^{-2} to 24.59Nmm^{-2} (-30.46%) at the end of 28 days of immersion; from 35.36Nmm^{2} to 21.03Nmm^{-2} (-40.53%) at the end of 56 days of immersion; and from 35.36Nmm^{-2} to 17.63Nmm^{-2} (-50.14%) at the end of 84 days of immersion. The compressive strength reduction between 28 days and 56 days of immersion is not very different from the compressive strength reduction between the 56 days and 84 days of immersion. This is, probably, due to the fact that the 10% concentration of the acid is still strong enough to cause as much damage to the concrete between 56 days and 84 days of immersion as it did between the 28 days and 56 days of immersion. The reduction in strength shows that at the end of the first immersion period (i.e. 28 days), the compressive strength of the concrete has been reduced to below an acceptable value.

In the case of 15% concentration of the acid the retained compressive strength from 35.36Nmm^{-2} are 21.63Nmm^{-2} (-38.83%), 18.81Nmm^{-2} (-46.80%), and 15.12Nmm^{-2} (-57.24%) at the ends of 28 days, 56 days, and 84 days of immersion, respectively. There appears to be no sharp difference between the reduction in the compressive strength values of between 28 days and 56 days of immersion periods and that of 56 days and 84 days of immersion periods. This is so because the concentration of the acid at 15% is strong enough to exert uniform effect throughout the immersion period. However, it should be observed that the 15% concentration of the acid has rendered the compressive strength of the concrete unacceptable at the end of the first immersion period of 28 days.

In 20% concentration of the acid, the retained compressive strength from 35.36Nmm^{-2} after 28 days of immersion period is 15.70mm^{-2} (-55.60%), at the end of 56 days of immersion the retained compressive strength is 15.60Nmm^{-2} (-55.18%), while at the end of 84 days of immersion the retained compressive strength is 11.70Nmm^{-2} (-66.91%). In the first 28 days of immersion in this concentration, more than one-half of the compressive strength of the acid has been lost, which invariably rendered the concrete useless. The reduction in strength between 56 days and 84 days of immersion is far greater than that between 28 days and 56 days of immersion. This could be due to the fact that while the concrete has already been seriously weakened by the acid at the end of 56 days of immersion, the 20% concentration of the acid was still very strong at the end of 56 days of immersion. The resultant effect being that the acid becomes more damaging as the already weakened concrete offered little resistance to the acid attack.

5. CONCLUSIONS

1. The compressive strength of the concrete in the zero percentage concentration increased, while the compressive strength decreased in all other concentrations of the acid throughout the immersion period.
2. The higher the concentration of the acid, the greater the reduction in the compressive strength of the concrete.
3. The degree of strength reduction is not directly proportional to the concentration of the acid.
4. The longer the duration of immersion, the greater the value of compressive strength reduction. However, the extent of strength reduction is not directly proportional to the duration of immersion period, since the acid medium was stagnant and there was no possibility of renewal
5. 10% and above concentration of the acid reduced the compressive strength of the concrete to an unacceptable value within 28 days of immersion period; while it takes 56 days of immersion period for the 5% concentration of the acid to reduce the compressive strength below an acceptable value.
6. In areas with high concentration of enfluents from chlorine or chloride-based manufacturing plants, areas with high level of use or sales of chloride-based products, or areas with high concentration of effluents from animal rearing units, it is possible to recognize hydrochloric acid attack on concrete by a greenish-coloured gel on the surface of the concrete plus a softened concrete surface.

6. RECOMMENDATIONS

Erection of concrete structures on chloride-rich soils should, as much as possible, be avoided.
If concrete structures must be erected on chloride-rich soils, adequate provisions must be made to protect the concrete from corrosive action of chlorides by using acid resisting cements or by coating parts of the concrete in contact with the soil with an impermeable and acid resisting material such as bitumen.

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