EVALUATION OF COMPRESSIVE STRENGTH OF CONCRETE SUBJECTED TO CHEMICALLY AGGRESSIVE ENVIRONMENTS

BY

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OCTOBER, 1992

DECLARATION

I, MUSA Abdulmtallib Osiregbhemhe, hereby declare that:

This thesis has been designed and implemented by me;

This thesis is a record of a research work carried out by me;

This thesis has not been accepted in any institution or any previous publication for a higher degree;

The sources of information have been duly acknowledged by means of references, and quotations therefrom have been distinguished by means of quotation marks.

MUSA A.O.

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CERTIFICATION

This thesis entitled "Evaluation of Compressive Strength of concrete Subjected to Chemically Agressive Environments" by MR. MUSA Abdulmtallib Osiregbhemhe meets the regulations governing the award of degree of Master of Science (Civil Engineering Construction Materials) of Ahmadu Bello University, Zaria, Nigeria; and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This thesis is dedicated to my parents:

Alhaji Musa Ozekhomhe, and Mrs Rekhiatu M. Ozekhomhe.

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THANKS BE TO ALMIGHTY ALLAH. The successful completion of this programme is, surely, a result of the guidance and infinite blessings of the Almighty Allah.

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ABSTRACT

This Thesis presents the results of theoretical and experimental studies of the corrosive effects of hydrochloric acid, nitric acid and sulphuric acid on concrete.

Concrete of three distinct grades - 30, 40 and 50 - were cast and cured in moist environment for 28 days. They were thereafter immersed in three distinct acid media (HC1, $HN0_3$ and H_2S0_4) of varied concentrations (0%, 5%, 10%, 15% and 20%). The ages of curing in the aggressive media were 28, 56 and 84 days.

A reduction in the compressive strength of the concrete was observed for all cases, except for zero percent concentrations of the acids. The percentage reduction in compressive strength varies from 23.33% for 5% concentration of HC1 at 23 days of immersion to 76.95% for 20% concentration of H_2S0_4 at 84 days of immersion for grade 30 concrete; from 28.67% for 5% concentration cf HC1 at 28 days of immersion to 76.70% for 20% concentration of H_2SO_4 at 84 days of immersion for grade 40 concrete; and from 8.77 for 5% concentration of HNO_3 at 23 days of immersion to 75.79% for 20% concentration of H_2SO_4 at 84 days of immersion for grade 50 concrete.

The degree of reduction of the compressive strength of concrete was observed to be a function of the type of acid, the concentration and the duration of the immersion period.

On the whole 369 concrete cubes were tested.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Concrete, for many years, has been one of the major materials used in the construction of buildings and other civil engineering structures. Concrete is a civil engineering material resulting from the mixture of cement, coarse and fine aggregates and water. The materials when properly batched and thoroughly mixed sets through the process of hydration and hardens into a concrete mass which is capable of resisting compressive stresses. The extent to which a given concrete can resist the compressive stresses acting on it depends on its compressive strength. The compressive strength in turn depends on the quality of the concrete.

Many factors exist that affect the quality of concrete. They include the type of cement, the type and nature of aggregates and the quality of water; the batching, mixing, compaction and curing procedures adopted. Others include the presence of deliterious materials such as the presence of organic matters in the aggregates, and the presence of aggressive chemicals in areas where the concrete is serving. Since this Thesis is aimed at the evaluation of the compressive strength of concrete in areas of chemical

aggression, more attention will be paid to effects of chemical aggression.

Chemical aggression has been known to produce devastating effects on concrete. Subjection of concrete to sulphuric acid, nitric acid, hydrochloric acid and cabonic acid among other chemicals will definitely impair the satisfactory performance of the concrete. Two major sources of chemical aggression can readily be identified.

(1) The natural sources such as seawater and soils rich in sulphates, nitrates, chloirides and carbonates.

(2) The artificial sources such as chemical manufacturing industries, sales and usage of industrial chemicals and catchment areas for enfluents from animal rearing units.

Sulphates, nitrates and chlorides (and many other salts) when present in the environment of the concrete could be individually and severally responsible for the reduction in the compressive strength of the concrete as a result of their adverse effects on the quality of concrete.

Ammonium chloride, for instance, causes strength reduction in concrete by leaching calcium hydroxide from the set concrete. Hydrochloric acid is particulary destructive, especially in hot weather.

Ammonium nitrate solution is particularly known to

cause severe strength reduction in concrete by leaching calcium hydroxide from the set cement matrix of concrete[1].

Most sulphate solutions are known to have a vigorous attack on concrete. The intensity of the attack increases with the concentration of the solutions. The concrete suffers severe attack from the sulphate in solution by its diffusion through the concrete pores. The concrete softens and swells as a result of the chemical reaction between the sulphates and the constituents of hydrated portland cement, and distruption by expansion as they crystalize[1].

1.2 BACK GROUND

The importance of durable, stable and functional buildings and other civil engineering structures in the development drive of any nation cannot be over emphasised. Through the years civil engineers have taken a lot of giant strides towards enhancing the satisfactory performance of concrete structures. These include the development of recommendations and mathematical formalae through researches, for the satisfactory design and construction of concrete structures for safety and durability. Extensive researches into concrete structures by various organisations all over the world have also led to the development of codes and standards that are aimed at enhancing the satisfactory performance of concrete

structures.

For instance, intensive research have led to the emergence of the Limit State Design that brought about a formidable compromise between the purely current reliability theory and the load factor theory. The limit state design concerns itself with the designs such that specified limit states are not reached. The limit state is simply a state when a structure becomes unfit for the purpose for which it was designed. CP110 prescribes two limit states, viz:

- the ultimate limit state.
- the serviceability limit state.

When the ultimate limit state is reached, the structure becomes unsafe. For example, an ultimate limit state is reached when a structure or part of it loses equilibrium when considered as a rigid body; when it ruptures at a section or degenerates into a mechanism.

The serviceability limit state may be reached when a structure becomes unfit for its design purposes. Excessive deflection, cracking, fire, extensive corrosion and excessive viberation may impair serviceability.

The important thing to be noted here is that though the limit state design have given recognition to corrosion of buildings and civil engineering structures but certain facts about corrosion such as the extent of corrosion, the causative agents and the degree of

concentration vis-a-vis the damage done by the causative agent have not be clearly defined.

In a bid to ensure successful functionability of concrete structures under "severe" condition of exposure, which include subjection to acid fumes, CP110 prescribes a nominal cover to reinforcement of 50mm, 40mm, 30mm and 25mm for concrete grades of $25N/mm^2$, $30N/mm^2$, $40N/mm^2$ and $50N/mm^2$ or over respectively. Under "very severe" condition of exposure such as exposure to sea water or moorland water and with abrasion CP110 prescribes a nominal cover to reinforcement of 60mm and 50mm to concrete grades of $40N/mm^2$ and $50N/mm^2$ or over respectively.

Some other codes have also presented their contributions towards this subject of corrosion.[2]

1.3 NECESSITY OF THE RESEARCH

Most structures are made of concrete constructions. In cases where some structures are either of metal or wood constructions, the floors are usually of concrete material. In fact, it can comfortably be stated that every structure, no matter the predominating material used in its construction, has an element of concrete material at some part or section of it. This popularity of concrete material in construction makes it very necessary to carry out studies aimed at enhancing the performance of contrete as a construction material.

From the cited instances in section 1.2 it seems that concrete corrosion has been given, more or less, too global a treatment to actually effect adequate protection of concrete structure against chemical aggression. CP110 Part 1 has specified requirements of the type of cement, minimum cement content (kgm^{-3}) with respect to maximum size of aggregate(mm), and maximum water-cement ratio to be used for concrete exposed to different concentration of sulphate expressed as SO_3 percent in soil and parts per million in ground water. What should be noted here is that these requirements have taken cognisance of the sulphates alone, leaving out other agents of chemical aggression such as nitrates, carbonates and chlorides. More over, the percentage concentration of sulphates in the soil does not clearly indicate how much damage is expected. Since the actual damage to concrete structures is caused by the sulphuric acid formed as a result of the reaction of the sulphates with water, the amount of water available for reaction is also an important factor to be seriously considered. It should also be noted that the amount of ground water is not constant and this will definitely affect the amount of sulphuric acid formed at any given time. The amount of sulphates can also be affected by leaching actions. A high sulphate concentration in a relatively dry soil will produce little or no damage.

Therefore, there exist the need to narrow down the seemingly global treatment of corrosion by acids on concrete to a local level whereby the effects of each of the acids at different concentrations on concrete structures can be properly evaluated. Devastating effect of the different acids at deifferent concentrations can then be correlated. This will enable a more adequate protective measures of concrete structures against acid corrosion to be adopted.

Many companies and individuals engage in the manufacturing and sales of industrial chemicals including acids without an adequate knowledge of their corrosion or in cases where the knowledge is available, proper attention is not being paid to it. It is essential that these companies and individuals be educated on the dangers of this chemicals to concrete structures. For this recommended education to be effective, the knowledge of how each of the acids at any given concentration affects the concrete structure is highly necessary. This knowledge will also become very useful in the case of accidental spillage.

Added to the artificial sources of chemical aggression are the natural sources of chemical aggression on concrete structures. These include sea water, sulphates and nitrates rich soils and catchment areas for enfluents from animal rearing units. Adequate protection of concrete structures can be

effected through the knowledge from this research.

1.4 AIMS AND OBJECTIVES OF THE RESEARCH

1.4.1 Aims: This research is specifically aimed at evaluating the deteriorative effects on the compressive strength of concrete subjected to chemically aggressive environments. It will also assess the degree of effects on the compressive strength of concrete at different concentration of the chemicals.

1.4.2 Objectives: The research is designed to produce experimental results which can be used to establish a correlation between the concentration of the chemicals and their resultant effects on the compressive strength of concrete. The correlation so established will be useful in designing, construction and maintainance of concrete structures subjected to chemically aggressive environments for satisfactory performance.

1.5 LIMITATION OF THE RESEARCH

Compressive strength has been known to be the major property that describes the general quality of concrete. All other properties of concrete are directly related to its compressive strength. The research is, therefore, limited to the effects of aggressive environments on the compressive strength of concrete.

Simulation of the aggressive environment is

limited to the use of three types of acids-HC1, HNO_3, and H_2SO_4 - with concentrations of 0%, 5%, 10%, 15% and 20% for each of the acids.

1.6 SIGNIFICANCE OF THE RESEARCH

Though the main aggressive agent on concrete is the acid formed from the reaction of the salts with water, many researchers have concentrated their attentions more on the investigation of the chemical effects on concrete using the salts of nitrates, chlorides and sulphates. The percentage of the salt used does not really give a clear percentage of the attacking agent, the acid formed; since the formation of the acid from the salt depends on many other environmental factors. This research has not only endeavour to simulate the chemical effects on concrete by direct use of the acids, but has also brought into play the use of sufficient varying concentrations and a more realistic subjection periods. The research is to a very large extent a pathfinder towards a better and more realistic approach to solving the problem of chemical aggression on concrete.

CHAPTER TWO

LITERATURE REVIEW

2.1.0 GENERAL

The safety, durability and functionability of any structure is of primary importance to designers, contractors and owners alike. It is not surprising, therefore, that any process that is likely to initiate or propagate the failure of a structure is always of immense concern to designers, contractors and owners. Of the many known processes that can cause failure of structures include the subjection of the structure to chemical aggression with the resultant corrosive effects. Corrosion may be defined as the spontaneous or gradual detrioration of materials and structures or parts of structures due to chemical or electrochemical reaction in a given environment.

The durability of buildings is an important desired quality both for safety and economic reasons. Therefore, special attentions should be paid to the study and the development of building materials, especially cement mortar and concrete. The building materials mortar and concrete may be subjected under severe service conditions to dissolving and expanding attacks by waters, soils and gases which may impair the properties, as for instance, bearing capacity and volume stability.

Spillage of chemicals acidic in nature, high humidity and condensation of vapours and gases, and intensive vaporisation and crystalization effects-particularly in reinforced cement concrete prilling towers-appear to be the main cause of deterioration of concrete.

As far back as the 17th century, there has been growing concern with the deterioration of concrete structures due to chemical aggression. Discussing two of the papers on corrosion resistance of reinforced concrete presented at the proceedings of Institution of civil Engineers, Part I, 1990, Sharp[3] cited a research carried out by Pullar-Streaker which goes back to the patent for use of calcium chloride in concrete in 1885 to butress his points. Numerous researches, published and unpublished, have been carried out on the subject of the corrosion of concrete structures. Through his research, Vicant[4] has since 1818 tied the chemical attack of cement by sea water to the presence of magnesium sulphate.

According to Moskvin et al[5] the large variety of types of corrosion can be divided into three main groups: Corrosion of the I, II and III types.

The first group (corrosion type I) covers all kinds of corrosion processes, which arise in concrete under the action of water of small temporary (carbonated) hardness, when components of the cement

stone are dessolved and carried away by running water. These processes progress with higher intensity when aggressive water filtrates through the concrete, when the contact area between water and cement stone is rather large, the quantity of components of the cement stone dessolved and carried away by the water is large and the destructive processes take place not only at outer surface, but also penetrate into the inner layers of concrete.

When aggressive water contains salts which do not react readily with the components of the cement stone the ionic strength of the solution and the solubility of the cement stone becomes higher and the progress of corrosion process is more intensive and accelerated.

The second group (type II) covers all corrosion processes arising in concrete under the action of aqueous solution of salts and acids (to a lower degree of alkaline)entering into exchange reactions with the components of the cement stone, with substitution of the calcium cation. The product formed during this reaction are either dissolved and carried away by the water or remain deposited in the form of an amorphous mass with no binding qualities. Corrosion processes occuring in concrete under the action of acids, solution of magnesium salts and a number of other salts are representative examples of this type of corrosion.

The third group (corrosion type III) covers those

corrosion processes, in which internal stresses arise in concrete under the action of the ambient medium, causing tensile stresses in the pores and other voids, as in the capillaries of the concrete. A representative example of this type of corrosion is the effect of salt solutions, the reaction of which concrete causes the formation of low soluble salts (for example, of sulphates); accumulation and crystallization of those salts (gypsum, hydrosulphoaluminate, calcium and others) cause in some portions of the concrete considerable ultimate stresses in the concrete. This type of corrosion and the resulting failure of concrete may develop and progress not only due to chemical reactions, but also when salts are accumulated in certain portions of the concrete during the capillary lift, evaporation (e.g. under the action of mineralised ground-water in hot and dry climatic conditions) and freezing. Corrosion of this third type may occur when as a result of physical and chemical processes in concrete, osmotic cells are formed and considerable osmotic pressure is developed in them.

Concrete is probably exposed to a greater variety of potentially harmful exposure conditions than any other construction material. Since 1916 the Portland Cement Association (PCA) laboratories have studied the ability of concrete to withstand the regours of such

exposures.[6]

During corrosion all the constituents of concrete can be attacked. A dense concrete with a high cement content has been described to offer a good resistance to chemical and physical attack.[2-19] However the cement, the sand, the aggregates and the steel reinforcement can be degraded.

The problem of concrete corrosion is extremely complex for it brings into play a certain number of parameters which are not always easy to isolate and which react in varying degrees according to the composition and the condition of conservation of the materials. To chemical decomposition of cement and aggregate can be added physical alteration due to shock, expansion, erosion, creep and shrinkage.

The deterioration of mortar and concrete is tied to the crystallization of gypsum, ettringite and thaumasite into fibres locallized at the edges of the cracks in heavily carbonated paste. Comparison of the x-ray diffraction diagrams of the cores taken at different levels from a dike, a wall 11.0m high constructed between 1840 - 1850, revealed that the most degraded sample has the highest thaumasite content. It seems that the thaumasite comes from the transformation of the ettringite triggered by the the carbon dioxide and the silica. The heavily carbonated cement paste proves the presence of an important amount of carbon

dioxide. The carbonation liberates silica in the form of gel. Lukas[4] suggested that the passage of ettringite to thaumasite took place through the intermediary woodfordite,

$$Ca_6Al_{1.5}(SO_4.SiO_3.CO_3(OH)_{10.5}.15H_2O$$

To the expansive crystallization of gypsum fibres are added the cracking and the decompoisition of certain micaceous aggregates.

Mohan and Rai[7] concluded in their research that sulphates, chlorides and nitrates of ammonia are highly aggressive to concrete. Intense reactions and loss of calcium hydroxide result in the formation of large amounts of sulphates, chlorides, nitrates and corresponding sulphoaluminate, chloroaluminate and nitroaluminate hydrates. It is quite likely that the volatilization of ammonia causing a decrease in pH to about 9.5 to 10.0 helps in the deterioration process. The crystallization effects particularly with ammonia sulphate cause cracking, whereas ammonium chloride and ammonium nitrate cause very serious deterioration without significant amount of visual cracks. These salts may get leached out to some extent, depending upon the ingress of excess water into the concrete pores.

Under the action of inorganic acids the CaO content of the cement stone is transformed into soluble compound. Corresponding to the acid root, $CaSO_4$, $CaCl_2$

or, with nitric acid, $Ca(NO_3)_2$ are formed. These compounds are dissolved or scoured at a rate depending on their solubility. The decomposition of cement minerals can be described by the following general equation,

$$nCaO.mSiO_2 + pH_2SO_4 + aqu \rightarrow nCaSO_4 + mSi(OH)_4 + aqu.$$ [8]

The awareness of the concrete susceptibility to chemical aggression has informed the necessity to specify some reasonable amount of cover of concrete to reinforcement. However, the specified minimum covers vary from one code to another. It is also apparent that professional opinion among engineers frequently differ sharply from the current provisions of the codes and standards regarding the amount of concrete cover needed for the protection of steel reinforcement in chemically aggressive areas.

Hoad (1990), [3] for instance, suggested the adoption of 100mm cover as compromise in the more critical locations. Experience from the literatures reviewed has shown that 100mm cover is the highest amount of concrete cover recommended so far. But can 100mm concrete withstand the rigours of very severe chemical aggression?

It was observed during intensive and extensive literature review that most researchers have ignored one of the most dominant factors in the corrosion

process. They have concentrated their attentions mainly on the concentration of the salts without adequate attention to the amount of water available for their reaction.

It is obvious that the availability of water is a critical factor to be considered in the analysis of any corrosion process. In fact water is the initiator of corrosion. A completely dry salt will have no corrosive effects. The degree of corrosivity does not only depend on the salts' concentrations but also on the amount of water available for their reactions. It is, therefore, imperative that water should be given as much recognition as is given to the salts.

Barr (1990)[3] supported the importance of water in the corrosion process when he viewed that the key to durability of reinforced concrete structures is to understand the passage of water in, around through concrete because all corrosion problems which arise seem to have water as a root cause.

Mohan and Rai[7] are of the opinion that the overall resistance of concrete against crystallization pressure and crack formation also would depend upon the availability of water and environmental factors.

In support of the necessity of water for chemical aggression, Biczak[8] opined that the deteriorating action does not ensue, unless the destructive agent

has access to concrete in the form of a wet gas, a fluid in dissolved form, but first of all in an ionised condition. Substances in a solid phase are harmless.

The aggressivity of the environment to which a concrete structure is subjected, is a function of both its macro-environment and micro-environment. Any evaporite salt can occur locally, depending on the bedrock geology. An important point is that evaporite salts can concentrate in a situation where moisture is lost by evaporation and, therefore, the actual amount of salt present as indicated by the ground soil and soil water analyses may be much higher in reality when concrete or contaminating aggregates are being attacked.[3]

The extent of concrete corrosion depends primarily on the properties of the external medium, i.e. the attacking substance, thus for instance on the chemical composition of water (ground water), the quality of rocks (soils) in contact with water, the depth of the ground water table, chemical conditions, microbiological environment, etc.[8]

The attack of the surface which destroys the external micro-structure of concrete or mortar is understood to be due to detrimental effects of solutions and gases of the environment or to erosion caused by freezing-thawing cycles.[9]

Another factor in the development of corrosion is

concrete itself. The significant features in this respect include the mineralogical composition, the method of concreting, its structure and age.

It has been pointed out that the attack from the interior can be caused by certain components of aggregates which undergo sever expansion reaction with the cement. Such reactions are cuased by, for example, sulphate containing aggregates, porous dolomite lime stone, or aggregates containing reactive silica or silicates.[9]

The internal attack also can take place if the cement is of inferior quality and contain an excess of calcium oxide (CaO) or magnesium oxide (MgO), or impurities taken up at a later stage or aggregates containing these materials. In most cases, however, a good dense mortar or concrete is favourable against external attack, but remains ineffective against internal expansion.

The under listed factors have been found to be individually and severally responsible for the destructive effect of aggressive water on concrete either by decreasing or increasing the corrosive effects. They are: [2 - 19]

(i) the type of cement used, its chemical and physical properties;

(ii) the quality of concrete aggregates, the physical properties and gradation;

(iii) the method used for preparing concrete, the water-cement ratio, the proportion of cement, the placement of concrete, i.e. its compaction and the age of concrete;

(iv) the condition (smoothness, carbonation) of the surface exposed to aggressive water;

(v) the composition and concentration of the aggressive water, as well as the manner in which the aggressive fluids act on the concrete structure.

The extent of corrosion is influenced further by a few physical factors which may intensify, yet moderate, deterioration. Such factors are, for instance:

(vi) the movement, respectively stagnation of ground water;

(vii) temperature;

(viii) capillary rise;

(ix) oxidation;

(x) the dimension of the concrete structure;

(xi) the evapouration surface;

(xii) the unbalanced water pressure;

(xiii) solubility.

2.2.0 SULPHATES' CORROSION

The action of sulphate-containing solutions and soils is a case of typical sulphate attack on mortars and concretes. Sulphates can be introduced into the soil by various methods:

(i) in the form of minerals containing sulphur compounds or as compounds resulting from the chemical changes of these minerals;

(ii) in the form of solution products of soluble organic substances. Oxidation may be caused or completed by biological factors as well, namely by consuming the atmospheric oxygen, unless these factors are destroyed by the ensuing sulphuric acid.[3]

The great majority of destructive processes due to the formation of salts can be traced to aggressive sulphates. For this reason sulphate attack will first be considered more closely and in more detail than the other salts.

In all corrosion studies sulphate attack has received greatest attention, so that chemical attack and sulphate attack have frequently been used synonymously in the literature. For this reason the deterioration of concrete by sulphates should be examined most extensively.

The degradation of maritime structures in mortar or concrete are of a chemical and/or physical nature. If fully immersed the attack of the material by seawater is essentially chemical. It has been tied to the expansive formation of calcium trisulphoaluminate, $Ca_3Al_2O_6.3C_aSO_4.31H_2O$, which lead to swelling, cracking and spalling of concrete. In

alternate immersion, the attack is of both chemical and physical nature. The mechanical action of waves, the rotation of the tide, the swelling and shrinkage caused by alternate saturation and drying, atmospheric conditions (freezing, wind, exposure to sun), and the electrochemical corrosion of steel reinforcement are all of added destruction of a chemical nature. Results have shown that the stability of concrete and mortar in sea water is prportional to their denseness, their cement content and the chemical resistance of the cement.[4]

The sulphate ions SO_4^{2-} combine with the liberated calcium ions Ca^{2+} given birth to a secondary gypsum $CaSO_4.2H_2O$. The later reacts with the alumina of the cement aluminates, precipitating a secondary expansive ettringite $C_3A.3CaSO_4.31H_2O$ which leads to swelling of the cement paste when it is already present in certain cohesion. The dissolution of the compounds rich in lime and the formation of a secondary expansive ettringite are the two principal factors in the degredation of cement in seawater.[4]

Lafuma[9] observed that the topochemical formation of expanding ettringite occurs at high lime concentrations in liquid phase greater than 1.08g CaO/Litre, and high pH value. A calculation has been derived from Lafuma's observation which gives the modulus of aggression defined as follows:

$$G = \frac{CaO(56)^{-1}}{1.5SiO_2x(60)^{-1}+3Al_2O_3(102)^{-1}} \leq 0.81$$

The expression can, however, be modified to take into account the influence of MgO (in the numerator) and Fe_2O_3 (in the denominator).

$$G = \frac{MgO(56)^{-1}}{1.5SiO_2x(60)^{-1}+3Fe_2O_3(102)^{-1}} \leq 0.81$$

2.2.1 Effects of Sulphate Solutions On The Components of Cement

Sulphates as ions causing corrosion are, in small or greater quantities, present practically in every free water, ground water, and particularly seawater, in aqueous solution of sulphuric acid or its salts. Sulphate is understood as SO_4 ion. The occurence is further common in mineral soil layers. The sulphate ion content of ground water is especially high in clay soils. Ground water with an appreciable sulphate content is not found in sandy soils, except in the case of inflow or an external pollution. In early practice the aggressivity of soil or water was specified in terms of the SO_3 content. SO_3 data can be converted into terms of SO_4 by considering that the molecular weight of SO_3 is 80, while that of SO_4 is 96.

Consequently,

$$SO_4 = \frac{96}{80} = 1.20.\ SO_3$$

$$SO_4 = \frac{80}{96} = 0.83.\ SO_4$$

2.2.1(a) Calcium Silicates

In 1925, Shelton[8] reported that the extent of attack on tricalcium silicate is appreciably higher than that on dicalcium silicate. At a high tricalcium aluminate content, Bogue found C_3S to be of beneficial effect, since relatively high C_3S content provokes early mortar strength, so that the solutions cannot penetrate the test specimen at a very high rate. It is believed that early strength is advantageous in resisting better the expansive efforts. It was also found that mortar specimens of pure C_2S and C_3S to be deteriorated by Na_2SO_4 solutions - Thorvaldson et al.[8]

Thus, it will be appreciated that sulphate action is of highly complex nature. It has been pointed out that the corrosion of concrete should not be evaluated by the resistance of C_2S and C_3S, but rather by the behaviour of $Ca(OH)_2$ liberated therefrom in the course of hydration.[8]

One of the main reasons for the detrimental sulphate action is gypusm, which is formed as a result of the reaction between the sulphate ions of water and the $Ca(OH)_2$ of cement in the pores of the concrete, and which crystallizes under the absorption of two molecules of crystal water. This chemical and crystallization process is accompanied by an increase in volume and induces the pores of the concrete,

particularly in the surface layer, to expand and burst. This leads ultimately to the deterioration of concrete. Bogue has shown that the crystallization of gypsum is accompanied by a 17.7% increase in volume. If magnesium ions are present, the development of magnesium hydroxide results in a volume increase of around 19.6%.[8]

2.2.1(b) Tricalcium Aluminate

Laboratory experiments and field observations have brought sufficient evidence to indicate that the significance of the combination of calcium hydroxide with SO_4 ions is of secondary significance for the resistance of cements to sulphates. Sulphate corrosion is primarily due to the tricalcium aluminate content of cement. C_3A reacts with gypsum produced from the sulphate ions and $Ca(OH)_2$, or with the originally incorporated gypsum solution, whereby a complex calcium sulphoaluminate hydrate is formed which does not readily dissolve in water. This compound crystallizes by combining 31 molelcules of crystal water and, owing to the considerable increase in volume, develops a high internal pressure. This complex salt is refered to as the Michaelis-Candlot-Deval Salt, which occurs in nature as well, and is known under the name of ettringite.[8]

The chemical process involved can be described,

according to E. Candlot[8] as follows:

$$3CaSO_4+CaO.Al_2O_3+31H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O$$

or in the presence of gypsum, according to Lerch and Bogue.[8]

$$3CaSO_4+3CaO.Al_2O_3+12H_2O-3CaO.Al_2O_3.3CaSO_4.12H_2O$$

The complex salt, according to Candlot, crystallizes from a saturated solution in the form of needle-shaped crystals and, during this process the salt components $CaSO_4$ and C_3A expand with 31 molecules of hydrate water according to calculations of Bogue and Lerch as well as Taylor - to about 22% (i.e. on the average 2.5 times) of the original volume (Henkel, Rost 1953, 1945).[8]

2.2.1(c) Tetracalcuium Alumino Ferrite

In the experiments of Bogue, Lerch (1934) and Thorvaldson (1938), hardened mortars of pure C_4AF were exposed to 2% aqeous solution of Na_2SO_4 and $MgSO_4$. These mortars, although showing an essentially higher resistance than those made with pure C_3A were considerably inferior to calcium silicate. According to Bogue, mortar prisms made from cements containing up to 15% C_4AF, and stored for 10 years in different Na_2SO_4 solutions, revealed no signs of expansion. It is interesting to note that at higher C_4AF contents (up to 25 to 27%) the test specimens were destroyed after two years. C_4AF is thus capable of causing expansion, although an essentially weaker one than C_3A.[8]

2.2.2 Development of corrosion Caused by Different Sulphate Solutions.

It has been observed that there exist different stages of sulphate corrosion depending on the type of sulphate involved. For example, corrosion of Portland Cement by sodium sulphate increases as the concentration of sodium sulphate, Na_2SO_4, of the solution is increased; but the violence of corrosion is not directly proportionate to the inccrease in concentrations but follows a milder trend. At the same time, however, the type of corrosion also undergoes a change. The first stage of the corrosion is purely of sulphate type which is replaced by a sulphate gypsum corrosion; and later only a pure gypsum corrosion can be observed. Sulphate corrosion takes place at concentrations below 1000 mg/litre. With increasing concentrations, simultaneous gypsum corrosion is initiated. Pure gypsum corrosion assumes predominance only when the concentration attains very high values.[8]

Magnesium sulphate is generally considered especially dangerous, because of the combined action of sulphuric acid and magnesium attack. The corrosion process taking place in concrete is greatly influenced by the concentration of the attacking $MgSO_4$ solution. Kind has distinguished three different process of $MgSO_4$ corrosion based on concentration. The first case is

the sulphate corrosion which occurs at $MgSO_4$ content of 4000mg/litre. The second case is a corrosion of sulphoaluminate gypsum character taking place at $MgSO_4$ content of 4000 to 7500 mg/litre. The third case is the magnesium corrosion which ensues at concentrations exceeding 7500mg/litre; Lerch et al (1929); Guttman and Gille (1930) unanimously corroborated the findings of Kind that no ettringite is formed, however high the concentration of the magnesium sulphate solution may be because, according to them the hydroxyl ions, OH^-, concentration is reduced by the resulting gelatinous magnesium hydroxides to below the value necessary for the formation of Candlot's salt.[8]

Water containing calcium sulphate (gypsum) and referred to also as selinitic is of a highly corrosive effect on Portland cement. The quantity of $CaSO_4$ salt in the ground water may attain a value as high as 1.2g/litre or in a saturated solution of sodium- or calcium chlorides it may be even 10g/litre (Duriez 1953). Chloride-selenitic waters are more aggressive than those containing selenite only. The effect of selenite water is sufficiently aggressive to deteriorate good quality concrete and to transform it into a pulpy mass. The destructive effect may be of a physical or a chemo-physical character caused by crystallization owing to the intrusion of gypsum

crystals and to the reaction between $CaSO_4$ and calcium aluminate hydrates, waters containing gypsum induce high internal stresses, which loosen within a short period the texture of the concrete by the expansion of gypsum.[8]

2.2.3 Comparison of sulphates corrosion

Ammonium-, calcium-, magnesium-, and sodium sulphates are most detrimental to Portland cement. Potassium-, copper- and aluminium sulphates are relatively milder. Barium salphate and lead sulphate are insoluble in water and thus harmless to concrete. The effect of strotium sulphate is similar to that of calcium sulphate.[8]

Kind (1955)[8] drew the conclusion among others from the result of tests performed with sulphate solutions of different kinds and concentrations that, "solutions of gypsum ($CaSO_4$) are commonly regarded as more aggressive than those of the other two sulphate salts, namely Na_2SO_4 and $MgSO_4$, occuring in natural waters. It could however be demonstrated by experiments and microscopic investigations that in relatively small amounts the effect of all three salts on Portland cement is identical for all practical purposes .... effect is due almost exclusively to the presence of sulphate ions and it is hardly effected by the character of the metal".

2.2.4 The Critical Sulphate Content

It has been established that the most aggressive salts in natural waters are the sulphate salts. Critical sulphate content has been defined as the lower limit of sulphate concentration above which protective measures should be specified.[8]

Definite limit values have been quoted by several investigators, below which they considered the suphate content is harmless. However, fundamental discrepancies exist between these values. This is validated on the realization that the values are based on experiments carried out under different circumstances with difeferent materials. Grun (1973) put the harmless SO_3 content at a limit value of 500 to 600 mg/litre. The upper limit of harmless sulphate content in aggressive water has been set at 3000mg/litre by the National Institute for Testing Materials. Vendl (1952) gave a critical sulphate content of 190-250mg/litre; while Klut and Haegermann gave 3000mg/litre. Data of the Research Institute in Berlin-Dahlem, shows the lower limit of aggressivity to lie between 70 and 130mg/litre; while that of "Marsh-committee" says it is 116mg/litre. The value quoted by Tillmann is, on the other hand, 1000mg/litre.[8]

The differing opinions of the various authors about critical sulphate content is not surprising if one considers the fact that critical sulphate content

is not a function of the sulphate alone but a function of all the factors involved in corrosion. For instance, under adverse conditions ground water containing lower amount of sulphates may be more detrimental than one containing a higher amount of sulphate per litre under less severe conditions.

2.2.5 Sulphuric Acid(H_2SO_4)

The action of sulphuric acid has been described to be of two fold effect. Together with $Ca(OH)_2$ of cement it forms the poorly soluble gypsum. Gypsum thus produced tends initially to seal the pores and to offer a certain degree of protection. In the case of continuous exposure to sulphuric acid, concrete is destroyed by the expansion of gypsum. The wastes of factories producing sulphuric acid destroys concrete sewers during a very short period, unless neutralised before being discharged into the sewer. Conventional concretes and cement mortars are equally attacked by sulphuric acid in both weakly and highly concentrated solutions, and are destroyed sooner or later.[8]

The formation of sulphuric acid from the chemical elements, radicals, and compounds in the soil is an important step that has not been given a proper attention in almost all the literatures reviewed. Under favourable conditions sulphuric acid could be formed in the soil by simple or complex chemical reactions of the substances mentioned above.

For example, many acid hydroxides can be obtained by addition of water to the respective non-metallic oxide.[10]

$$SO_3+H_2O \text{ ----> } H_2SO_4$$

2.2.6 Mechamisms of Sulphates' Corrosion

From experimental results, Ludwing[9] formulated the following reaction mechanism for sulphate attack. "A reaction front of topochemically formed ettringite just below the surface causes the formation of the first cracks. This front penetrates the mortar or concrete. Changes in the equilibrum of the liquid phase caused by the reaction itself brings the ettringite formation on the rear of the reaction front to an end and decompose the firstly crystallized ettringite. The cracks due to the ettringite formation are filled gradually with gypsum. The gypsum formation within the cracks is a secondary reaction which could be an explanation of the often observed rehealing process. On the other hand, the crystallization of gypsum may possibly contribute to the total expansion. However, the ettringite formation is the intial reaction of every sulphate attack. The intensity of the attack depends more or less on the type of cation in the sulphate solution".

There seems to be a general consesus on the theoretical processes of sulphate corrosion.

The general theoretical opinion on sulphates

corrosion mechanisms is that sulphates react with the calcium hydroxide, $Ca(OH)_2$, in the cement to produce first, a secondary gypsum, $CaSO_4.2H_2O$. The gypsum reacts with tricalcium aluminate, C_3A, of the cement to form calcium sulphoaluminate hydrate (ettringite), $C_3A.3CaSO_4.31H_2O$, which leads to swelling, expansion and disintengration of the concrete.

The action of sulphuric acid on cement can be adequately represented by the following stages of equations to conform with the general theoretical idea - formation of gypsum; the gypsum reacting with C_3A and combines 31 molecules of water to form the ettringite.

(i) $H_2SO_4 + Ca(OH)_2 - CaSO_4.2H_2O$

(ii) $3CaSO_4.2H_2O+3CaO.Al_2O_3+25H_2O$

$- 3CaO.Al_2O_3.3CaSO_4.31H_2O$

Calcium sulphoaluminate hydrate (ettringite).

2.3.0 CHLORIDE CORROSION

The problem of chloride related corrosion has been identified long ago. Numerous researches have been carried out in order to access the process of chloride related corrosion and the possibility of eliminating or, at least, reducing its adverse effects on reinforced concrete structures.

Middle east, for example, where there is prevalence of salts, high temperatures and cycling humidities, have witnessed a good number of these researches on chloride related corrosion.[11,12]

It should however, be noted that most of these researchers have been more concerned with the adverse effects on steel reinforcements rather than concrete.

Chlorides-caused corrosion in reinforced concrete structures has been recognised for at least 75 years. But this was mainly seen as affecting the steel reinforcement and its effect on concrete was either not known or ignored. As early as 1917 a survey published in the Engineering News Record on marine structures in North America showed that a number of structures less than 10 years old had evidence of deterioration resulting from the corrosion of steel above water line.[11,12]

Lack of adequate knowledge on the adverse effects of chlorides on concrete, probably, encouraged the

deliberate use of chlorides as admixtures in concrete constructions. In the 1960s and early 1970s it was common practice to add up to 2% (by weight of cement) of flaked calcium chloride to reinforced concrete to act as an accelerator and hardener. This 2% level is equivalent to 1.5% of the anhydrous salt or 1% chloride ion by weight of cement. this was the level permitted in the original (1972) version of CP110 and was still being recommended as late as 1976 by International Union for Testing and Research Laboiratories for Materials and Structures, RILEM.[11,12]

During the 1960s chlorides of sodium and calcium were being used as de-icing agent in the construction of North American bridge decks; and in the early 1970s premature deterioration of bridge decks were recorded and this was considered to be due to reinforcement corrosion.[11,12]

As the years rolled by the subject of chloride related corrosion, though still more related to reinforcement, was being better understood, and there was a growing campaign against the use of chlorides as additives in refinforced concretes. Fookes and Collins (1976)[11,12] appear to have been the first people to make a general recommendation that strict limits on chloride levels in fresh concrete be set, particularly to Middle East construction works. They specified a total level of acid soluble chloride (as Nacl) of 0.5% by weight of

cement (equivalent to 0.3% chloride ion by weight of cement) as well as limits on individual constituents of the concrete. This was far lower than anything that had been specified at that stage by any US or UK code of practice, even though interest in the subject had being growing in the research world for some years.

In 1977 there was a major change in design practice. Ammendment was issued to CP110 in which the use of calcium chloride as accelerator was prohibited and maximum chloride levels in cement of 0.3% and 0.06 by weight were specified for Ordinary Portland cement and Sulphate Resisting Cement, respectively; in the same year American Concrete Institute (ACI) issued a guide to durable concrete. In this a maximum chloride level in cement of 0.1% by weight was specified for reinforced concrete in moist environment and exposed to chloride, a level which was presumably based on the American bridge deck experience.[11,12]

The reason for the lower limits on chloride within the fresh concrete arose from experimental research on the mechanisms of chloride corrosion and practical experience of structures with different chloride levels. Experimental research has established that there exist a critical chloride level near reinforcement in concrete at which corrosion is initiated. Estimates of this level have varied widely (as shown in table 1) but the most frequently quoted

value is 0.4% chloride ion by weight of cement.

Table 1 Thresholds of chloride content in concrete for the onset of corrosion of embedded steel.[12]

Source	Chloride content in Cement :wt%	Concrete for typical concrete mixtures kg/m^3
Weigler and Segmullar 1973	0.4	1.65
CP110: (1972, 1979)	0.36	1.47
ACI Committe 201 on Durability of Concrete in service (1977): - Moist environment but not exposed to chloride	0.15	0.60
-Moist environment exposed to chloride	0.10	0.39
Stratfull et al (1975)	0.15	0.60
Clear (FHWA) (1976)	0.20	0.81
Knofel (1975)	0.20	0.81
Hausmann (1967) for pH = 12.5	0.05	0.20
for pH = 13.2	0.7	2.8
Lewis (1962)	0.15	0.60

One of the reasons for some of the practical limits being less than 0.4% may be the effect of carbonation in releasing bound chlorides in cement paste in the concrete pore solution. Carbonation is the process whereby carbondioxide, diffusing into the partially saturated pores in the surface of the

concrete, reacts with the calcium hydroxide in the cement paste and converts it to calcium carbonate.

$$Ca(OH)_2+CO_2 \text{ -----> } CaCO_3+H_2O$$

The carbonation process, in releasing bound chlorides into the pore solution at the surface of the concrete, sets up diffusion process in which chloride ions migrate from the area of high concentration at the surface to areas of lower concentration further into the concrete. The chloride level at the reinforcement might initially be acceptable, but this diffusion process can increase it to an unacceptable value and before the carbonation front reaches the reinforcement. The initiation of corrosion can occur very rapidly, as a single carbonated crack or carvity can lead to an attack. This process helps to explain the lower overall chloride limts that have been found necssary in Middle East concretes where chemical process such as carbonation proceed much rapidly. Early examples of critical chloride level noted in Middle East countries include 0.12-0.16 wt% of concrete for buildings in Bahrain and 0.2 wt% of cement for buildings in Kuwait.[12]

Safier (1989)[3] joined in the campaign against inclusion of chlorides in concrete when he submitted that so far as corrosion is concerned all engineers should observe O'level chemistry and that no body should bring chloride in contact with steel and expect

the steel not to corrode. He contended, "I have never permitted the use of chloride in concrete nor experienced any trouble there from."

2.3.1 Concrete Corrosion Due to Chlorides

Though much attention of chloride corrosion has been paid to steel reinforcements for ages, but concrete has not been left out entirely. From the 1930s there was a growing interest in the corrosion of concrete by chlorides. Numerous researches have been carried out in this regard.

2.3.1(a) Aggressive Effect of Chlorine Ions

The nature of the ions and their concentrations can govern the types of delitrious chemical reactions occuring in structural concretes exposed to the salt solutions. Strong solutions of sodium, potassium, calcium and magnesium chlorides, to mention but few chlorides, react with the $Ca(OH)_2$ present in the Portland Cement paste and even gradually destroy calcium silicate hydrate. These reaction initially produce surface softening followed by strength loss due to reaction proceeding inwards into the concrete. The detection of the onset of deterioration would be delayed considerably in large concretes as would the dimensional changes that are caused by the deliterous chemical reaction.[13]

There is in general a relatively little chlorine

in soil, nor can much (30 to 100mg/1) be detected in ground water. It should be noted here that waters leaching manure and faeces may have a chlorine content as high as 700 to 1000 mg/litre. Industrial wastes may also contain much chlorine, especially where domestic salt is used.[8]

2.3.1(b) Aluminium Chloride

Aluminium Chloride, $AlCl_3$, has been reported to be detreimental to concrete. It is aggressive to all concretes and cement mortars, regardless of quality. Structures exposed to it must be protected.[8]

2.3.1(c) Ammonium Chloride

Ammonium chloride, NH_4Cl, is said to be particulalrly aggressive to concrete. The free lime of concrete decomposes ammonium chloride with the resultant release of ammonia and formation of calcium chloride. Calcium chloride is readily dissolved and leached, thereby resulting in the softening of the concrete.[8]

Grun[8] reported that concrete is destroyed by softening upon exposure to hot ammonium chloride solution of up to 5%, while it remains unaffected by hot ammonium sulphate solutions. Mohr[8] in his experiment found that all types of cements are susceptible. Even weak solutions have been noticed to be detrimental. No signs of expansion can be observed, but concrete is softened.

2.3.1(d) Mecury Chloride

Mecury chloride, $AgCl_2$, is highly detrimental to concrete. Kleinlogel (1950)[8] observed that it is necessary to protect concrete against concentration as low as 0.7%.

The detrimental effect of mecury chloride solution is proportionate to their concentrations. Mecury chloride combines with free lime of concrete to form calcium chloride, which is readily soluble in water, while the other product of the reaction is mecury oxide. In experiments with a 7% sublimate solution, Kleinlogel[8] observed a rapid deterioration of concrete and reinforcement.

2.3.1(e) Iron Chloride and Manganese Chloride

Iron chloride, $FeCl_2$ and mangnese chloride, $MnCl_2$, have been reported to be acidic and therefore detrimental to concrete.[8]

2.3.1(f) Lime Chloride

Chloride of lime in high concentration occurs, besides the producing plants, in paper industries and bleaching plants. Chloride of lime is considered to be slightly acidic and moderately detrimental to concrete.[8]

2.3.1(g) Zinc Chloride

Zinc chloride, $ZnCl_2$, is encountered in chemical

plants and in connection with the impregnation of wood. With the calcium hydroxide of concrete it combines to form calcium chloride. It is regarded as a boundary case as far as corrosion is concerned. Zinc chloride is said to have a slow distengration effect on concrete.[8]

2.3.2 Hydrochloric Acid, HCl

"Hydrochloric acid (HCl) decomposes the calcium hydroxide, $Ca(OH)_2$, of cement into $CaCl_2$, which being readily soluble in water, is either washed from concrete or crystallizes. Therefore, weak solutions are already detrimental. Hydrochloric acid is extremely corrosive to clinker minerals as well, so that effective protection must be provided for concrete."[8]

Hydrochloric acid has been reported by some researchers as the acid causing the greatest damage to building structures. 10% hydrochloric acid is also adopted, for most materials, as the standard by which "acid resistance" is measured. Materials that is capable of resisting exposure to 10% hydrochloric acid is classified as "acid resistant". Even 0.5% solution of hydrochloric acid has been reported to attack conventional concrete and destroy it completely within few weeks.[8]

The formation of hydrochloric acid from the chlorides in the soil has not been reflected in almost

all the literatures reviewed. However, from relevant texts of chemistry, there exists a wide range of possibilities of chlorides and water reacting at room temperature to form HCl.[10,14].

2.3.3 Mechanisms of Chlorides Corrosion

It has been reported that chloride ions, Cl^-, present in sea water form with the alumina, a mono-chloroaluminate, $C_3A.CaCl_2.10H_2O$ which crystallizes into the hexagonal platelets unstable in the presence of sulphates.[4]

There is also a general agreement in literatures that the chloride react with the lime in cement to form calcium chloride hydrate. The calcium chloride hydrate react with the tricalcium aluminate with the combination of 10 molecules of water to produce calcium chloroaluminate hydrate which is responsible for the softening of the concrete and weakening its bonds.

The following reactions represents this process.

(i) $2HCl + Ca(OH)_2 \rightarrow CaCl_2.2H_2O$

Calcium chloride hydrate.

(ii) $3CaO.Al_2O_3 + CaCl_2.2H_2O + 8H_2O \rightarrow$

$3CaO.Al_2O_3.CaCl_2.10H_2O$

(Calcium Chloroaluminate hydrate)

the initial period and does not reduce subsequent strength below 28-day figures.[15]

2.4.2 Ammonium Nitrate

Of all the ammonium compounds, ammonium nitrate has been described as the most dangerous. "The most dangerous ammonium compound is ammonium nitrate (NH_4NO_3) which is aggressive to all concrete and mortars regardless of the cement used. Ammonium nitrate is highly corrosive in contrast, for example, to potassium-, sodium- and calcium nitrate, which are indifferent."[8]

The process of concrete corrosion by the action of ammonium nitrate (NH_4NO_3) results in the development of a highly soluble calcium nitrate salt ($Ca(NO_3)_2$) and low soluble calciumnitroaluminate ($3CaO.Al_2O_3.Ca(NO_3)_2.10H_2O$. "Lea" established that concrete cubes kept in 5 percent ammonium nitrate solution over a period of 4 years showed no external signs of deterioration inspite of a significant drop in strength.

Table 2 Tensile Strength of Cements Stored in Water and in nitrate.

Stored for 7 years in	Portland Cement(kg/cm^2)
Water	42
Sodium nitrate	43
Ammonium nitrate	8

Calcium nitrate	35
Magnesium nitrate	37
Aluminum nitrate	27
Lead nitrate	35

As can be seen from table 2 seriously destructive is ammonium nitrate (artificial manure) alone, while aluminum nitrate is of a much moderate effect. The reason for this is that the free lime of the concrete combines with the acid radical and forms calcium nitrate, while the ammoniac escapes in gas form.[8]

However, inspite of the notion that nitrates, with the exception of ammonium nitrate, are harmless; and that they can be detrimental only when their content is high, it has been recommended that concrete should be protected against dry salts and highly diluted solutions.[8]

2.4.3 Nitric Acid

Nitric acid (HNO_3) occurs in chemical plants producing exploves, artificial manure and similar products. Although nitric acid is not as strong an acid as sulphuric acid, its effect on concrete at brief exposure is more destructive, since it transforms the $Ca(OH)_2$ of concrete into the highly soluble calcium nitrate. The extreme destructive power of nitric acid is demonstrated by the fact that even highly diluted solutions may result in extensive deterioration.[8]

Like sulphates and chlorides almost all the literatures reviewed did not pay adequate attention to the natural formation of nitric acid. However, texts on chemistry have shown that under suitable conditions water can react with some relevant compounds to form nitric acid.[10, 14].

2.4.4 Mechanisms of Nitrates' Corrosion

The process of concrete corrosion by the action of nitrates involves the development of a highly soluble calcium nitrate salt, $Ca(NO_3)_2$ and a low soluble calcium-nitroaluminate hydrate,

$3CaO.Al_2O_3.Ca(NO_3)_2.10H_2O$

The process can be represented by the following chemical equations.

$2HNO_3 + Ca(OH)_2 \longrightarrow Ca(NO_3)_2.2H_2O$

$Ca(NO_3)_2.2H_2O + 3CaO.Al_2O_3.8H_2O \longrightarrow 3CaO.Al_2O_3.Ca(NO_3)_2.10H_2O$

(Calcium nitroaluminate hydrate).

In addition to sulphates, chlorides and nitrates discussed above, carbonation and alkali-silica reaction also constitute common sources of corrosion in concrete.[2-17]

CHAPTER THREE

EXPERIMENTAL PROCEDURE

3.1.0 Materials

3.1.1 Concrete Materials

3.1.1(a) Cement

The cement used in the process of this research is the Ordinary Portland Cement. The Ordinary Portland Cement is the Ashaka brand manufactured by the Ashaka Cement Company, PLC, Bauchi, Nigeria. The cement was obtained from local cement dealers in Zaria. Care was taken to ensure that the cement was of recent supplies and free of adultration.

3.1.1(b) Fine Aggregates

The fine aggregate was naturally occuring clean sand obtained from the supplies to the Department of Civil Engineering, A.B.U., Zaria for experimental purposes. Seive analyses was carried out on the fine aggregate and graded to determine its zone for mixed design purposes. Two different samples A and B were obtained from two different sections of the fine aggregate heap. From the analyses the fine aggregate was found to be in zone 2. Results of the analyses are shown in Appendices 1A,1B, and 1C.

3.1.1(c) Coarse Aggregates

The coarse aggregate was made of crushed granite obtained from the supplies to the Department of Civil

Engineering, A.B.U., Zaria, for experimental purposes. By seiving through 19.05mm and 12.7mm seives, the size of coarse aggregate used lies between 12.07 and 19.05mm. This was done to ensure the removal of dust and smaller sizes of aggregate and to realise the maximum aggregate size of 20mm that was used in the mixed design.

3.1.1(d) Water

Pure and clean tap water fit for drinking was used.

3.1.2 Chemicals

3.1.2(a) Sulphuric Acid, H_2SO_4

This acid was obtained from dealers on industrial chemicals in Lagos and Kaduna. It has a concentration of 96% and a specific gravity of 1.84 gcm^{-3} at a temperature of $20^{o}C$. Four different concentrations of 5%, 10%, 15% and 20% in clean tap water were used in the course of this research. The concentrations were volumetrically determined.

3.1.2(b) Nitric Acid, HNO_3

This was obtained from industrial chemicals' dealers in Lagos and Kaduna. It has a concentration of 70% and specific gravity of 1.42 gcm^{-3} at $20^{o}C$. 5%, 10%, 15% and 20% concentrations in clean tap water were the four different concentrations used. The

concentrations were determined volumetrically.

3.1.2(c) Hydrochloric Acid, HCl

It was obtained from industrial chemicals dealers in Kaduna and Zaria. It has a concentration of 33% and specific gravity of 1.18 gcm^{-3} at $20^{o}C$. The use of 5%, 10%, 15% and 20% four different concentrations determined volumetrically was employed in this research.

The chemicals are shown in plate 1.

3.1.3 Plastic Bowls

Chemical resistant plastic bowls were obtained from Kano, Zaria and Kaduna. They have a capacity of 35 litres per bowl and were used as containers during the immersion period. Plate 2 shows samples of the plastic bowls.

3.2.0 Concrete Mix Design

Three grades of concrete were used in this research. They are grades 30, 40 and 50. Mix design was carried out for each of the grades of concrete.

General Requirements

(1) Characteristic Strength = $30Nmm^{-2}$, $40Nmm^{-2}$, $50Nmm^{-2}$ at 28 days to CP110

i.e. 5% defective, therefore, k = 1.64

(2) Cement type = OPC



Plate 1. Samples of polycans of Sulphuric Acid, Nitric Acid and Hydrochloric Acid.



Plate II. Samples of Plastic Bowls of 35litres Capacity Each Used As Curing Media.

(3) Slump = 10-30mm (assumed)

(4) Maximum size of Aggregate = 20mm

(5) Max. free water/cement ratio = 0.55 (assumed)

(6) Minimum cement content = 300 kgm^{-3} (assumed)

(7) Fine aggregate - Naturally occuring clean sand

:. Relative density (SSD) = 2.6 (assumed)*

(8) Coarse aggregate - Crushed granite

:. Relative density (SSD) = 2.7(assumed)*

(9) Standard deviation, S= 8Nmm^{-2} (No previous control data)**

* If no information is available regarding the relative density of the aggregate an approximation can be made by assuming value of 2.6 for uncrushed aggregate and 2.7 for crushed aggregate.[16]

** If previous control data are not available or where only few data are available a standard deviation of 8Nmm^{-2} should be used for concrete with a characteristic strength of 20Nmm^{-2} or more[16].

3.2.1 Concrete Grade 30

Step 1.0

1.1 Characteristic strength = 30Nmm^{-2} at 28 days.

1.2 Standard deviation = 8Nmm^{-2} (Appendix 1D, Fig. 2)

1.3 = k.s = 1.64 x 8

= 13 Nmm^{-2}

1.4 Target mean strength = 30 + 13

= 43 Nmm^{-2}

1.5 Type of cement = O.P.C.

1.6 Type of aggregates: coarse = crushed granite

fine = Naturally occuring clean sand.

1.7 Free water/cement ratio = O.53 (Appendices 1E, Table 3 and 1D, Fig 3)

1.8 Spelcified maximum free water/cement ratio = O.55

The lower value from results of 1.7 and 1.8 should be used. Therefore the free water/cement ratio for the mix design is O.53.

Step 2.O

2.1 Specified slump = 10 - 3Omm

2.2 specified max. agg. size = 2Omm

2.3 Free water content = 190 kgm^{-3} (Appendix 1E Table 4)

Step 3.O

3.1 Cement content = $\frac{190}{0.53}$

3.2 Maximum cement content - not specified

3.3 Minimum cement content = 300 kgm^{-3}

3.4 Modified free water/cement ratio = Nil, 358.5 > 300

Step 4.0

4.1 Relative density of aggregate (SSD) = 2.7

4.2 Concrete density (Appendix 1F Fig 4) = 2435 kgm^{-3}

4.3 Total aggregate content = 2435 - 358.5-190

= 1886.5 kgm^{-3}

Step 5.0

5.1 Grading of fine aggregate (3.1.1(b) = zone 2 (BS 882)

5.2 Proportion of fine aggregate = 30.5 to 38%

(Appendix 1G Fig 5)

say 35%

5.3 Fine aggregate content = 0.35 x 1886.5

= 660.27 kgm^{-3}

say 660 kgm^{-3}

5.4 Coarse aggregate content = 1886.5 - 660

= 1226.5 kgm^{-3}

Quantities carried to summary

Cement = 358.5 kgm^{-3}

Water = 190 kgm^{-3}

Fine aggregate = 660 kgm^{-3}

Coarse aggregate = 1226.5 kgm^{-3}

3.2.2 Concrete Grade 40

Step 1.0

1.1 Characsteristic strength = 40 Nmm^{-2} at 28 days

1.2 Standard deviation = 8 Nmm^{-2} (Appendix 1D, Fig 2)

1.3 Margin = k.s = 1.64 x 8

= 13 Nmm^{-2}

1.4 Target mean strength = 40 + 13

= 53 Nmm^{-2}

1.5 Type of cement = O.P.C

1.6 Type of aggregate: coarse = crushed granite

fine = Naturally occuring clean sand

1.7 Free water-cement ratio = O.45 (Appendices 1E, Table 3 and 1D, Fig 3).

1.8 Specified minimum free water/cement = O.55

O.45 is lower than O.55 and should be used in the design

Step 2.O

2.1 Specified slum = 10 - 30mm

2.2 Specified max. agg. = 20mm

2.3 Free water content = 190 kgm-3 Appendix 1E, Table 4)

Step 3.O

3.1 Cement content = $\frac{190}{O.45}$

= 422.22 kgm^{-3}

3.2 Specified max. cement content = Nil

3.3. Specified min. cement content = 300 kgm^{-3}

3.4 Modified free water/cement ratio = Nil, 422.22 > 300

Step 4.0

4.1 Relative density of aggregate (SSD)= 2.7

4.2 Concrete density (Appendix 1F, Fig 4 = 2435 kgm^{-3}

4.3 Total aggregate content = 2435 - 422.22-190

= 1822.78 kgm^{-3}

3 Step 5.0

5.1 Grading of fine aggregate = zone 2 (BS 882)

5.2 Proportion of fine aggregate = 30.5 to 38%

(Appendix 1G)

Fig 5)

say 35%

5.3 Fine aggregate content (3.1.1(b)) = 0.35 x 1822.78

= 637.973 kgm^{-3}

5.4 Coarse aggregate content = 1184.807 kgm^{-3}

Quantities carried to summary

Cement = 422.22 kgm^{-3}

Water = 190 kgm^{-3}

Fine aggregate = 637.973 kgm^{-3}

Coarse aggregate = 1184.807 kgm^{-3}

3.2.3 Concrete Grade 50

Step 1.0

1.1 Characteristic strength = 50 Nmm^{-2}

1.2 Standard deviation = 8 Nmm^{-2}

(Appendix

1D, fig. 2)

1.3 Margin = k.s = 1.64 x 8

= 13 Nmm^{-2}

1.4 Target mean strength = 50 + 13

= 63 Nmm^{-2}

1.5 Type of cement = O P C

1.6 Type of aggregate: Coarse = crushed granite

fine = naturally occuring clean sand

1.7 Free water - cement ratio = 0.38 (Appendices 1E, Table 2 and 1D, fig. 3).

1.8 Specified minimum free water/cement ratio = 0.55

0.38 is lower than 0.55 and should, therefore be used in the design.

Step 2.0

2.1 Specified slump = 10 - 30mm

2.2 Specified max. agg. = 20mm

2.3 Free water content = 190 kgm^{-3}

(Appendix 1E, Table 4)

Step 3.0

3.1 Cement content = $\frac{190}{0.38}$

= 500 kgm^{-3}

3.2 Specified max. cement content = Nil

3.3 Specified min. cement content = 300 kgm^{-3}

3.4 Modified water/cement ratio = Nil; 500 > 300

Step 4.0

4.1 Relative density of agg. (SSD) = 2.7

4.2 Concrete density = 2435 kgm^{-3}

(Appendix 1F, Fig 4)

4.3 Total aggregate content = 2435 - 500 - 190

= 1745 kgm^{-3}

Step 5.3

5.1 Grading of fine aggregate = zone 2 (BS 882)

5.2 Proportion of fine agg. = 30.5 to 38%

(Appendix IG, Fig 5)

say 35%

5.3 Fine aggregate content = 0.35 x 1745

= 610.75 kgm^{-3}

5.4 Coarse aggregate content = 1745 - 610.75

= 1134.25 kgm^{-3}

Quantities carried to summary

Cement = 500 kgm^{-3}

Water = 190 kgm^{-3}

Fine aggregate = 610.75 kgm^{-3}

Coarse aggregate = 1134.25 kgm^{-3}

3.3.0 Batching, Mixing, Compaction and Curing

3.3.1 Batching, Mixing and Compaction

The concrete materials were batched by weight in accordance with the results of mix design for grades 30, 40 and 50 conctretes in section 3.2.1, 3.2.2. and 3.2.3 respectively. The batches were thoroughly mixed in the laboratory batch mixer. The thoroughly mixed concrete was cast into (150x150x150)mm cube moulds and

compacted mechanically to the design density of 2435 kgm^{-3}.

A total of 369 numbers of cubes were cast. The total number is broken down as follows:

(a) 6 numbers of cubes were crushed for each of the three grades of concrete to determine the 28-day strength.

Here is a total of 6 x 3 = 18 No. cubes

(b) 9 numbers of cubes were immersed in each of the four different concentrations of the three different types of acids for the three different grades of concrete.

Here is a total of 9 x 4 x 3 x 3 = 324 No. cubes

(c) 9 numbers of cubes were used, throughout the three different crushing times of 28 days, 56 days and 84 days, for each of the three grades of concrete as controls for the immersed specimens.

Here we have a total 9 x 3 = 27 No. cubes

Grand total = 18 + 324 + 27

= 369 No. cubes

3.3.2 Curing

Concrete cubes were placed in a curing room and covered with sacks which were kept constantly moisted for 21 days. This method of curing, instead of complete immersion in water, was adopted to simulate one of the best site-curing conditions.

The concrete cubes were then air-dired in the

laboratory for 7 days before immersion. Air drying was considered necessary to avoid the concentrations of the acids being affected by the water in the pores of the concrete cubes.

3.4.0 Determination of concretre grades

Six numbers of cubes were crushed at the end of the 28 days of casting and curing to determine their strengths at the age of 28 days. The average of the six different values of test results was taken as the concrete cube strength at 28 days - the grade of concrete. Results are shown in Appendix II

3.5.0 Calculation of the Volumes of Acids Required In Water for the Different Concentrations

3.5.1 Slulphuric Acid, H_2SO_4

Specific gravity = 1.84 gcm^{-3}

Concentration = 96%

Weight in 1000 cm^3 of water = 1.84 x 1000g

= 1840g

Therefore 96% contains 1840g

and 1% contains $\frac{1840 \times 1}{96}$

= 19.1666g

But, 1840g = 1000 cm^3

$\therefore$ 1g = $\frac{1000\ cm^3}{1840\ g}$

19.1 666g $= \frac{1000}{1840} \times 19.1666$

$= 10.41666\ cm^3$

$= 10.42\ cm^3$

The calculations shows that 10.42 cm^3 of sulphuric acid is required in 1000 cm^3 of water to achieve a 1% concentration. This can be modified to arrive at any concentration given the volume of water.

3.5.2 Nitric Acid, HNO_3

Specific gravity $= 1.42\ gcm^{-3}$

Concentration $= 70\%$

Weight in 1000 cm^3 $= 1.42 \times 1000g$

$= 1420g$

70% contains 1420g

1% contains $\frac{1420}{70} = 20.2857\ g$

1420g $= 1000\ cm^3$

$\therefore$ 1g $= \frac{1000\ cm^3}{1420\ g}$

Therefore 20.2857 $= \frac{1000 \times 20.2857}{1420}$

$= 14.2857\ cm^3$

$14.3\ cm^3$

It follows, therefore, that 14.3 cm^3 of nitric acid is required in 1000 cm^3 of water to make 1% concentration. This can be modified for any desired concentration.

3.5.3 Hydrochloric Acid, HCL

Specific gravity = 1.18 gcm^{-3}

Concentration = 33%

Weight in 1000 cm^3 = 1.18 x 1000

= 1180g

Therefore 33% contains 1180g

And 1% contains $\frac{1180}{33}$ = 35.7576 g

But 1180g = 1000 cm^3

1 g = $\frac{1000\ cm^3}{1180\ g}$

And 35.7576 = $\frac{1000 \times 35.7576}{1180}$

= 30.3031 cm^3

30.3 cm^3

Therefore, 1000 cm^3 of water requires 30.3 cm^3 of hydrochloric acid for 1% concentration. This can also be modified to arrive at any required concentration with any volume of water.

3.6.0 Subjection to Aggressive Environment

At the end of 28 days of casting and curing, the various concentrations for the three different acids were prepared into the plastic bowls to receive the concrete cubes. In addition to the date of casting and grade of concrete impressed on the cubes, some other identification marks that clearly differentiate one cube



Plate III. Mixing Acid with water.



Plate IV. Concrete Cubes Immersed in Hydrochloric Acid.

from another were also impressed on the cubes to ensure a true comparison of the densities of any given concrete cube before and after immersion. Such identification marks consist of two numerals closely following each other and an alphabet at the end. The first numeral indicates the concentration of the acid, the second numeral shows the number of the cube in that set of cubes in that concentration of acid, while the alphabet is the code for the acid.

For instance, a concrete cube with the following identification marks:

28/2/92

G 30

5/1/c

shows that; 23/2/92 is the date of casting,

G30 is the grade of concrete,

5 is the percentage concentration of acid,

1 is the number of the cube in the set of cubes immersed in that concentration of the acid,

C is the code for hydrochloric acid.

Similarly, a conctrete cubes with the following identification marks:

06/03/92

G 40

10/4/N

shows that:

26/03/92 is the date of casting,

G40 is the grade of concrete,

10 is the percentage concentration of acid,

4 is a the number of the cube in the set of cube immersed in that concentration of the acid,

N is the code for nitric acid.

In the same manner, G50 represent concrete grade 50 and the letter S is the code for sulphuric acid.

If the first numeral in the identification mark is zero, then a control specimen of 0% concentration is indicated.

Mixing the acid with water produces an exothermic reaction and the mixtures were allowed to cool down to the room temperature before immersing the concrete cubes. Effects of the chemicals on the concrete cubes were determined after 28 days, 56 days and 84 days of immersion.

3.7.0 Test Procedure

3.7.1 23 days after Casting and Curing

At the end of 23 days after casting and curing in moist environment, the concrete cubes were weighed to determine their densities before immersion. Six concrete cubes for each of the three different grades of concrete were crushed. The average crushing load was taken as the 28 - day compressive strength of concrete. In other words, it is the grade of the concrete. Results are shown in Appendix II.

3.7.2 28 days Immersion

At the end of 28 days immersion period, three concrete cubes for each of the three grades of concrete were removed from each of the four different concentrations of the three different acids. These concrete cubes were rinsed thoroughly in clean tap-water and air-dried in the laboratory for 48 hours. They were weighed to determine their new densities and, then crushed. The average crushing load was taken as the compressive strength of the concrete after 28 days of immersion. Three concrete cubes for each of the three grades of concrete and zero percent acid concentration, the control specimens, were also weighed and crushed and the average crushing load represents the compressive strength at 28 days immersion period in zero percentage concentration.

The densities and compressive strengths of the test specimens and the control specimens were compared to their densities and compressive strengths before immersion. Results are presented in Appendices IIIA, IIID and IIIG for grades 30, 40 and 50 concretes respectively.

3.7.3 56 Days of Immersion

At the end of 56 days of subjection to the chemically aggressive environment, the same procedure as for the 28 day of immersion was followed. The only difference is that concrete cubes were air-dried in the

laboraltory for 72 hours. Results are shown in Appendices IIIB, IIIE and IIIH for grades 30, 40 and 50 concretes respectively.

3.7.4 84 Days of Immersion

The same procedure as for the 56 days of immersion was followed at the end of 84 days of immersion. Results are presented in Appendices IIIC, IIIF and IIII for grades 30, 40 and 50 concretes respectively.



Plate V. Concrete Cubes Immersed in Sulphuric Acid (Whittish) and Nitric acid (Brownish).



Plate VI. Cross Section of Concrete Cubes Immersed in Acid.



Plate VII. A View of a greater number of Concrete Cubes in the Curing Media.



Plate VIII. Concrete Grade 30 at the End of 28 days of Immersion Period. From left to right: Cubes Immersed in HCl, HNO_3, H_2SO_4 and H_2O

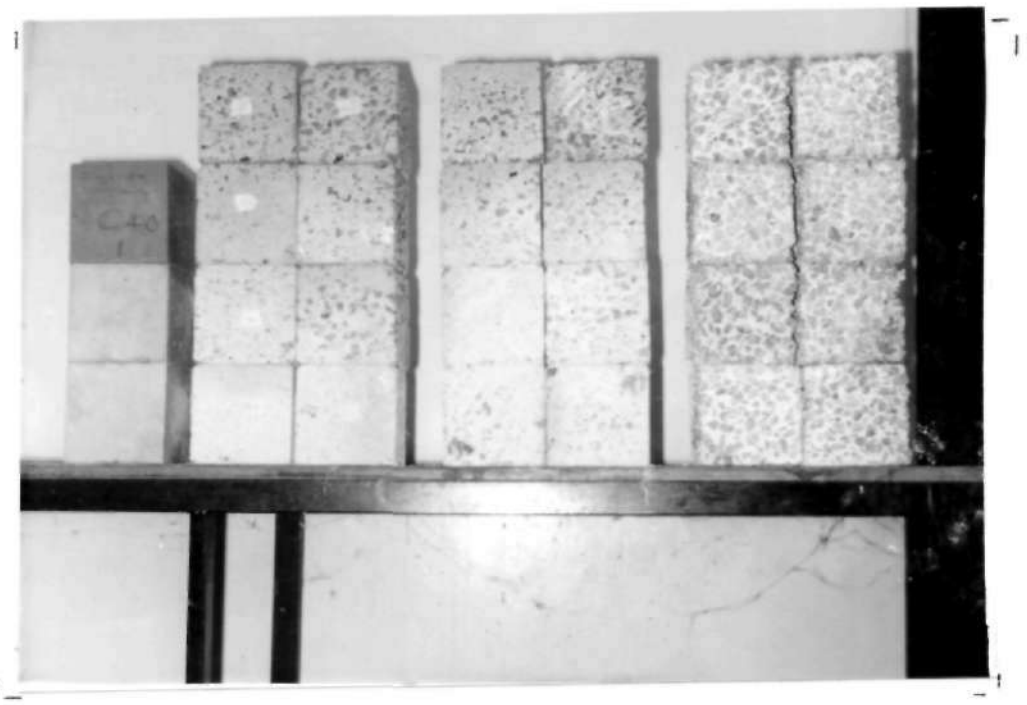


Plate IX. Concrete Grade 40 at the End of 28 days of Immersion Period. From left to right: Cubes Immersed in H_2O, HCl, HNO_3 and H_2SO_4



Plate X. Concrete Grade 30 at the end of 56 days of Immersion Period. From left to right cubes Immersed in H_2O, HCl, HNO_3 and H_2SO_4

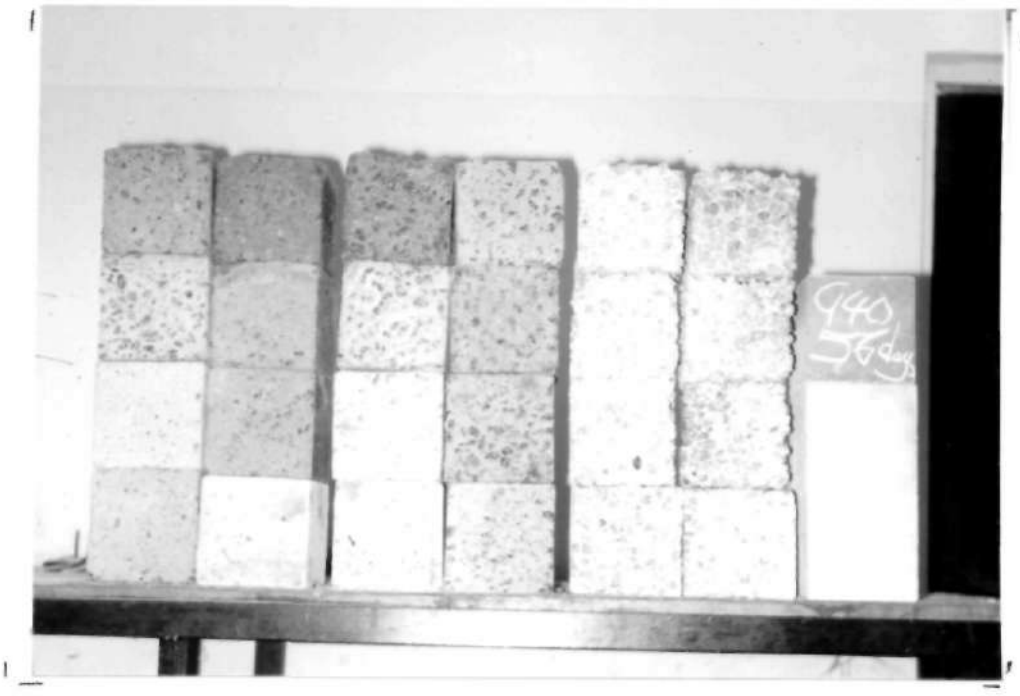


Plate XI. Concrete Grade 40 at the end of 56 days of Immersion Period. From left to right: Cubes Immersed in HCl, HNO_3, H_2SO_4 and H_2O



Plate XII. Concrete Grade 30 at the end of 84 days of Immersion period. From left to right: Cubes Immersed in H_2O, HCl, HNO_3, and H_2SO_4



Plate XIII. Concrete Grade 40 at the end of 84 days of Immersion Period. From left to right: Cubes Immersed in H_2O, H_2SO_4, HNO_3 and HCl.

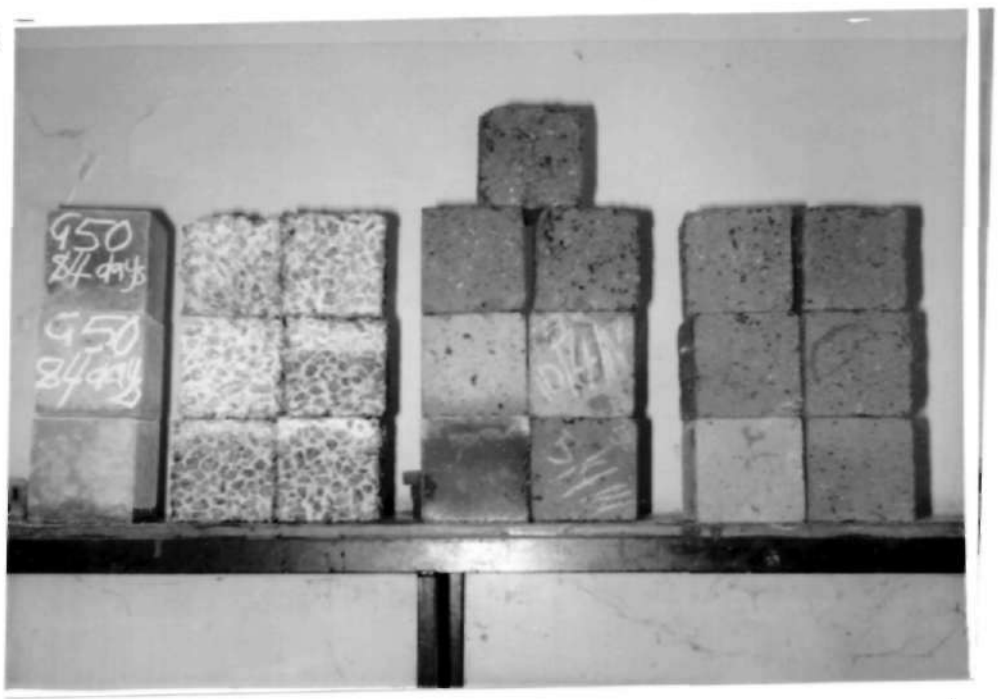


Plate XIV. Concrete Grade 50 at the end of 84 days of Immersion Period. From left to right: Cubes Immersed in H_2O, H_2SO_4, HNO_3 and HCl.

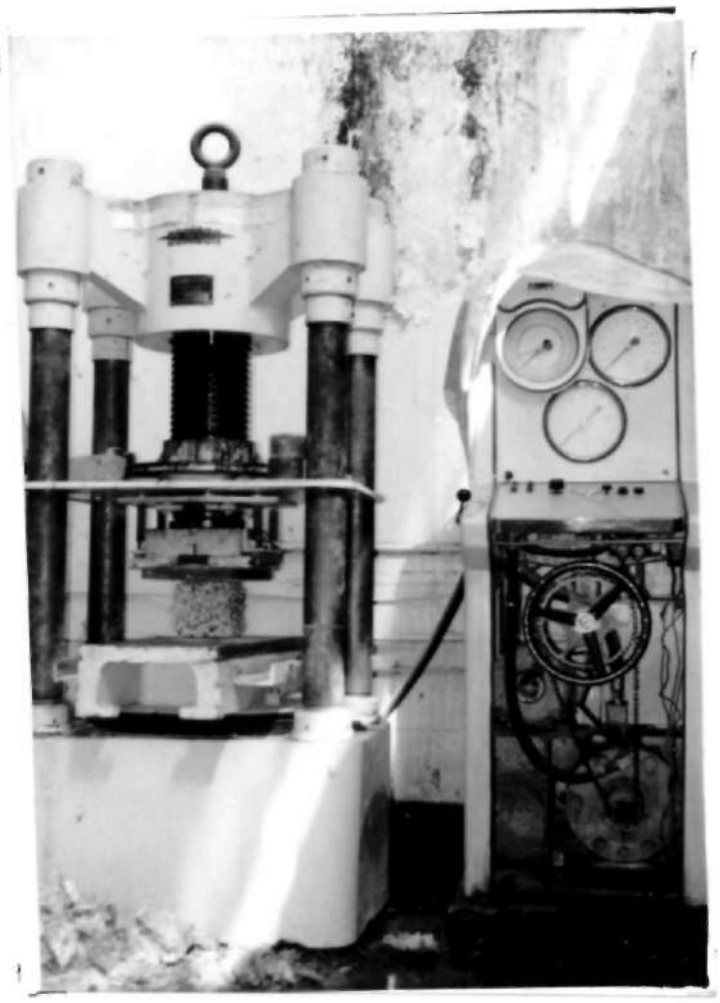


Plate XV. Compressive Strength Testing Machine



Plate XVI. Gelatinous whittish Precipitate from the Action of sulphuric acid on the Concrete Cubes.

CHAPTER FOUR

4.0 RESULTS: PRESENTION, ANALYSIS AND DISCUSSION

The results of the experimentation detailed in chapter 3 are presented, analysed and discussed in this chapter.

4.1.0 OBSERVATIONS

Exothermic reaction was observed on mixing the acid with water. The heat production in the case of H_2SO_4 was noticed to be higher than that of HCl or HNO_3.

Immediately the concrete cubes were introduced into the mixture a vigorous reaction in HCl and HNO_3 involving effervescence and boiling effect was produced. This vigorous reaction was not noticed in the case of H_2SO_4 at the introduction of concrete cube specimens. What could, however, be noticed immedately was the instant extrusion of cement paste-like particles considered to be hydration products.

The vigorous reactions in HCl and HNO_3 died down gradually. The mixture and the concrete cubes were turned green and brown in the cases of HCl and HNO_3 respectively. The intensity of the colours increases with age. In the case of H_2SO_4 the extrusion of the hydration products continued. The mixture remained colourless, while the concrete cubes were turned white. Plates 4,5,6 and 7.

In the cases of HCl and HNO_3, the concrete cubes remained intact on the surfaces but felt very soft to the touch and the mortar surround could easily be removed with the slightest rubbing force. This was different in the case of H_2SO_4 where the mortar surround was completely removed and deposited at the bottom of plastic bowls, as white gelatinous precipitate, leaving the free sides of the concrete cubes exposed of coarse aggregates. Some of the extruded particles through the top of the cubes also settled there in the form of white gelatinous substance.

The rate at which the volume of the mixture involving sulphuric acid decreased was faster than that of HNO_3 or HCl. It follows therefore that the rate at which the mixture involving sulphuric acid permeates into the concrete is faster than that of HCl or HNO_3.

The mixture involving hydrochloric acid was observed to be covered with greenish foam and a greenish grease-like deposit on top of the cubes. That of nitric acid was observed to be covered with a brownish foam and a brownish grease-like substance deposited on top of the cubes. The mixture in case of sulphuric acid was clear of foam.

4.2.0 PRESENTATION OF RESULTS

Appendix II deals with determination of the 28 - day mean strength for the various grades of concrete,

namely grade 30, 40 and 50. Appendix III shows the results as recorded during testing.

Appendices IVA - Z_2 is devoted to detail computation of the results. Appendices VA-I is designed to make out an easy comparison of effects of a given acid on a given grade of concrete at the end of the various immersion periods; while in a similar manner Appendices VIA - I presents the results in such a way that the effects of the various acids on a given grade of concrete at a given immersion period can easily be accertained.

Figures 6 to 14 show the relationship between the compressive strength of each of the concrete grades and the concentrations of each of the acids at the various immersion periods.

Figures 15 to 23 indicate the relationship between the compressive strength of each of the concrete grades and the concentrations of the three acids at a given immersion period.

Figures 24 to 38 show the relationship between the compressive strength of a given concrete grade and a given concentration of the three acids at the various immersion periods.

4.3.0 ANALYSIS AND DISCUSSION OF RESULTS

4.3.1 Concrete Grade 30

As can be seen from the results, the 28-day mean

compressive strength of the concrete of grade 30 is 35.36 Nmm^{-2}. This was obtained from the average crushing load for 6 cubes of concrete designed for this grade of concrete, (appendix II).

It is evident from the results that the cubes in zero percentage concentration, control cubes ,kept in water, increased in strength with time. At 28 days of immersion the compressive strength increased from 35.36 Nmm^{-2} to 37.04 Nmm^{-2} representing a percentage increase of 4.75%. At 56 days of immersion period the compressive strength increased from 35.36 Nmm^{-2} to 40.30 Nmm^{-2} representing a percentage increase of 13.97%. While in the case of 84 days of immersion period the compressive strength recorded an increase of 41.33 Nmm^{-2} from 35.36 Nmm^{-2}. This is an increase of 16.88%, (Appendices IVA - I, VA - C and VIA - C).

For all the three acids the magnitude of reduction in compressive strength is directly related to the concentration of the acid. For instance at 28 days of immersion period, the percentage reduction in compressive strength of the concrete at 5%, 10%, 15% and 20% concentrations of hydrochloric acid were 23.33%, 30.46%, 38.83% and 55.60% respectively; for 5%, 10%, 15% and 20% concentrations of nitric acid the reduction in compressive strength were 29.61%, 35.89%, 42.59% and 58.94% respectively; while in the case of 5%, 10%, 15% and 20% concentrations of sulphuric acid

the percentage reduction in compressivce strength were 48.05%, 63.12%, 64.82% and 67.31% respectively. Similar analysis can be presented for the 56 days and 84 days immersion periods, (Appendices IVA-IVI, and VA-C).

Figures 6, 7 and 8 show the relationship between the compressive strength and concentration of the acids for concrete of grade 30 at the end of 28 days, 56 days and 84 days of immersion periods respectively.

The degree of loss in compressive strength was also seen to depend on the duration of immersion. The longer the period of subjection to aggressive medium the higher the strength loss. For example, the compressive strength loss due to 5% hydrochloric acid at 28 days, 56 days and 84 days of immersion periods were respectively 23.33%, 35.49% and 43.01%; compressive strength reduction due to 10% nitric acid at 28 days, 56 days and 84 days immersion periods were 35.89%, 38.83% and 41.35% respectively; while 20% concentration of sulphuric acid at 28 days, 56 days and 84 days immersion periods produced losses in compressive strength of 67.31%, 71.52% and 76.95% respectively. These are, however, few selected examples and similar discussion can be presented for all the acids at different concentration during the immersion periods; (Appendices IVA - I and VIA - C).

Figures 15, 16 and 17 show how immersion periods influence the relationship between the concentrations

of the acids and the compressive strength of concrete of grade 30. For all concentrations and throughout the immersion periods it is clear from the results that sulphuric acid is the most aggressive of the three acids. However, such a clear distinction can not be drawn between the aggressivity of nitric and hydrochloric acids. At the end of 28 days of immersion, the nitric acid appeared to be more aggressive than hydrochloric acid. At the end of 56 days of immersion period hydrochloric acid was more aggressive at 5% and 10% concentrations while nitric acid showed more aggressivity at 15% and 20% concentrations. At 84 days of immersion period, hydrochloric acid was again more aggressive at 5%, 10% and 15% concentrations, while at 20% concentrations nitric acid showed greater aggressivity. However, it is clear that there is no appreciable difference in the degree of their aggressivities.

Figures 24 to 28 show the relationship between the compressive strength of grade 30 concrete and the immersion periods at the different concentrations of the acids. For zero percent concentrations (Fig 24) the compressive strength increased with the duration of the immersion period. For 5%, 10%, 15% and 20% concentrations of the acids, (figures 25, 26, 27 and 28 respectively) there is a clear decrease in compressive strength as the immersion periods increases.

Initially, the decrease in compressive strength is rapid. The decrease in the compressive strength becomes progressively slower with increasing immersion period.

4.3.2 CONCRETE GRADE 40

The 28-day mean compressive strength for this grade of concrete obtained from the average crushing load for 6 cubes of concrete designed for this grade of concrete is 42.58 Nmm^{-2} which indicates that the mix design and the casting procedures were okey. (Appendix II).

The results for this grade of concrete also show an improvement on the 28-day mean strength of concrete cubes of zero percent concentration, concrete cubes immersed in water, with time.

The improvement on the original compressive strength for zero percent concentration were 44.15 Nmm^{-2} representing an increase of 3.69% after 28 days of immersion; 46.67 Nmm^{-2} indicating an increase of 9.61% at 56 days of immersion; while that of 84 days of immersion is 51.70 Nmm^{-2} and shows an increase of 21.42%; appendices IVJ - R, VD - F and VID - F.

The magnitude of the compressive strength reduction relate directly to the concentration of the acids. For 5%, 10% 15% and 20% concentrations of hydrochloric acid at 28 days of immersion, the percentages of reduction in compressive strength were

28.67%, 37.36%, 43.64% and 49.91% respectively. For nitric acid, at 28 days of immersion, 5%, 10%, 15% and 20% concentration produced percentage compressive strength reductions of 27.97%, 37.36%, 47.46% and 56.86% respectively. 5%, 10%, 15% and 20% sulphuric acid concentrations, for the same period, resulted in a decrease in compressive strength of 49.55%, 56.86%, 62.78% and 65.22% respectively. The results of 56 days and 84 days of immersion in the different concentrations of the acids are similar to that of 28 days of immersion; (Appendices IVJ - R and VD - F).

Figures 9, 10 and 11 show the relationship between the concentrations of the acids and the compressive strength of concrete grade 40 at 28 days, 56 days and 84 days immersion periods respectively.

The magnitude of the reduced compressive strength of this grade of concrete was also observed to be influenced by the duration of the period of immersion. The reduced compressive strength in the cases of 56 days and 84 days of immersion were progressively higher than those at the 28 days of immersion period. For instance, the percentage reduction in compressive strength at 28 days, 56 days and 84 days immersion periods due to 5% concentration of hydrochloric acid were 28.67%, 35.30% and 39.46% respectively. For 5% concentration of nitric acid, the percentage reduction in compressive strength were 27.97%, 35.27% and 41.19%

for 28 days, 56 days and 84 days immersion periods respectively. In the case of 5% concentration of sulphuric acid at 28 days, 56 days and 84 days immersion periods the percentage loss in compressive strength were 49.55%, 55.45% and 57.89% respectively. A similar analysis can be presented for all other concentration of the acids for the different immersion periods; (Appendices IVJ - R and VID - F).

Figures 18, 19 and 20 show how the periods of immersion influence the relationship between the concentrations of the acids and the compressive strength of concrete grade 40.

Sulphuric acid was again, observed to be more aggressive than either the nitric acid or hydrochloric acid for all concentrations at all immersion periods. But in the cases of the nitric and hydrochloric acids, it is not clear which of them depicts greater aggressivity. For example, at 28 days of immersion period hydrochloric acid have a marginal lead in aggressivity at 5% concentrations; nitric acid is leading at 15% and 20% concentrations; while their aggressivity is the same at 10% concentration. At 56 days of immersion, there is very little difference in the aggressivity of the two acids at 5% concentration; hydrochloric acid is having a marginal lead at 10% concentration; while nitric acid is having a clear lead at 15% and 20% concentrations. 84 days of immersion

shows that hydrochloric acid is more aggressive at 15% concentration while nitric acid is more aggressive at 5%, 10% and 20% concentrations. Generally, there is no appreciable difference in their degree of aggressivities.

The relationship between the compressive strength of grade 40 concrete and the immersion periods at a given concentration of the three acids are shown in figures 29 to 33. At zero percent concentrations of the acids (fig 29) the compressive strength increases with increase in immersion period. At 5%, 10%, 15% and 20% concentration of the acids, (figures 30, 31, 32 and 33 respectively) there is reduction in compressive strength which increases with increase in immersion period. However, the initial rapidity in compressive strength reduction becomes progressively reduced as the immersion period increases.

4.3.3 Concrete Grade 50

The mix design and casting procedures for this grade of concrete were also shown to be okay as the average compressive strength from 6 concrete cubes yielded a compressive strength of 50.18 Nmm^{-2}, (Appendix II).

For concrete cubes immersed in zero percent concentration of acid, i.e. immersed in water, the compressive strength was increased to 53.85 Nmm^{-2}

representing a percentage increase of 7.31% at 28 days of immersion. The compressive strength increased at 56 days and 84 days of immersion periods to 59.25 (18.07%) and 62.81 (25.17%) respectively, (Appendices IVS - Z_2, VG - I and VIG - I).

Like the other grades of concrete (30 and 40) the magnitude of strength reduction is proportional to the concentration of the acid. Strength reductions of 9.97%, 17.34%, 24.43% and 32.10% were observed for 5%, 10%, 15% and 20% concentrations of hydrochloric acid at 28 days of immersion period. During the same period, nitric acid of 5%, 10%, 15% and 20% concentration produced percentage reductions in compressive strength of 8.77%, 17.34%, 23.24% and 29.73% respectively; while 5%, 10%, 15% and 20% of sulphuric acid produced percentage reductions of 37.43%, 42.13%, 46.19% and 51.87% respectively. Similar deductions can be made for other concentrations of the acids for the immersion period under consideration, (Appendices IVS - Z_2 and VG - I).

Figures 12, 13 and 14 show the relationship between the concentrations of the acids and compressive strength of concrete grade 50 at the end of 28 days, 56 days, and 84 days of immersion periods respectively.

For this grade of concrete the magnitude of the compressive strength reduction was also observed to be directly related to the duration of the period of immersion. The compressive strength reduction increases

as the duration of immersion period increases. This is evident in the results shown in appendices IVS - Z_2 and VIG - I. The percentage decline in compressive strength due to 5% concentration of hydrochloric at 28 days, 56 days and 84 days of immersion were, respectively, 9.97%, 22.66% and 26.21%, in the case of 5% concentration of nitric acid the percentage decline in compressive strength were 8.77%, 14.99% and 22.94% at 28 days, 56 days and 84 days immersion periods respectively; while the percentage decrease in compressive strength due to 5% concentrations of sulphuric acid at 28 days, 56 days and 84 days immersion periods were, respectively, 37.43%, 43.60% and 51.00%. Similar discussion holds for other concentrations of the acids during the immersion periods.

Figures 21, 22 and 23 show the influence of immersion periods on the relationship between the concentrations of the various acids and the compressive strength of grade 50 concrete.

Here, once again, sulphuric acid showed a glaring higher degree of aggressivity.

Here, too, there is no clearity as to which is more aggressive between nitric acid and hydrochloric acid. At 28 days of immersion period hydrochloric acid have a slightly higher degree of aggressivity at 5%, 15% and 20% concentrations; while both acids have the

same degree of aggressivity at 10% concentration. At 56 days and 84 days of immersion periods hydrochloric acid showed greater aggressivity than nitric acid. However, the differences in their degree of aggressivities are not appreciable.

Figures 34 to 38 indicate the relationship between the compressive strength of grade 50 concrete and the duration of immersion period at the various concentrations of the acids. In the case of zero percent concentrations of the acids, (fig 34) the compressive strength increases with increase in the duration of immersion period. In the cases of 5%, 10%, 15% and 20% concentrations of the acids, (fig 35, 36, 37 and 38 respectively) the compressive strength decreases with increase in the duration of immersion period. The reduction in compressive strength is more rapid at the initial stage and becomes slower as the duration of immersion period increases.

4.4.0 Degree of Corrosion

It might be difficult to make a clear definition of the degree at which the grades of concrete degrade under chemical aggression of the acids. this is because, the degree of corrosion did not follow a uniform pattern. The degree of corrosion became progressively lower with time. This is very envident in the computed results in appendix II.

For instance, 5% concentration of hydrochloric acid produced a compressive strength reduction of 8.25 Nmm^{-2} in concrete of grade 30 at 28 days of immersion period; the compressive strength reduction at 56 days of immersion was 12.55 Nmm^{-2} which shows only 4.30 Nmm^{-2} further decrease between 28 days and 56 days of immersion periods; while the compressive strength reduction at the end of 84 days immersion period was 15.21 Nmm^{-2} and shows only 2.66 Nmm^{-2} further reduction between 56 days and 84 days immersion periods. Put together the reduction is 6.96 Nmm^{-2} between 28 days and 84 days of immersion. This is less than the strength reduction within the first 28 days of immersion.

With 10% concentration of nitric acid and grade 30 concrete, the strength reductions are as follows:-

28 days after immersion	12.69 Nmm^{-2}
56 days after immersion	13.73 Nmm^{-2}
84 days after immersion	14.62 Nmm^{-2}

The results showed only 1.04 Nmm^{-2} further strength reduction between 28 days and 56 days immersion periods; and 0.89 Nmm^{-2} reduction in compressive strength between 56 and 84 days of immersion. The total reduction in compressive strength of 1.93 Nmm^{-2} is far less than that obtained within the first 28 days of immersion.

With 15% hydrochloric acid and concrete of grade

40, the compressive strength reductions were as follows:

At 28 days of immersion 18.58 Nmm^{-2}

At 56 days of immersion 20.80 Nmm^{-2}

At 84 days of immersion 23.17 Nmm^{-2}

The results indicate only 2.22 Nmm^{-2} additional strength reduction between 28 days and 56 days of immersion; while the reduction in compressive strength between 56 days and 84 days of immersion is 2.37 Nmm^{-2}. The total reduction in compressive strength which is 4.59 Nmm^{-2} is, again, far less than that within the first 28 days of immersion.

With 20% concentration of sulphuric acid and concrete of grade 50, the reduction in compressive strength are as follows:-

At 28 days of immersion 26.03 Nmm^{-2}

At 56 days of immersion 30.33 Nmm^{-2}

At 84 days of immersion 38.13 Nmm^{-2}

It can be seen from the results that 4.30 Nmm^{-2} reduction in compressive strength was recorded between 28 days and 56 days immersion periods. The strength decline between 56 days and 84 days of immersion is 7.70 Nmm^{-2}. A slight departure can be noticed here as the compressive strength reduction between 56 days and 84 days immersion periods is higher than that between 28 days and 56 days of immersion. This particular example is specially cited to show this slight departure from

the normal. It is perculiar to only sulphuric acid and happens in only few isolated cases. However, the total reduction in compressive strength of 12 Nmm^{-2} between 28 days and 84 days immersion periods is still far lower than the compressive strength reduction within the first 28 days of immersion.

The reasons responsible for the sharp decrease in aggressivity of the acids may be explained thus: Since the aggressive medium is stagnant and with a constant concentration, there is the tendency of strength of the acids getting progressively lower as a result of its reaction with the calcium hydroxide and other components of the cement in the concrete. These reactions produce neutralisation effects on the acids. The strength of the acids, therefore, is bound to decrease with time. Another possible adverse effect on the strength of the acid is air oxidation. The dissociated elements or radicals of the acids and water mixture may react, under favourable conditions, with oxygen of the atmospheric air to form less harmful substances, resulting in a subsequent reduction in the strength of the acid and the resultant reduction in aggressivity.

It is also believed that the cracks due the ettringite formation are filled gradually with gypsum formation within the cracks. This is a secondary reaction which could be an explanation of the often observed

rehealing process. This rehealing process in the concrete may assist in reducing the acid aggression on the concrete.

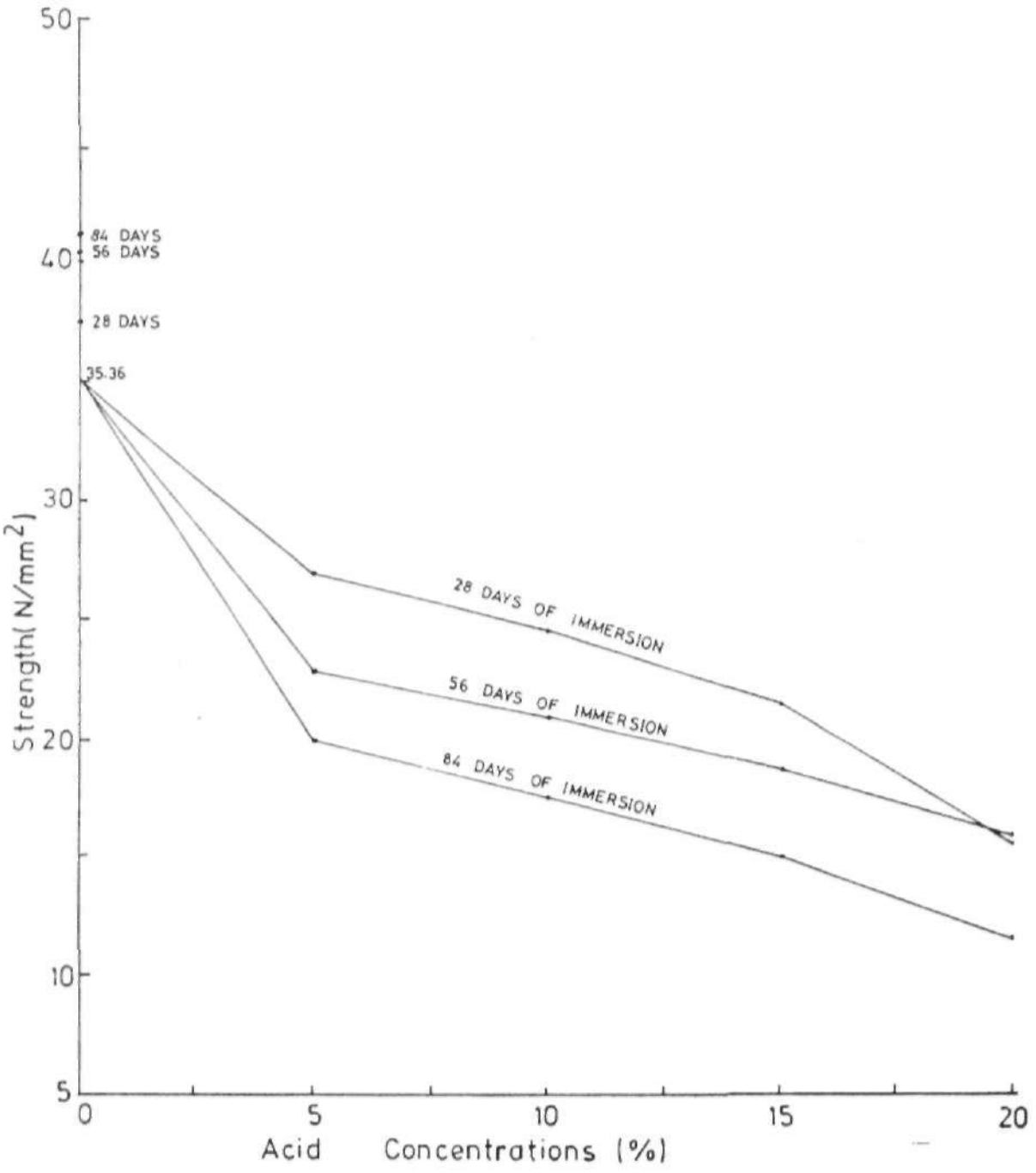


FIG.6 GRADE 30 CONCRETE IN HCL

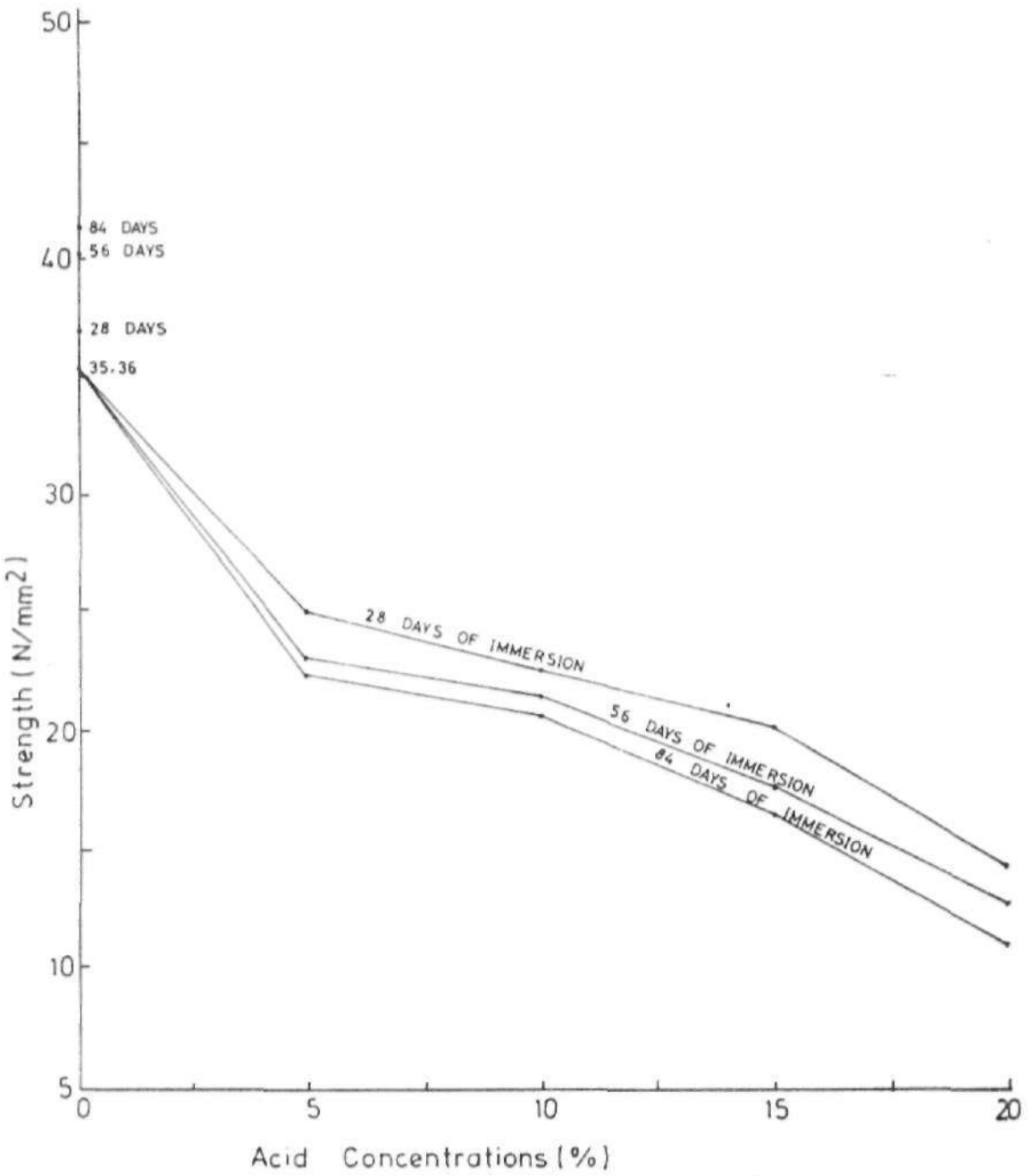


FIG. 7 GRADE 30 CONCRETE IN HNO_3

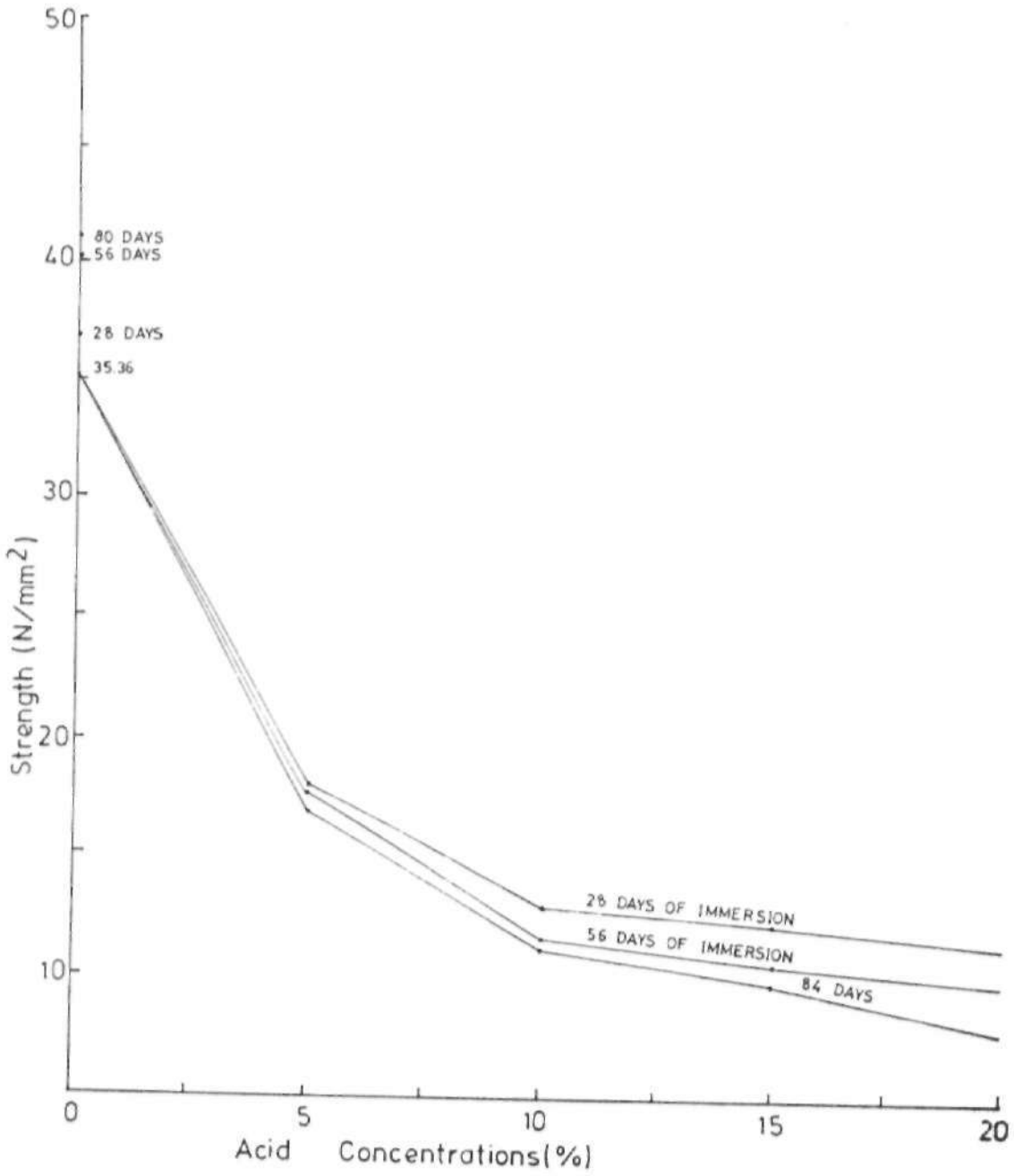


FIG.8 GRADE 30 CONCRETE IN H_2SO_4

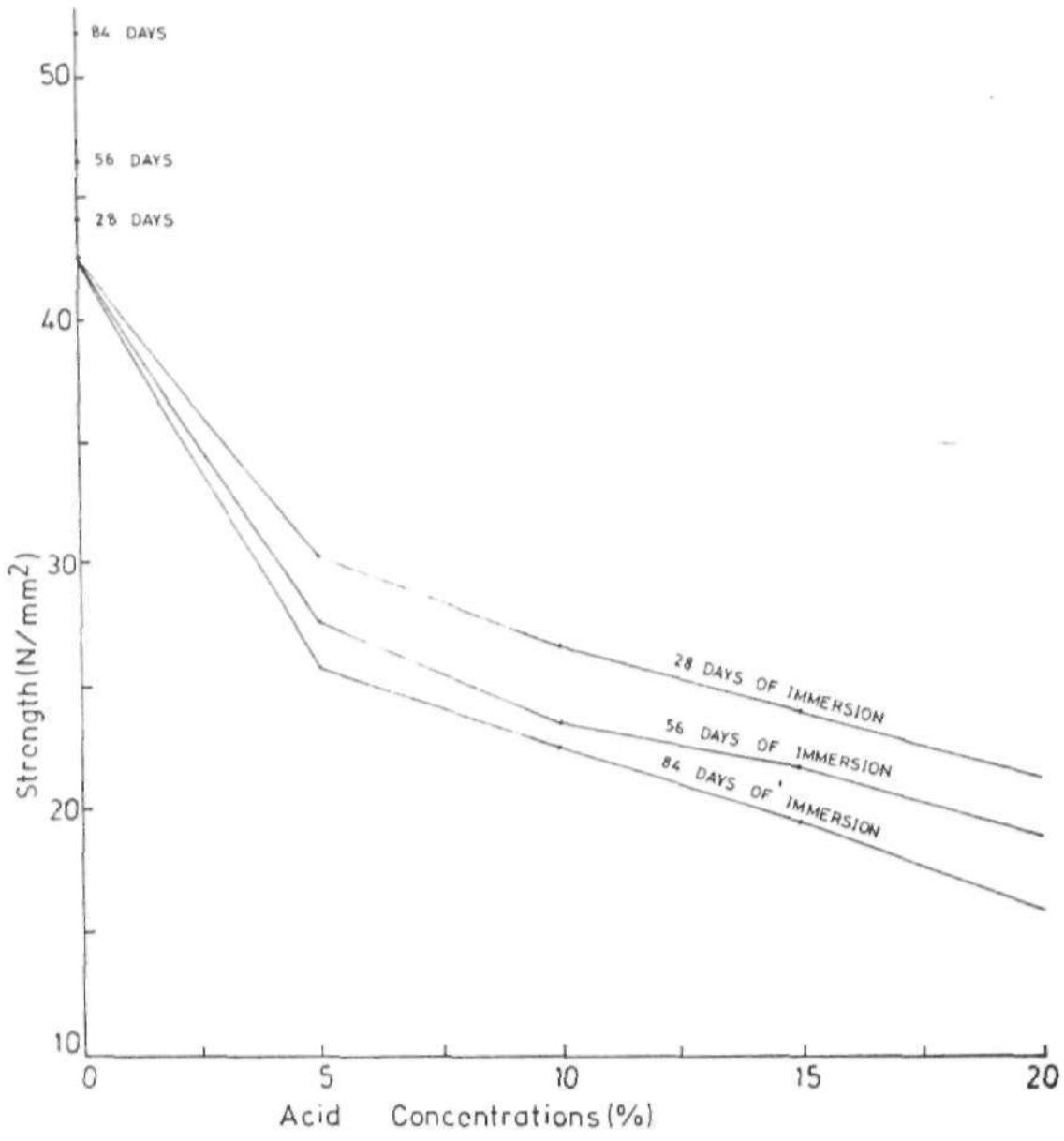


FIG.9 GRADE 40 CONCRETE IN HCL

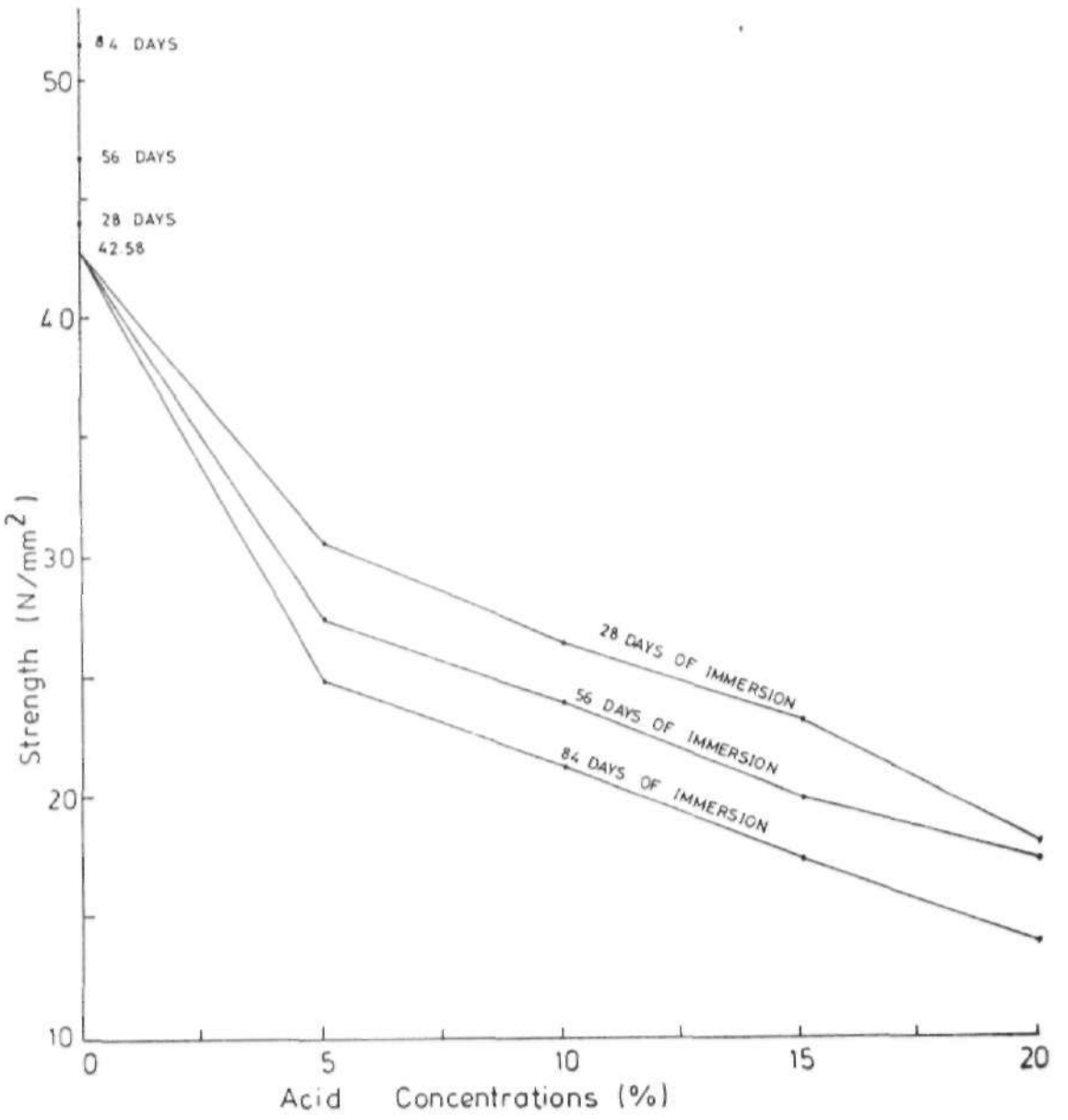


FIG. 10 GRADE 40 CONCRETE IN HNO_3

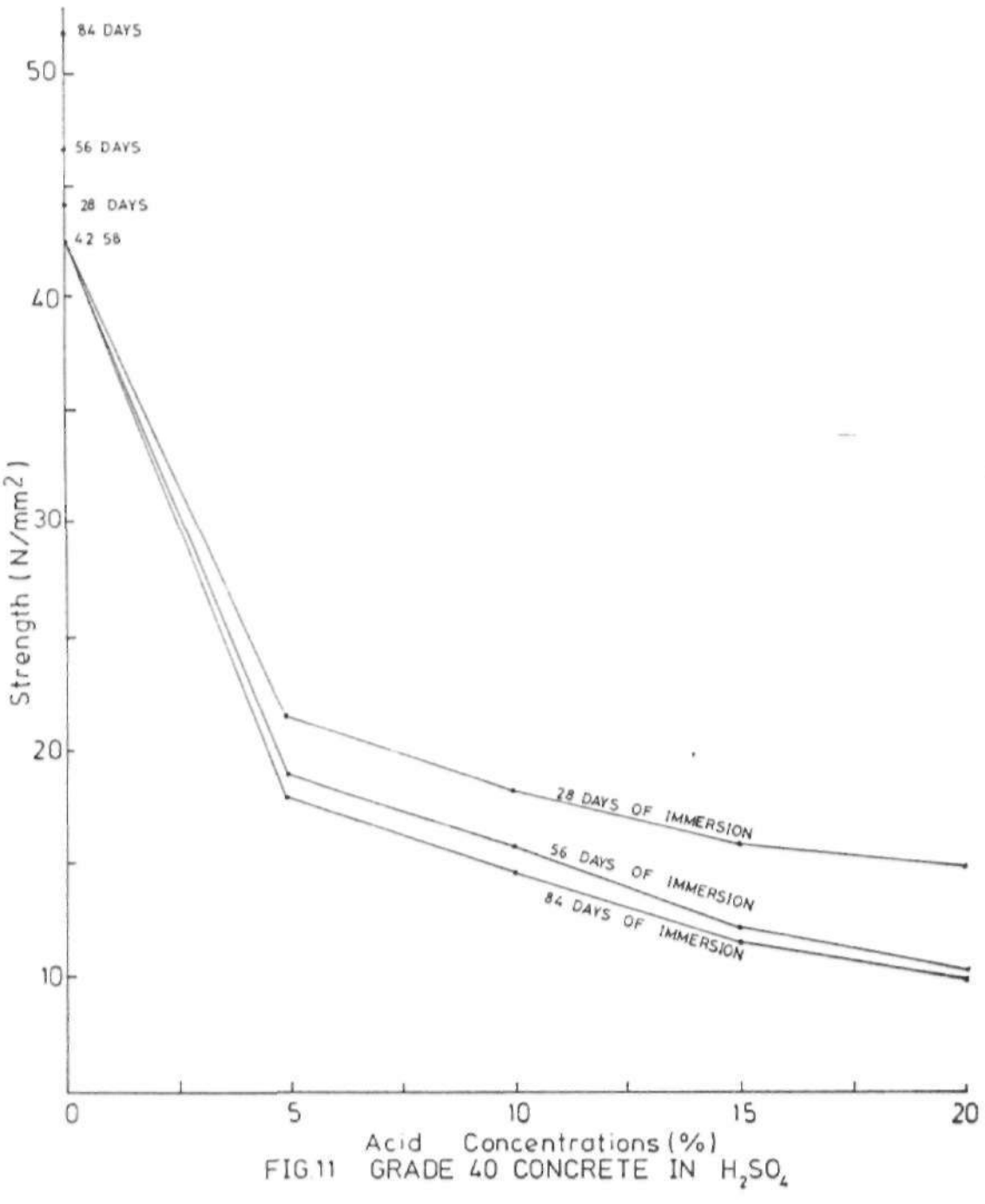


FIG 11 GRADE 40 CONCRETE IN H_2SO_4

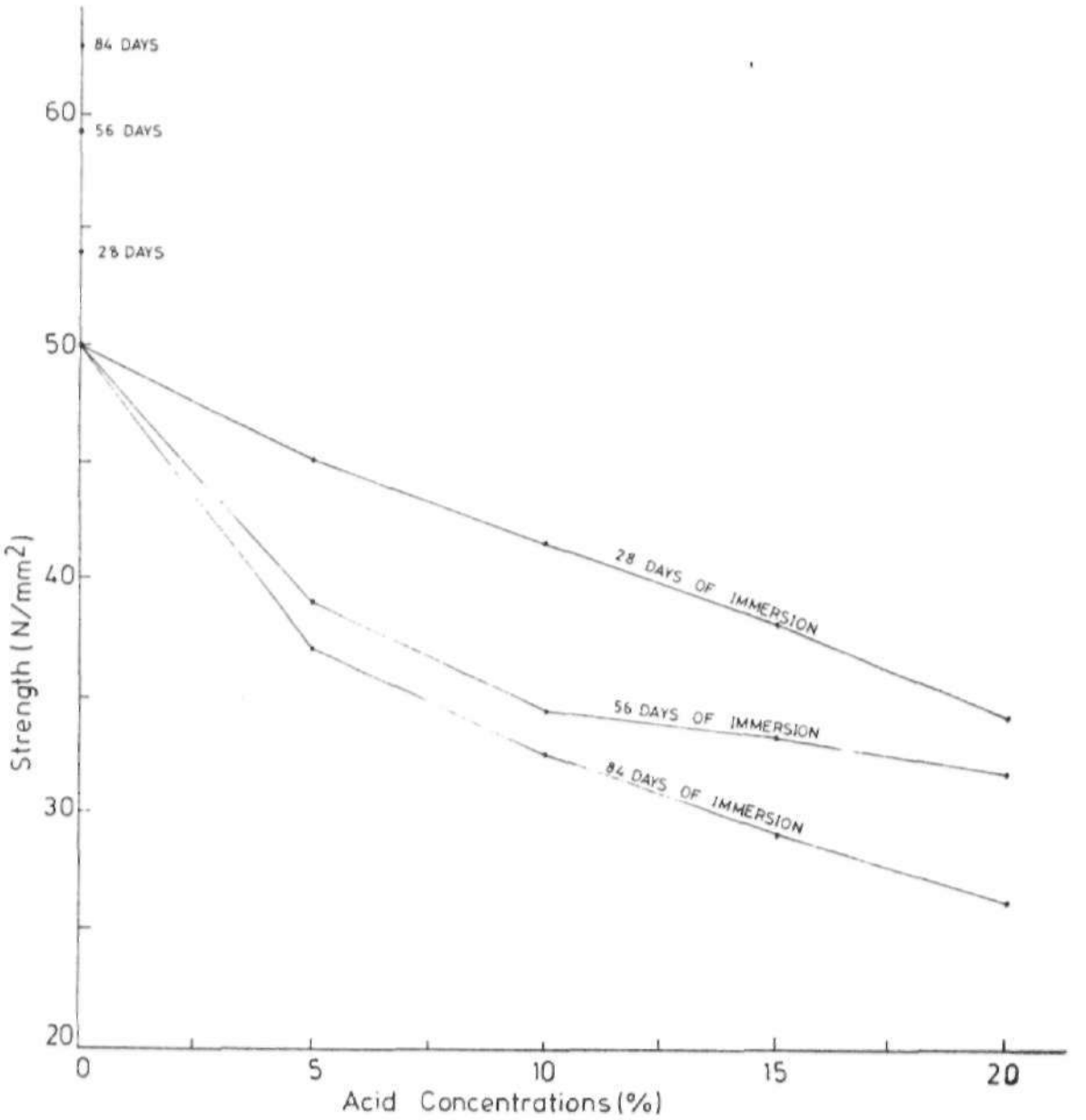


FIG.12 GRADE 50 CONCRETE IN HCL

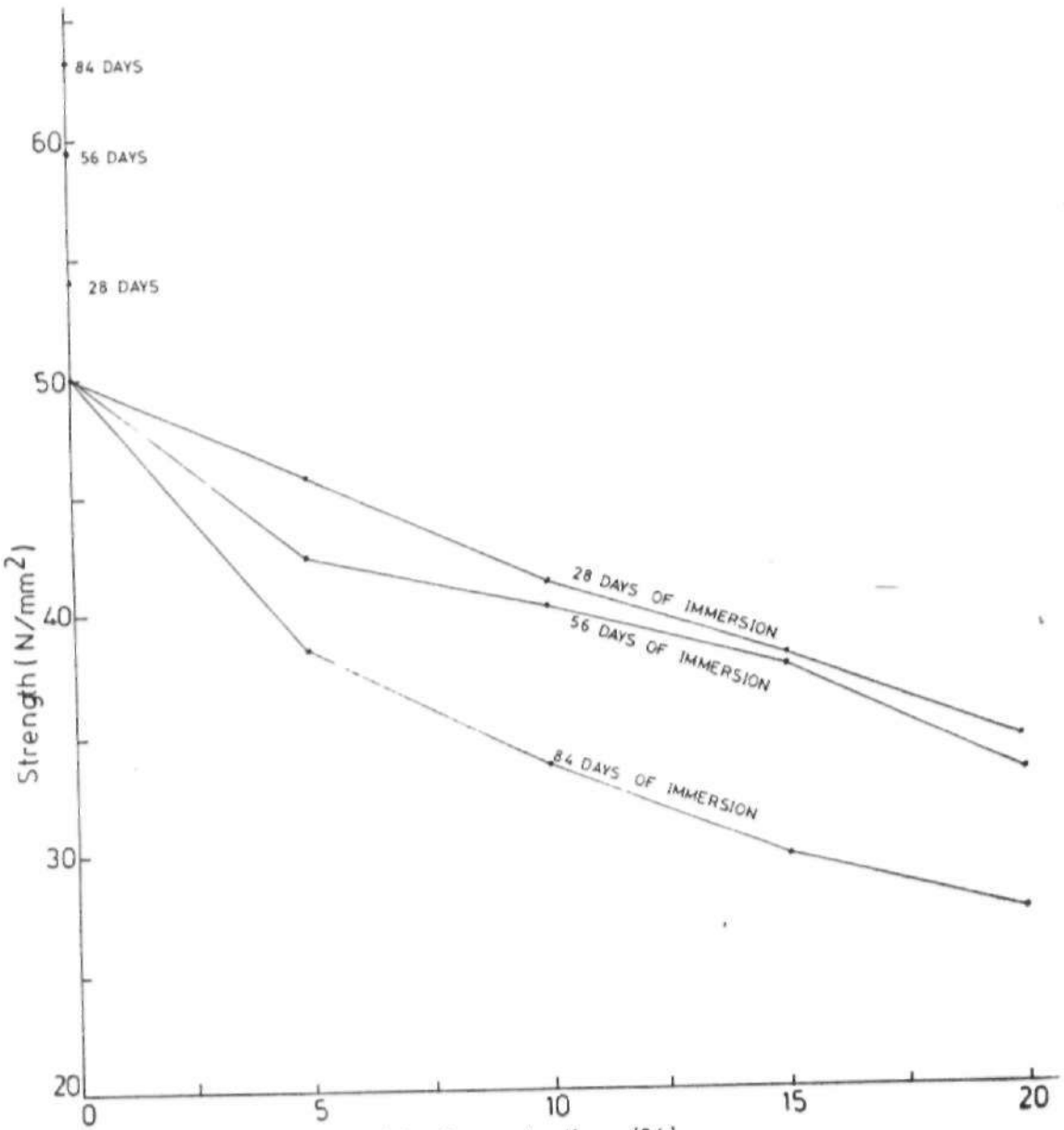


FIG.13 GRADE 50 CONCRETE IN HNO_3

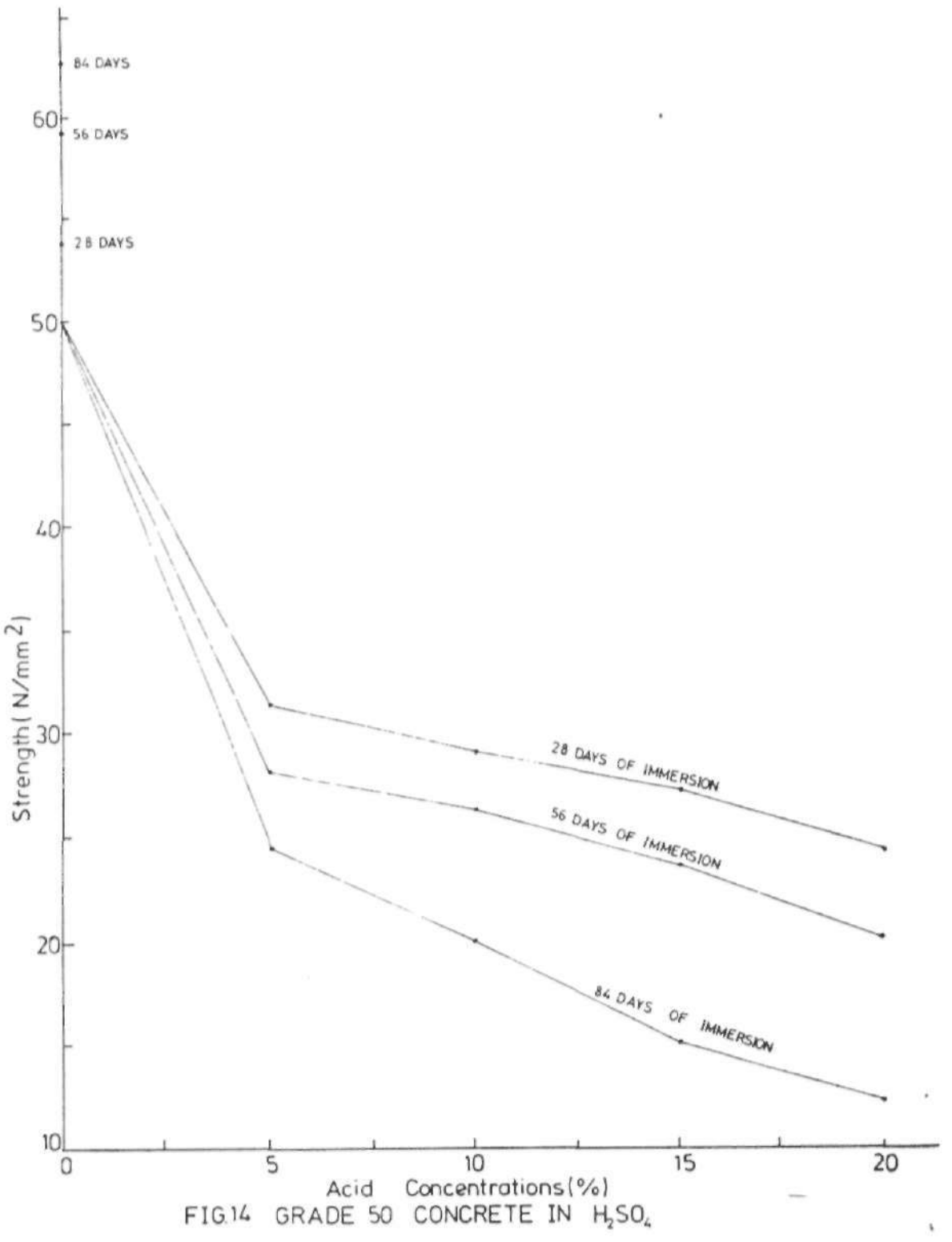


FIG.14 GRADE 50 CONCRETE IN H_2SO_4

41693

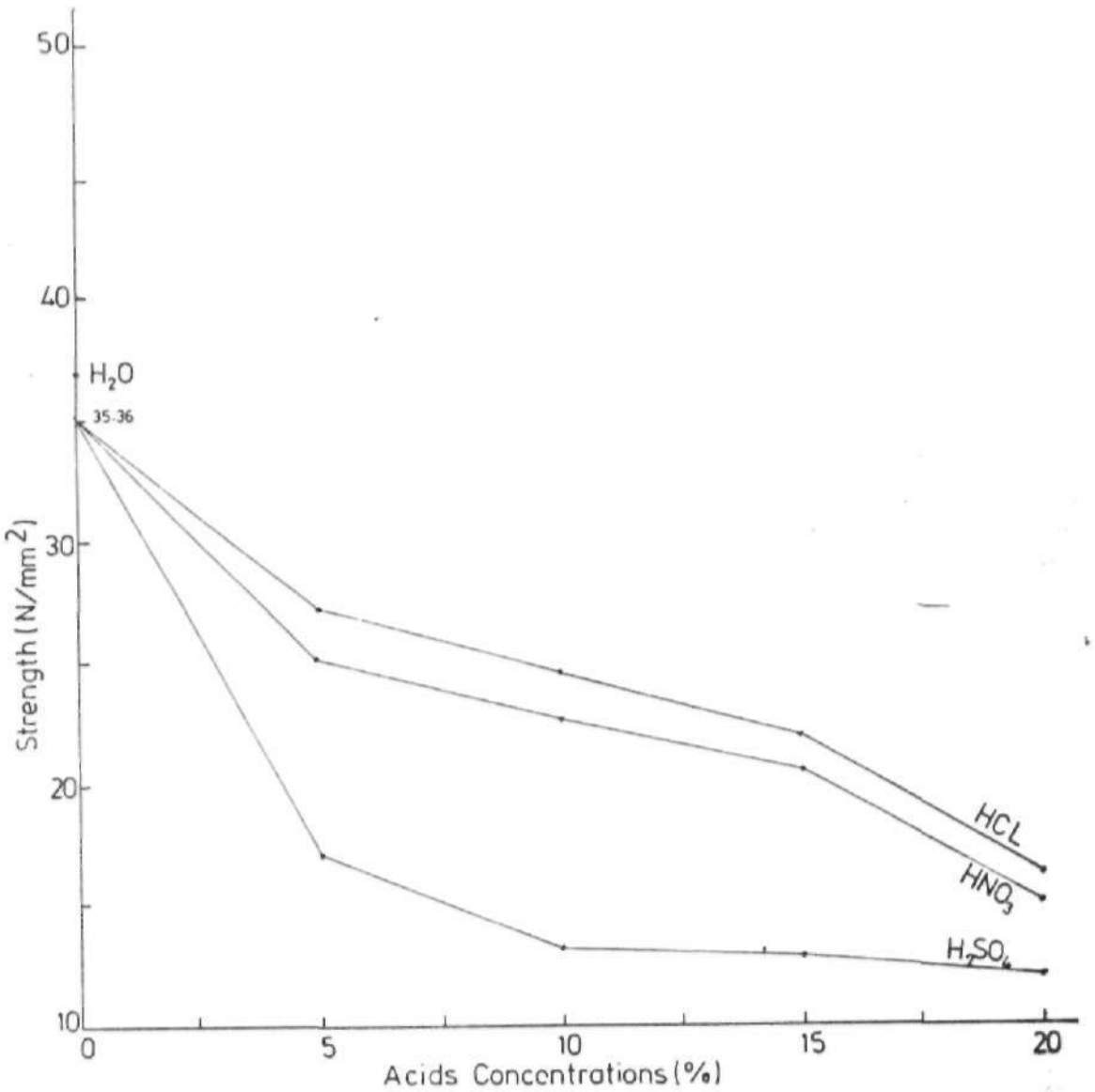


FIG.15 GRADE 30 CONCRETE AT 28 DAYS OF IMMERSION

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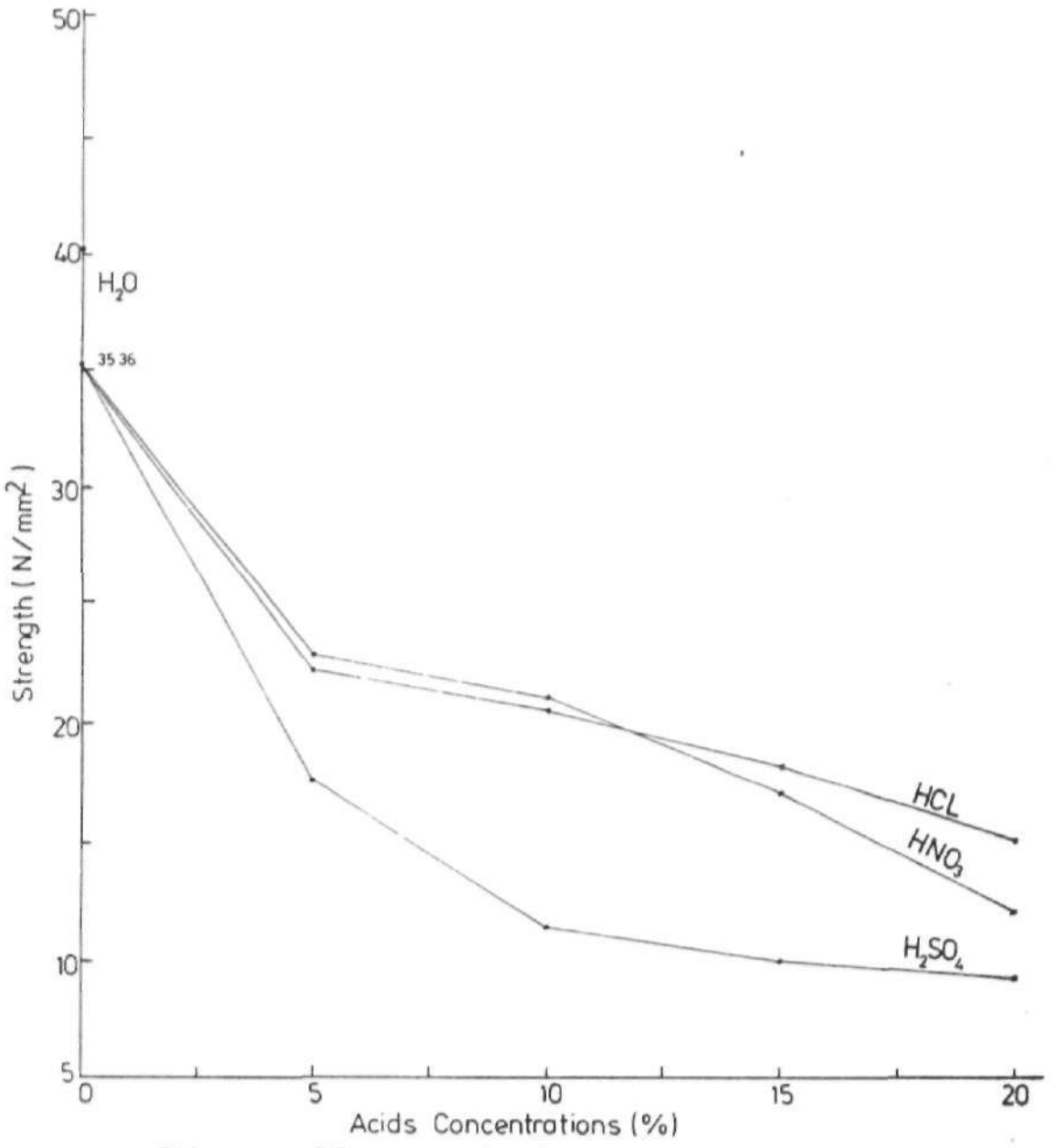


FIG 16 GRADE 30 CONCRETE AT 56 DAYS OF IMMERSION

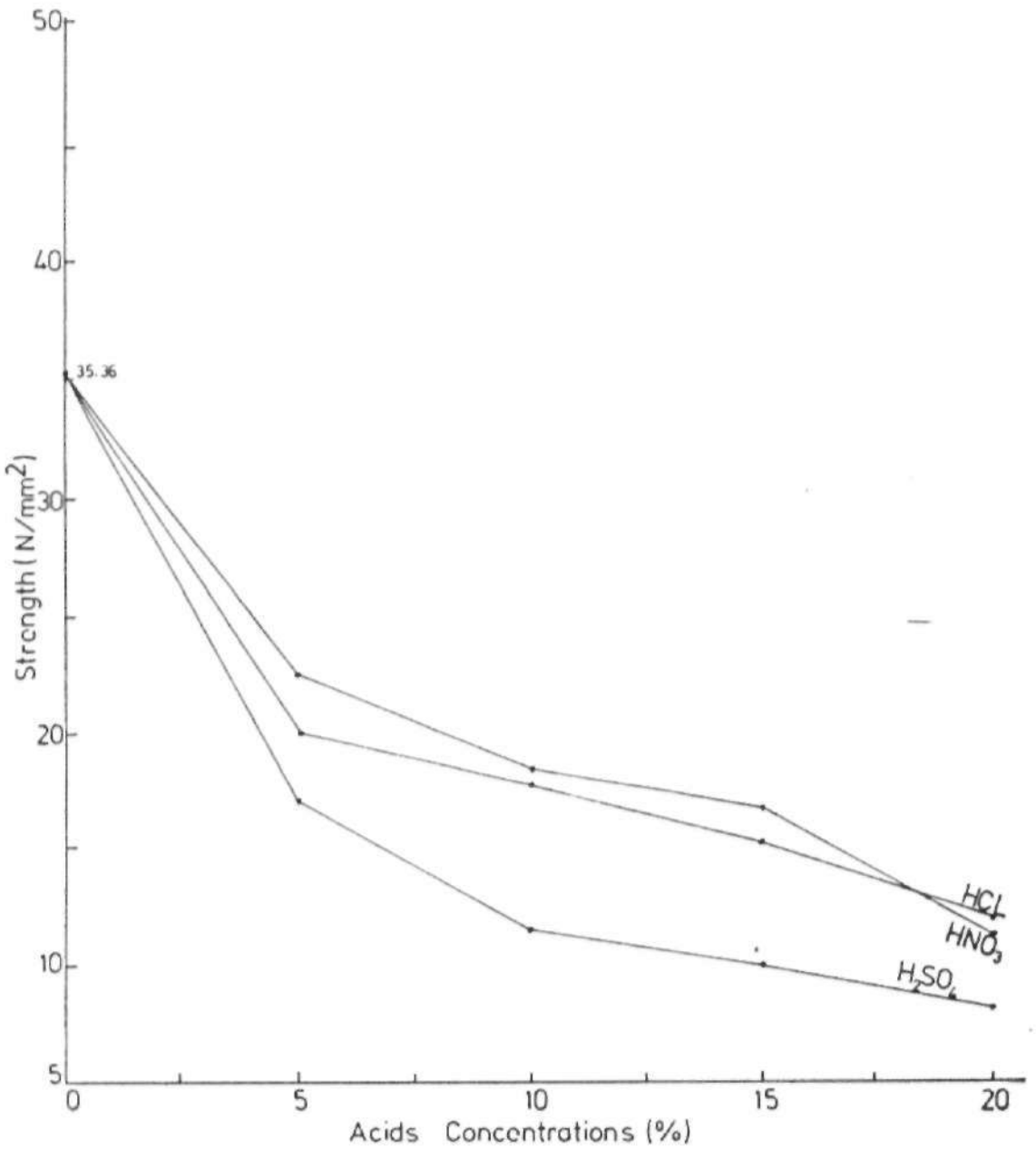


FIG. 17 GRADE 30 CONCRETE AT 84 DAYS OF IMMERSION

103

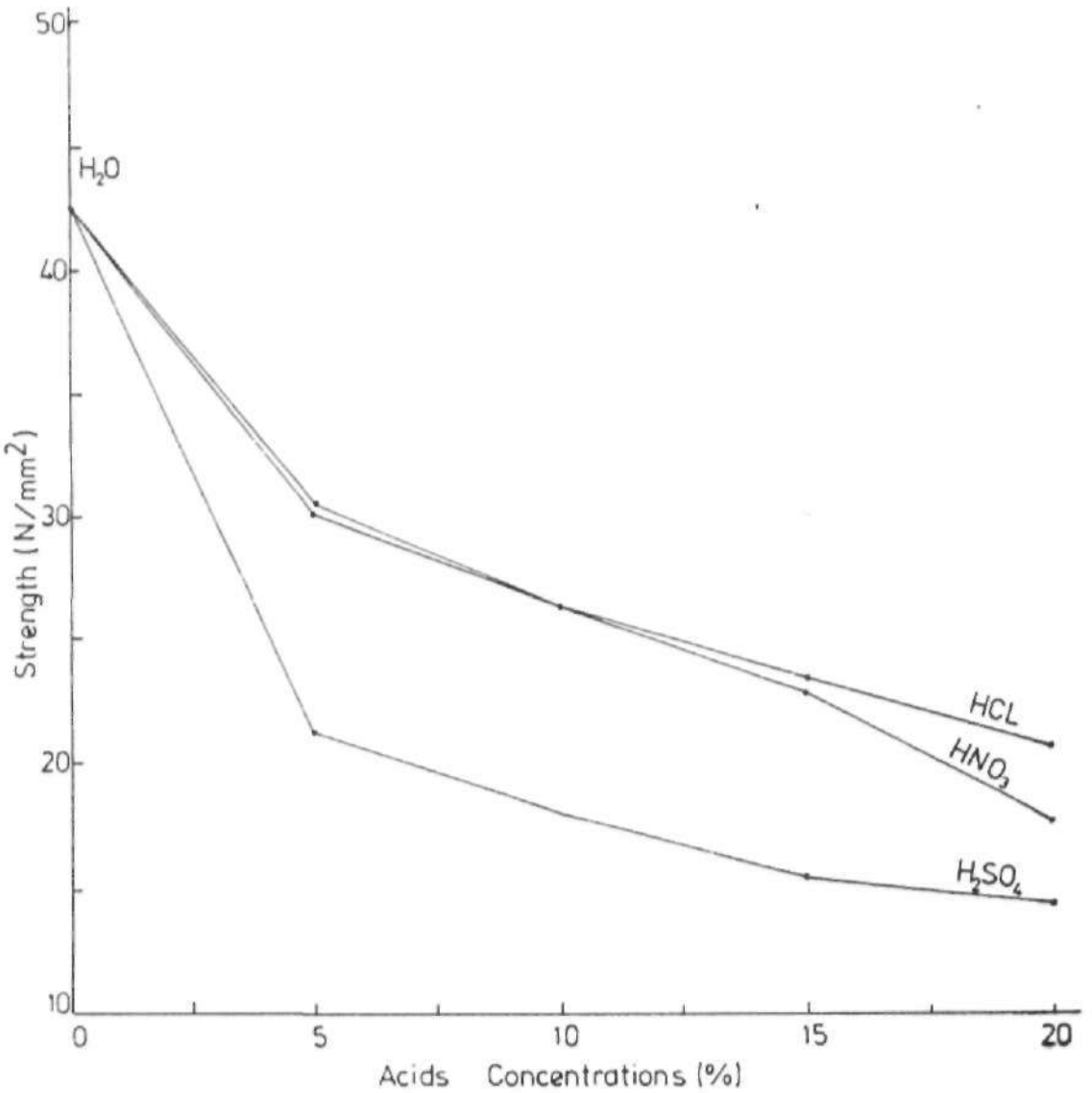


FIG 18 GRADE 40 CONCRETE AT 28 DAYS OF IMMERSION.

104

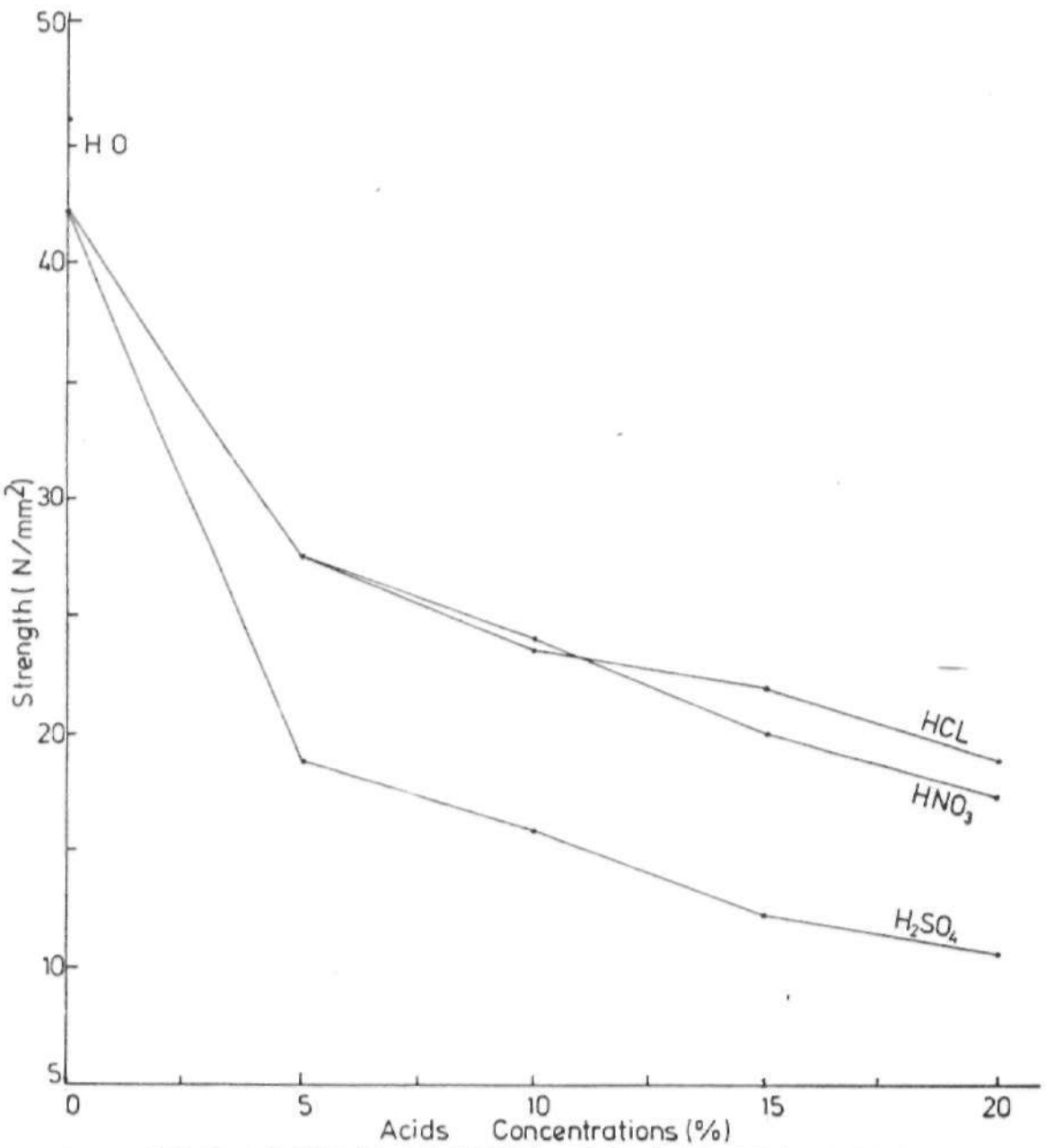


FIG.19 GRADE 40 CONCRETE AT 56 DAYS OF IMMERSION

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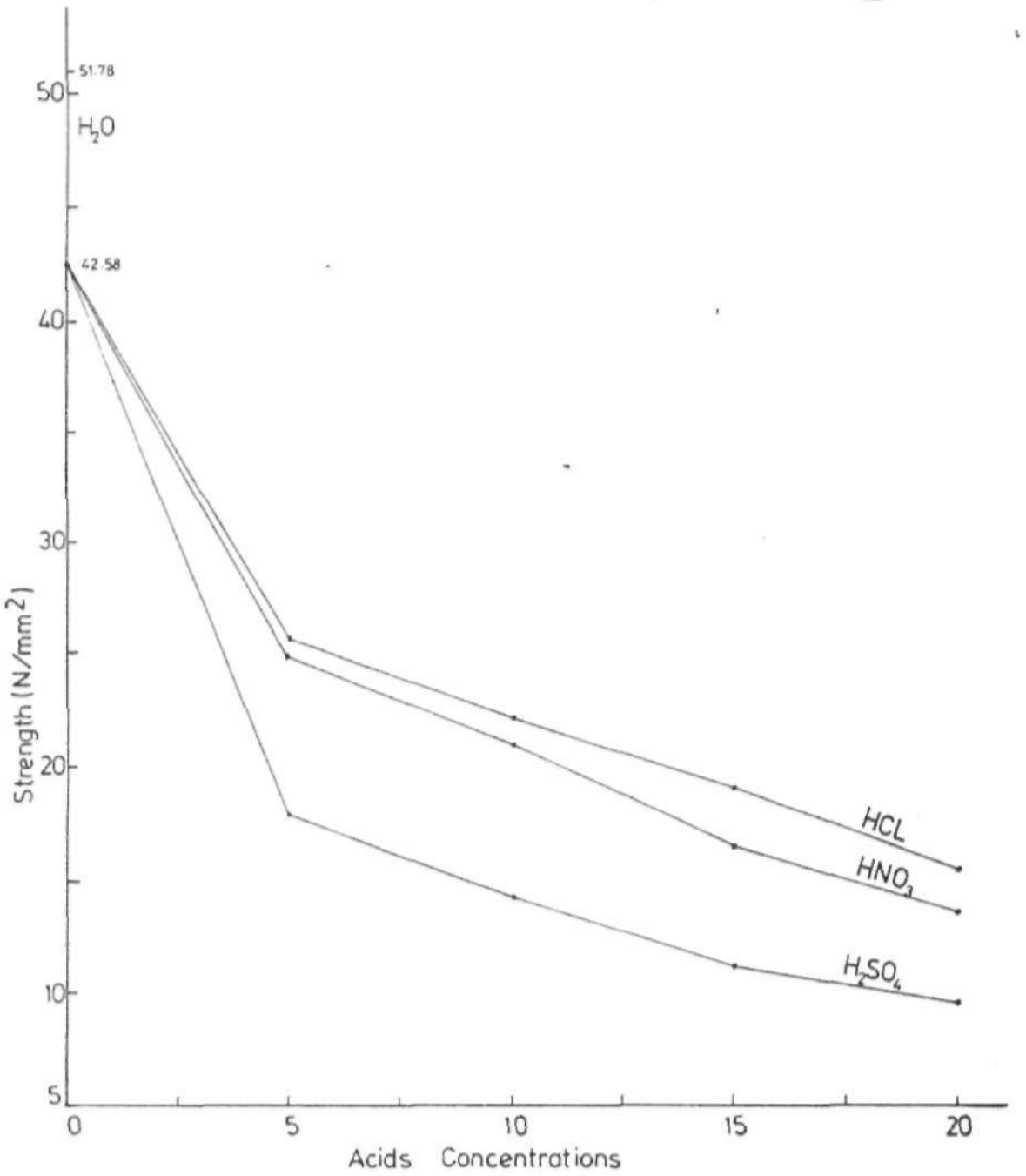


FIG. 20 GRADE 40 CONCRETE AT 84 DAYS IMMERSION

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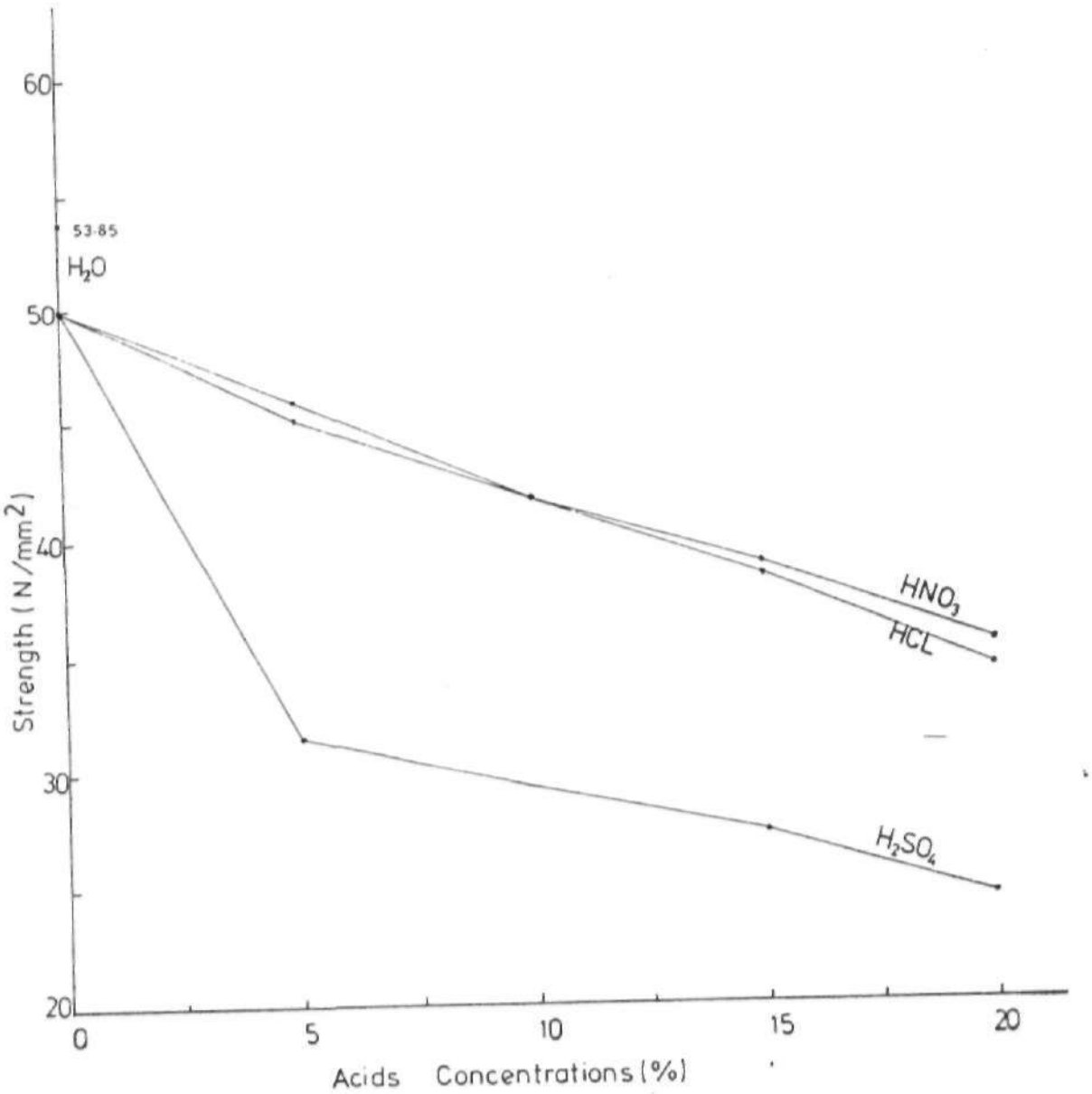


FIG. 21 GRADE 50 CONCRETE AT 28 DAYS OF IMMERSION

107

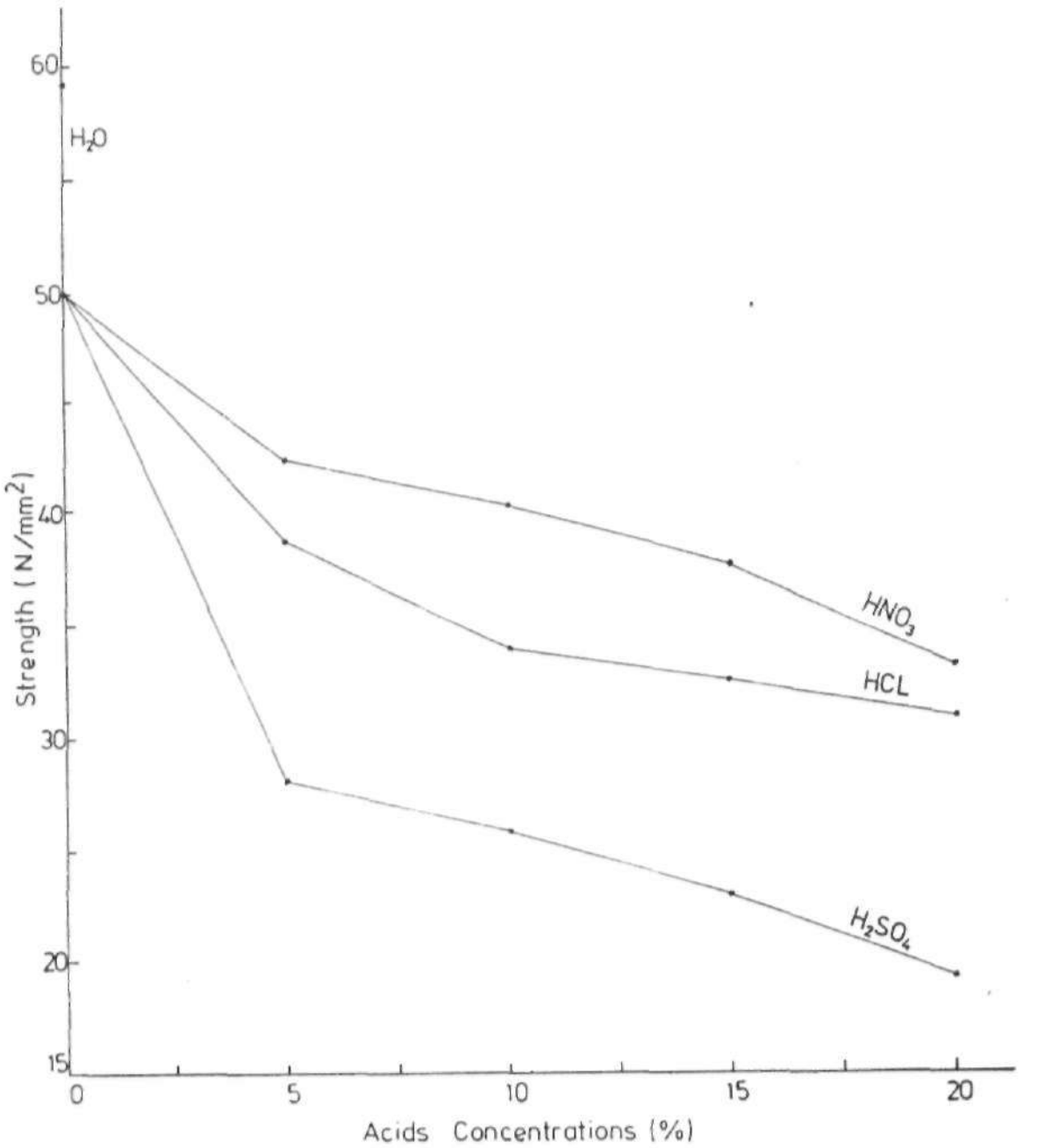


FIG 22 GRADE 50 CONCRETE AT 56 DAYS OF IMMERSION

108

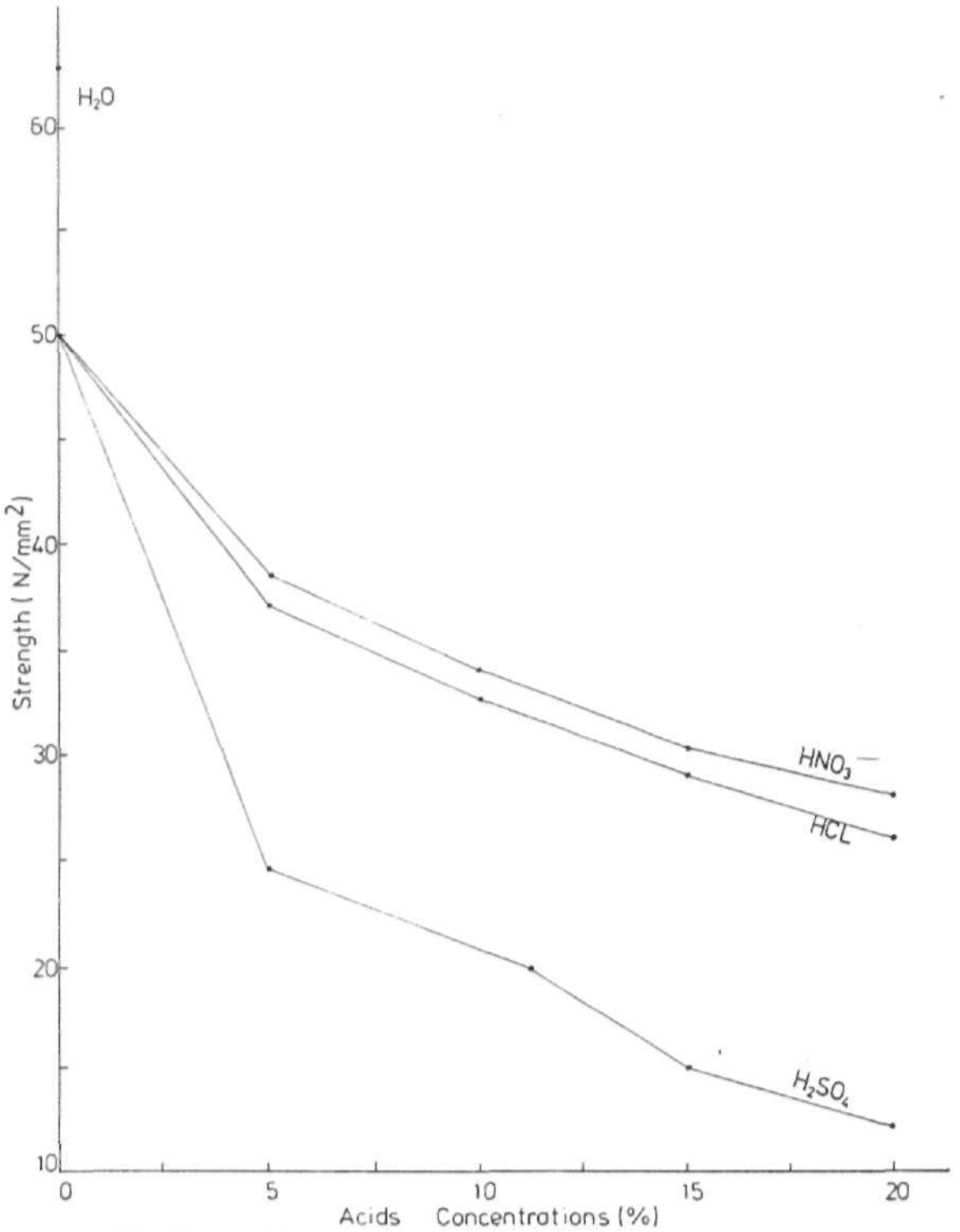


FIG. 23 GRADE 50 CONCRETE AT 84 DAYS OF IMMERSION

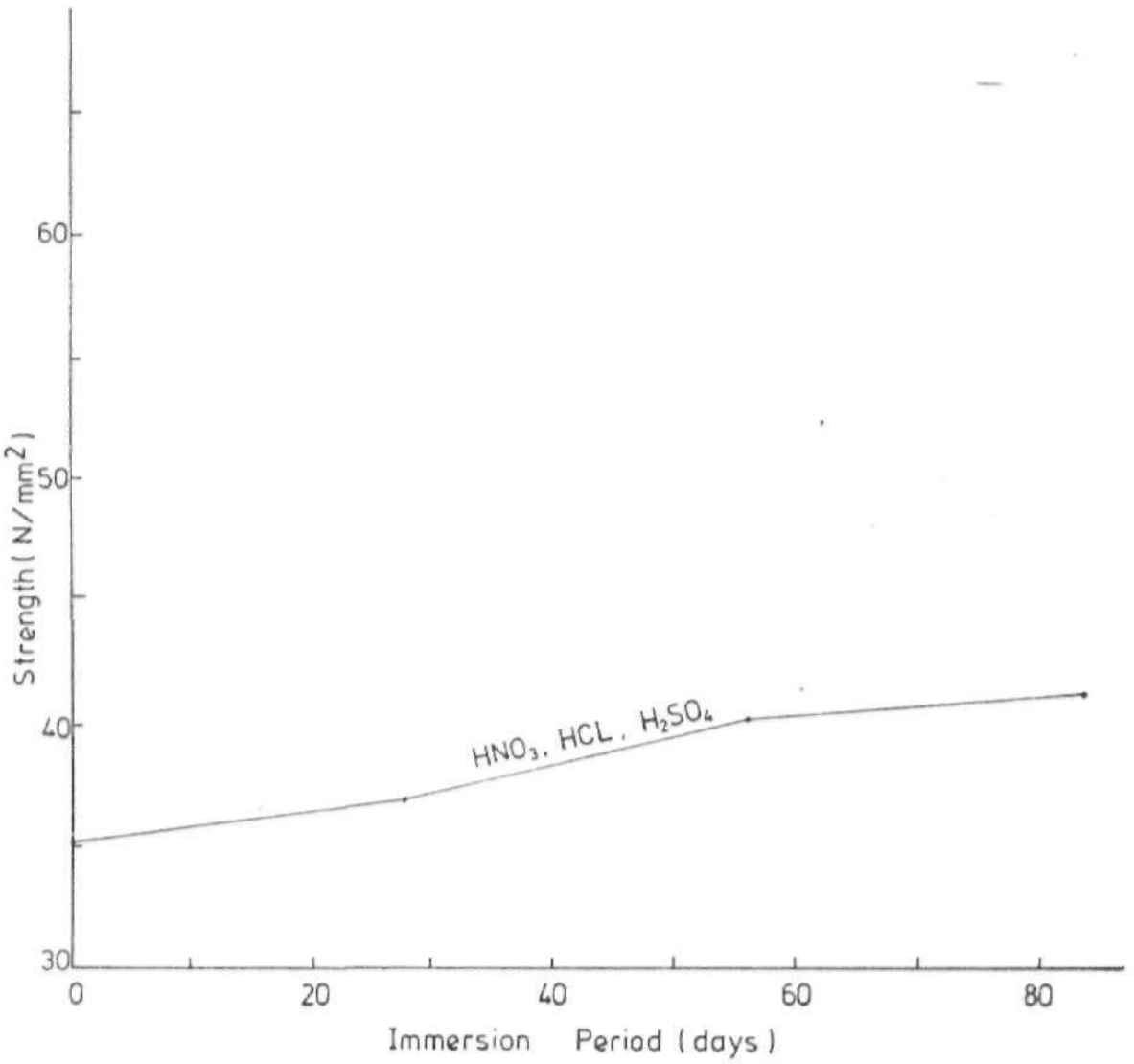


FIG 24 GRADE 30 CONCRETE; 0% CONCENTRATIONS

110

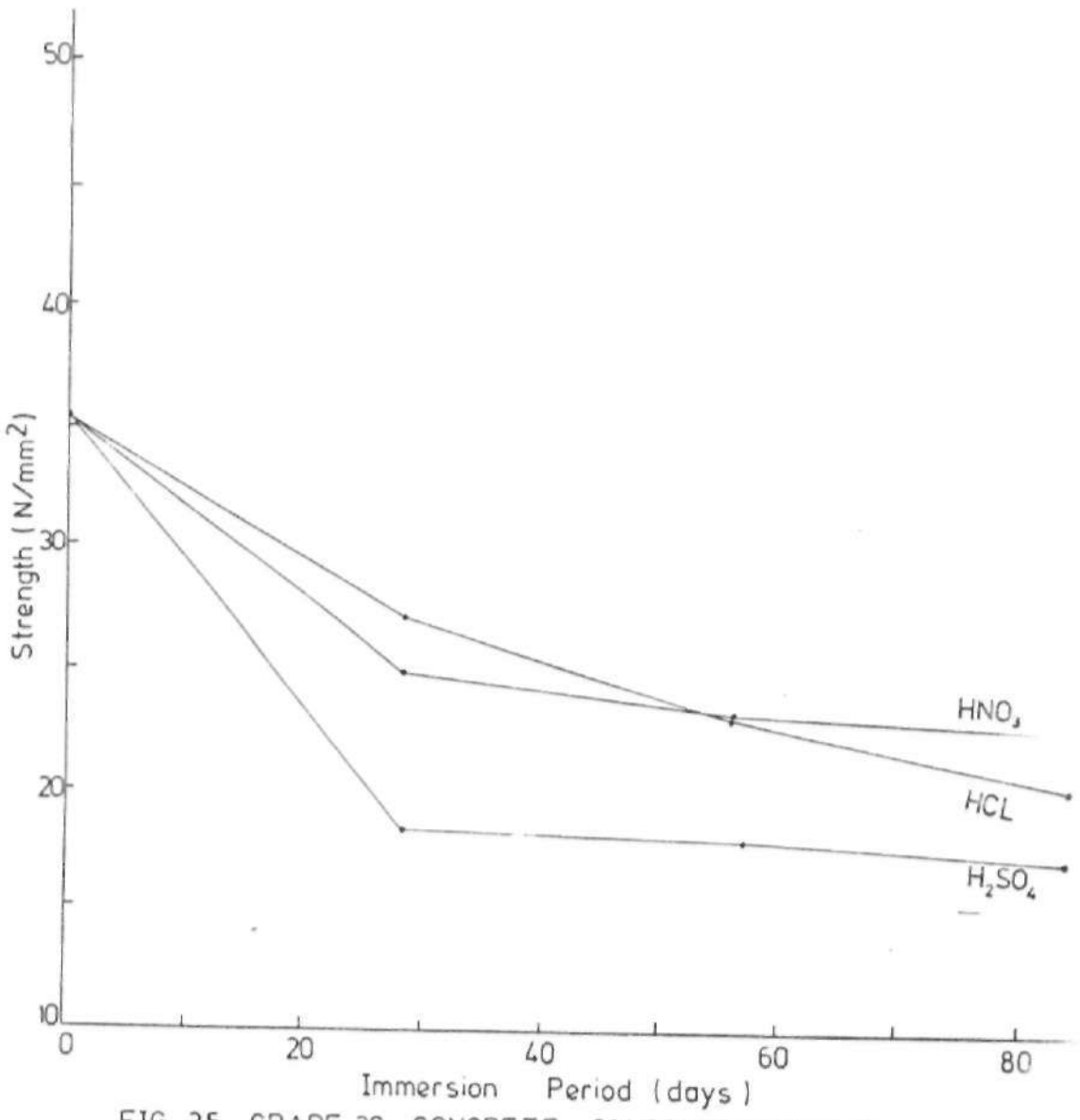


FIG. 25 GRADE 30 CONCRETE ; 5% CONCENTRATIONS

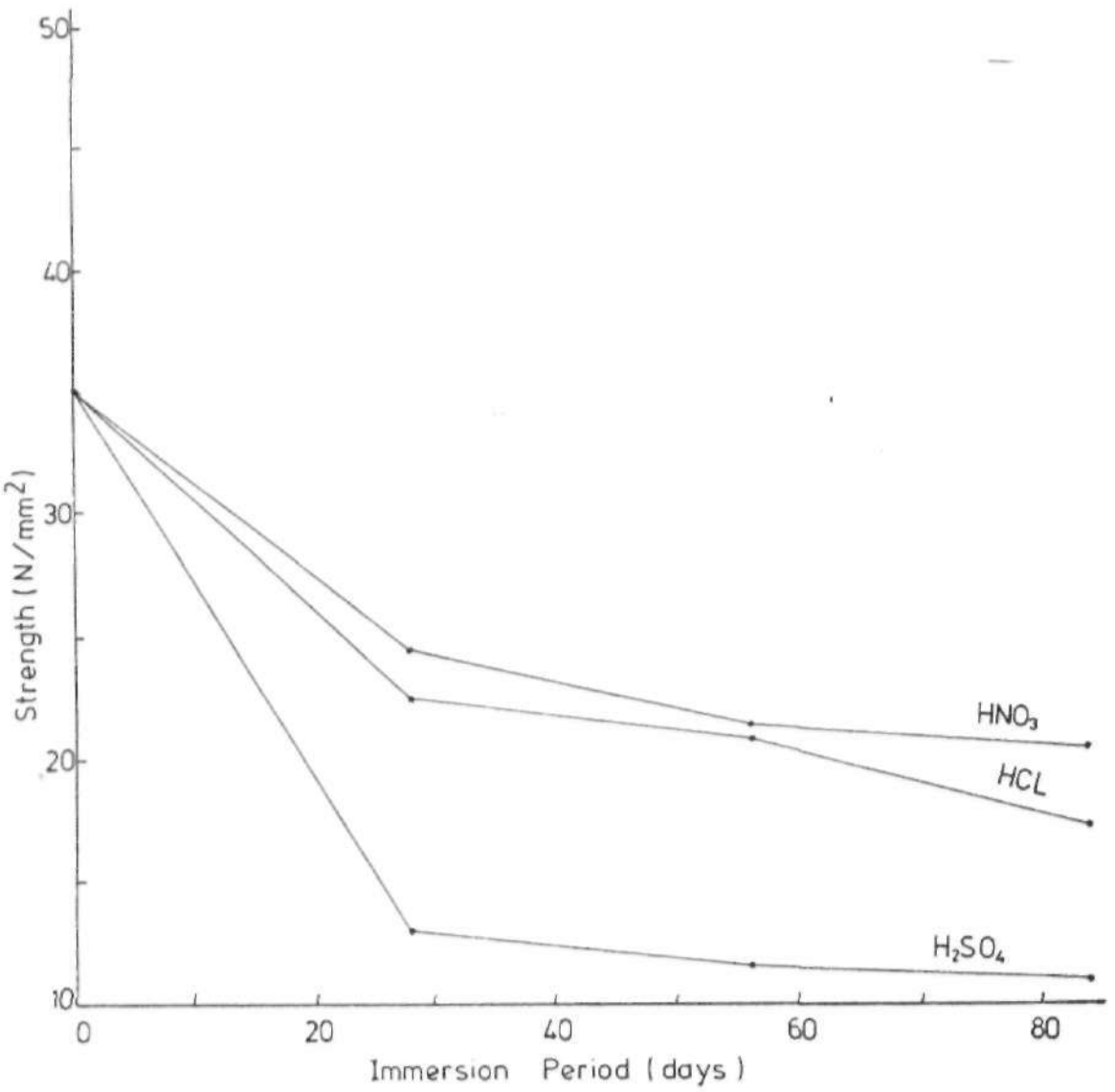


FIG. 26 GRADE 30 CONCRETE; 10% CONCENTRATIONS

112

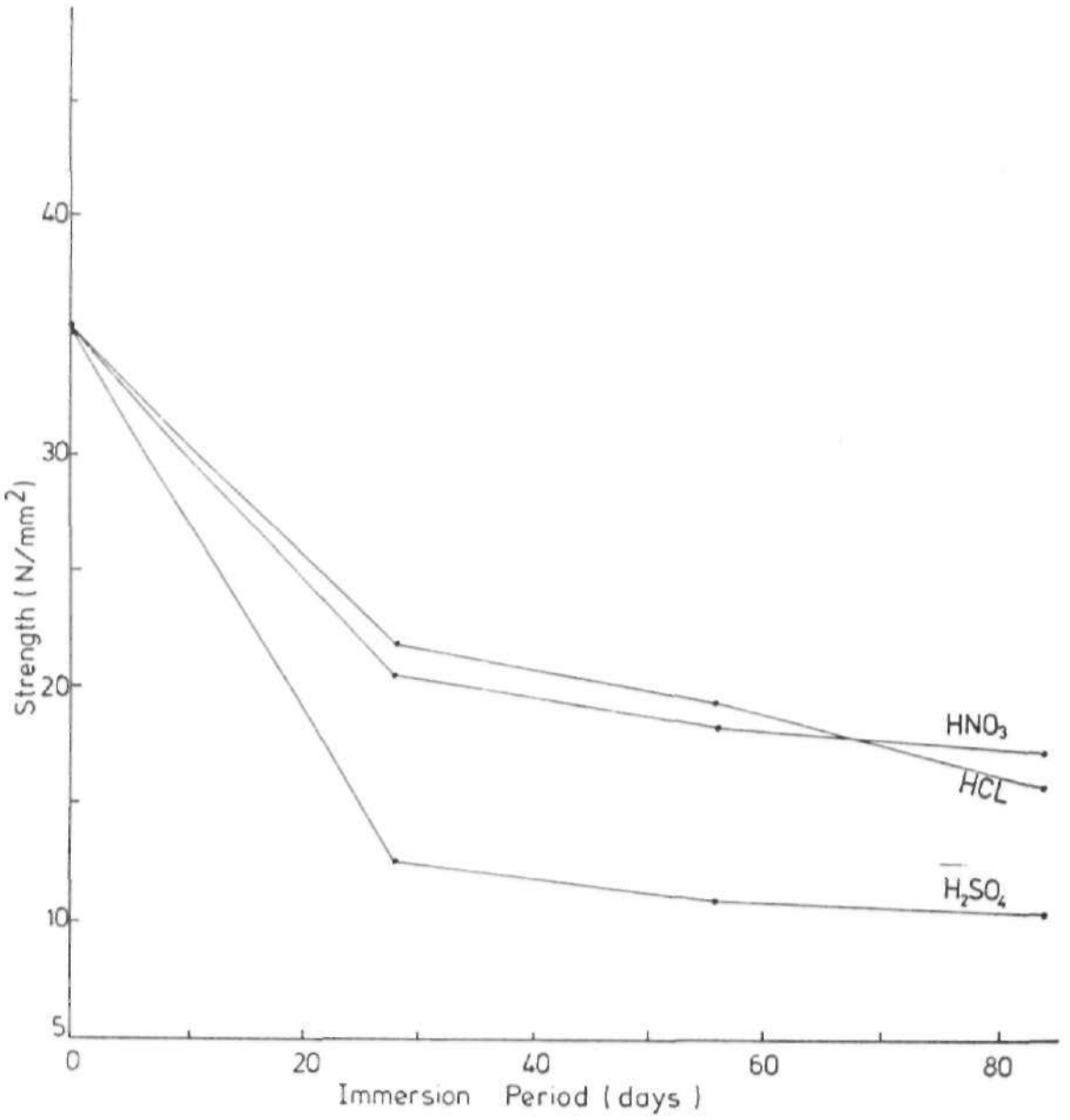


FIG 27 GRADE 30 CONCRETE; 15% CONCENTRATIONS

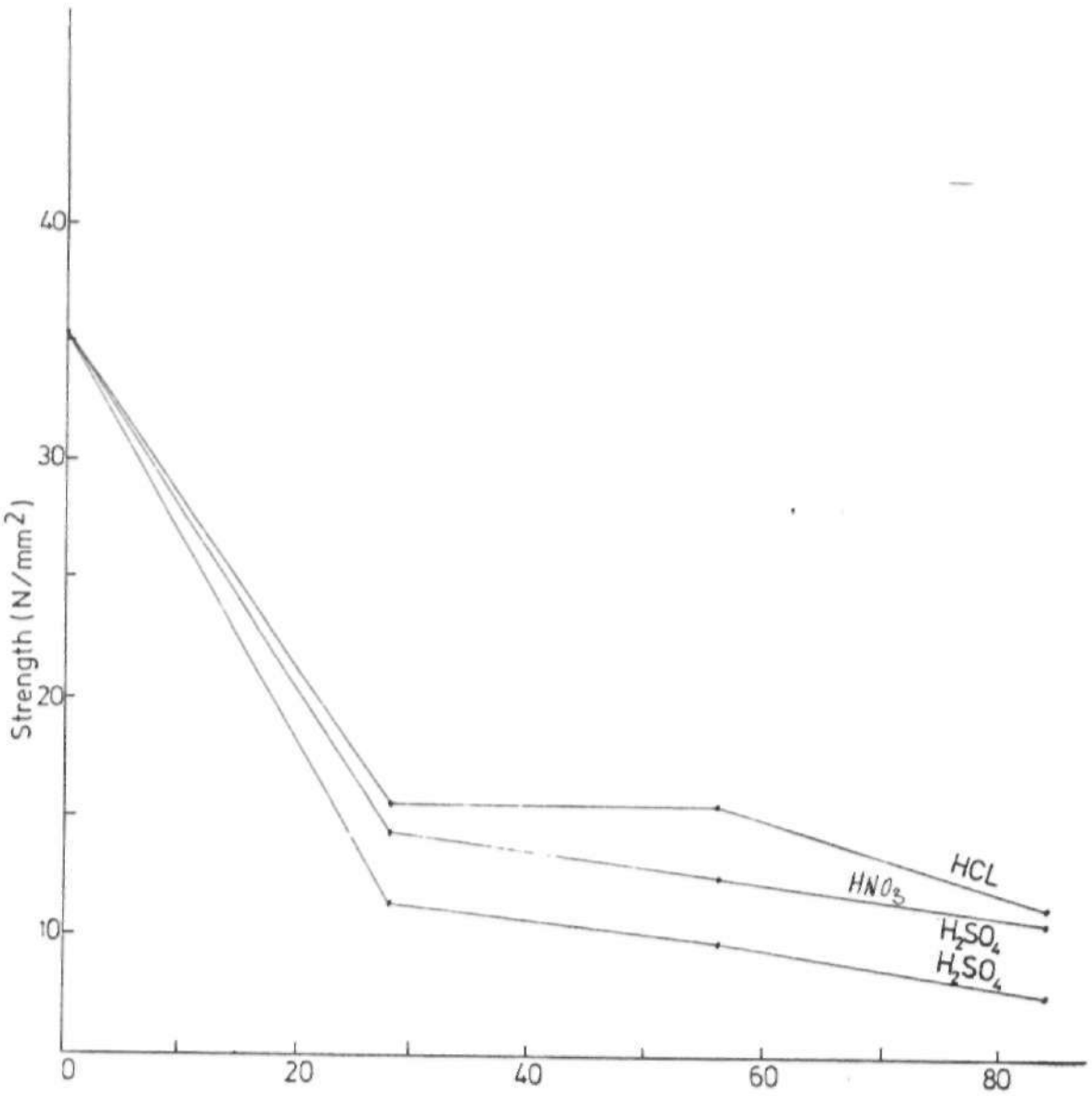


FIG. 28 GRADE 30 CONCRETE; 20% CONCENTRATIONS

114

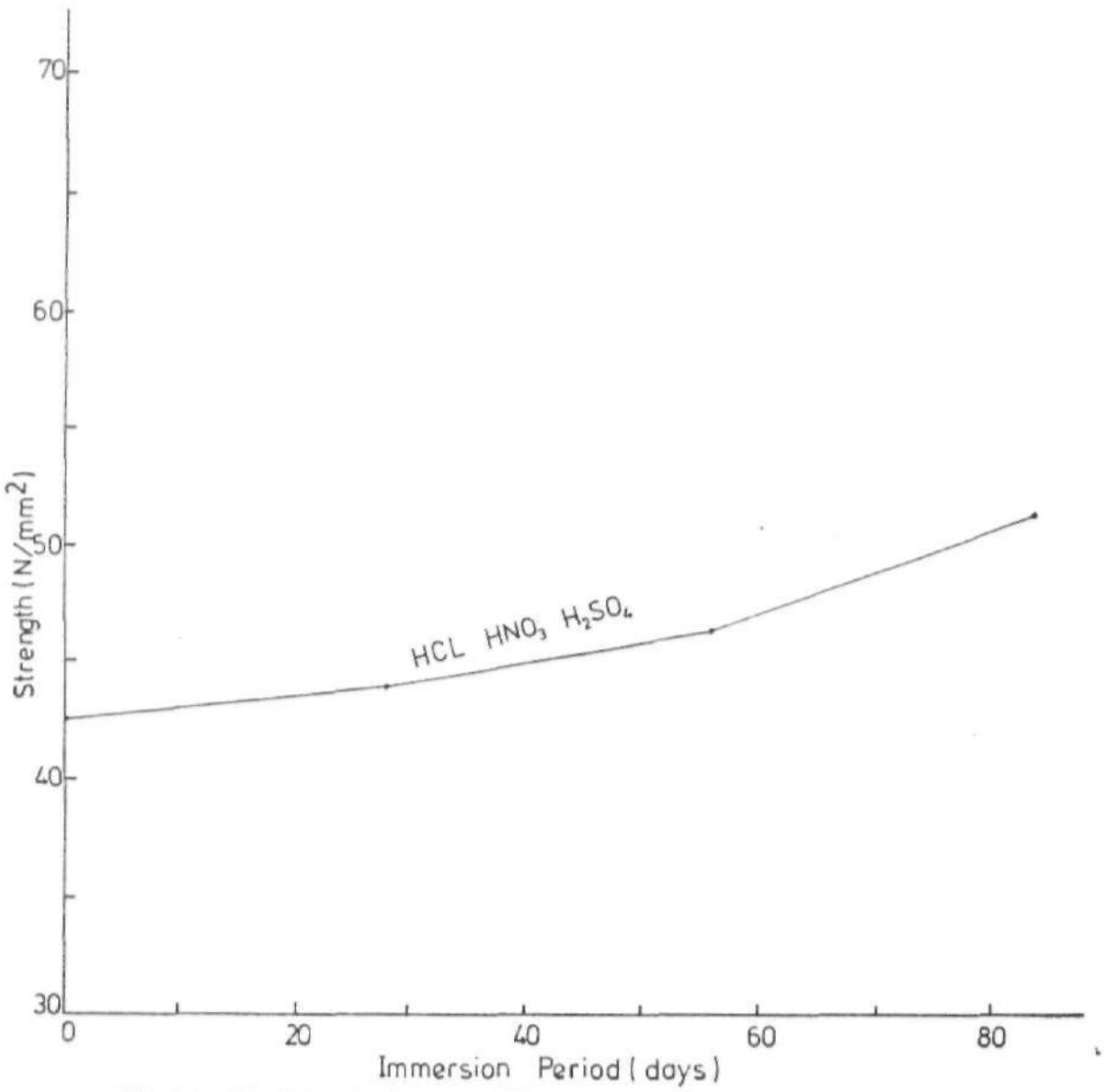


FIG. 29 GRADE 40 CONCRETE; 0% CONCENTRATIONS

115

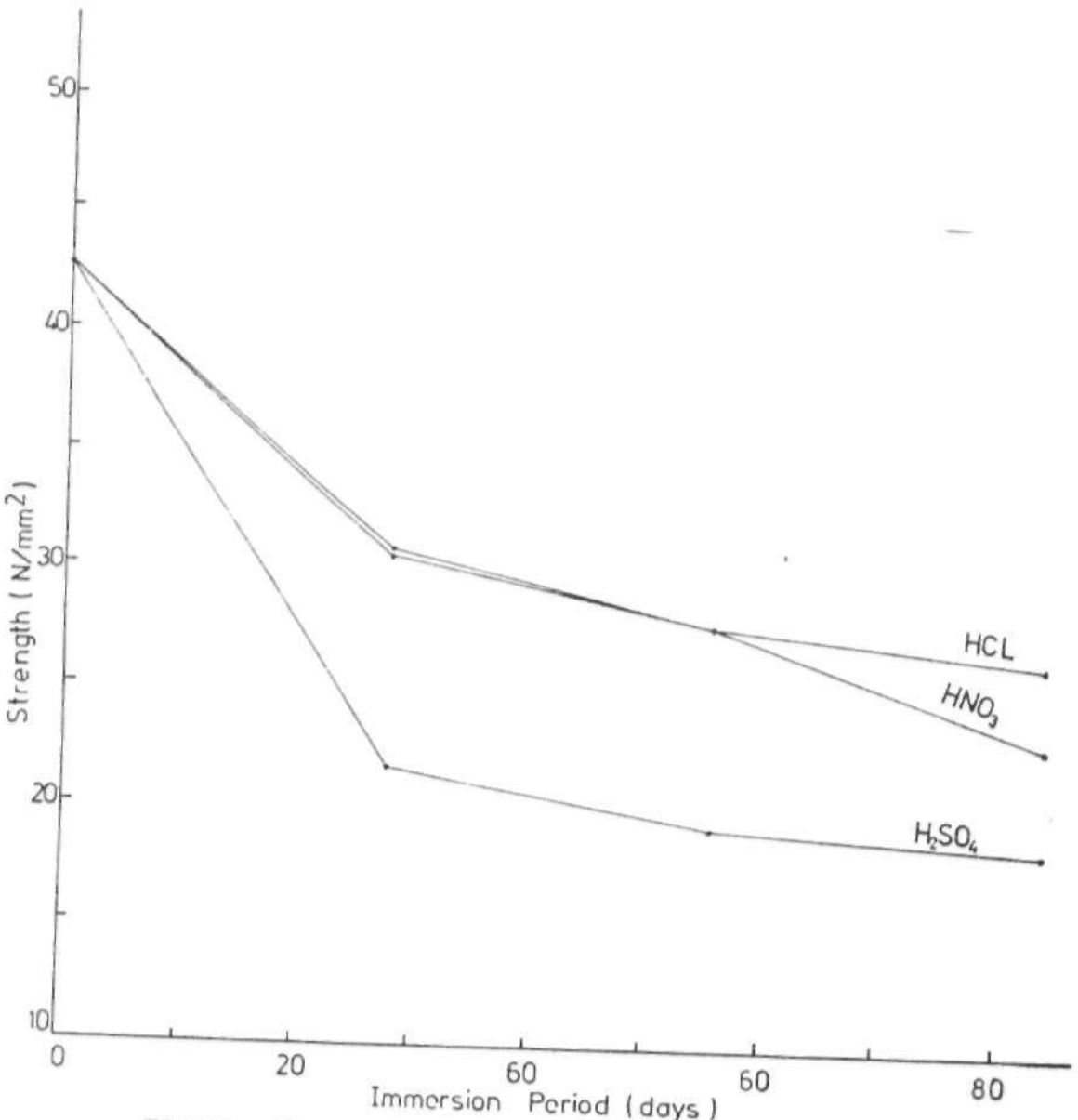


FIG. 30 GRADE 40 CONCRETE; 5% CONCENTRATIONS

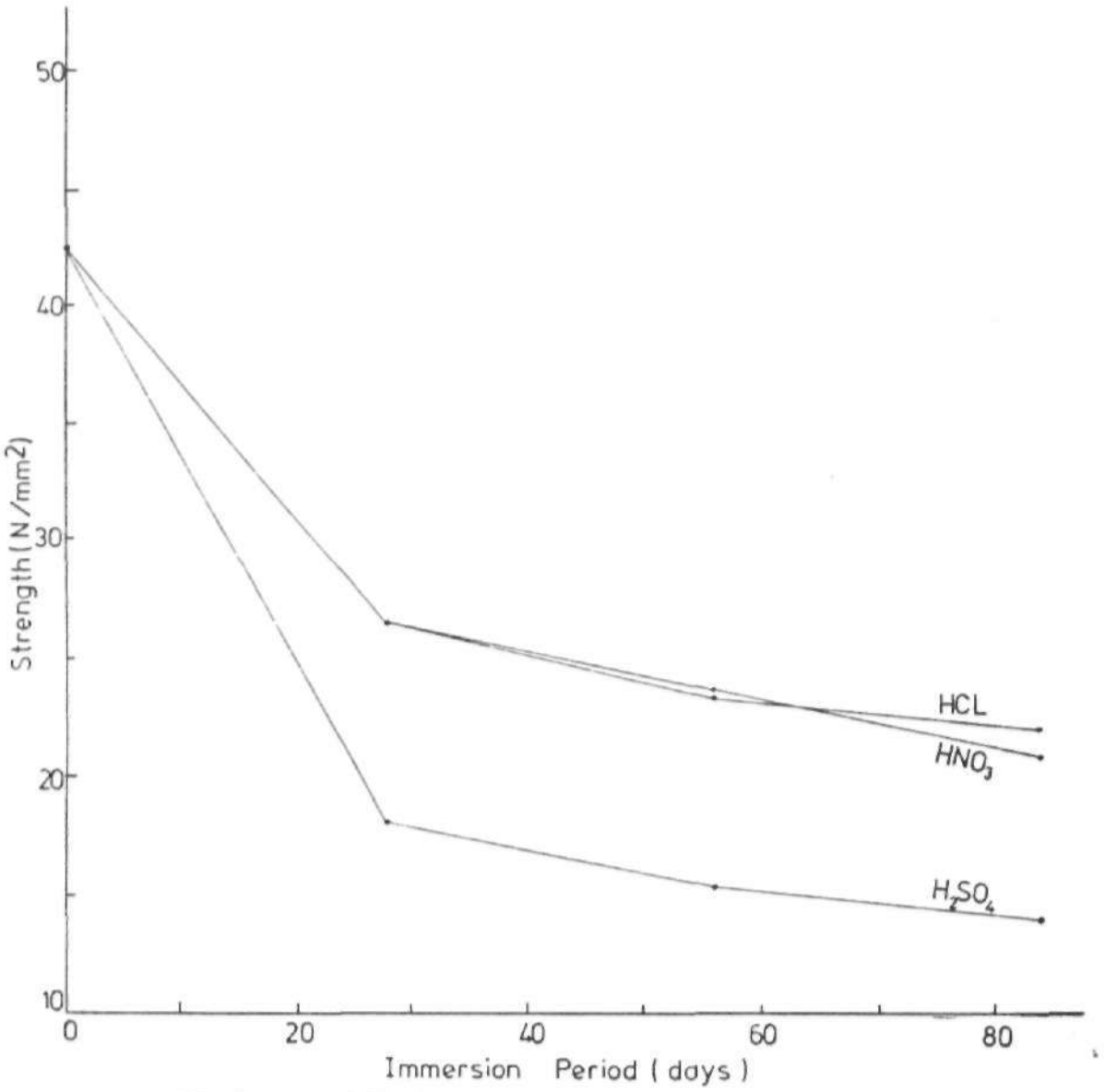


FIG. 31 GRADE 40 CONCRETE; 10% CONCENTRATIONS

117

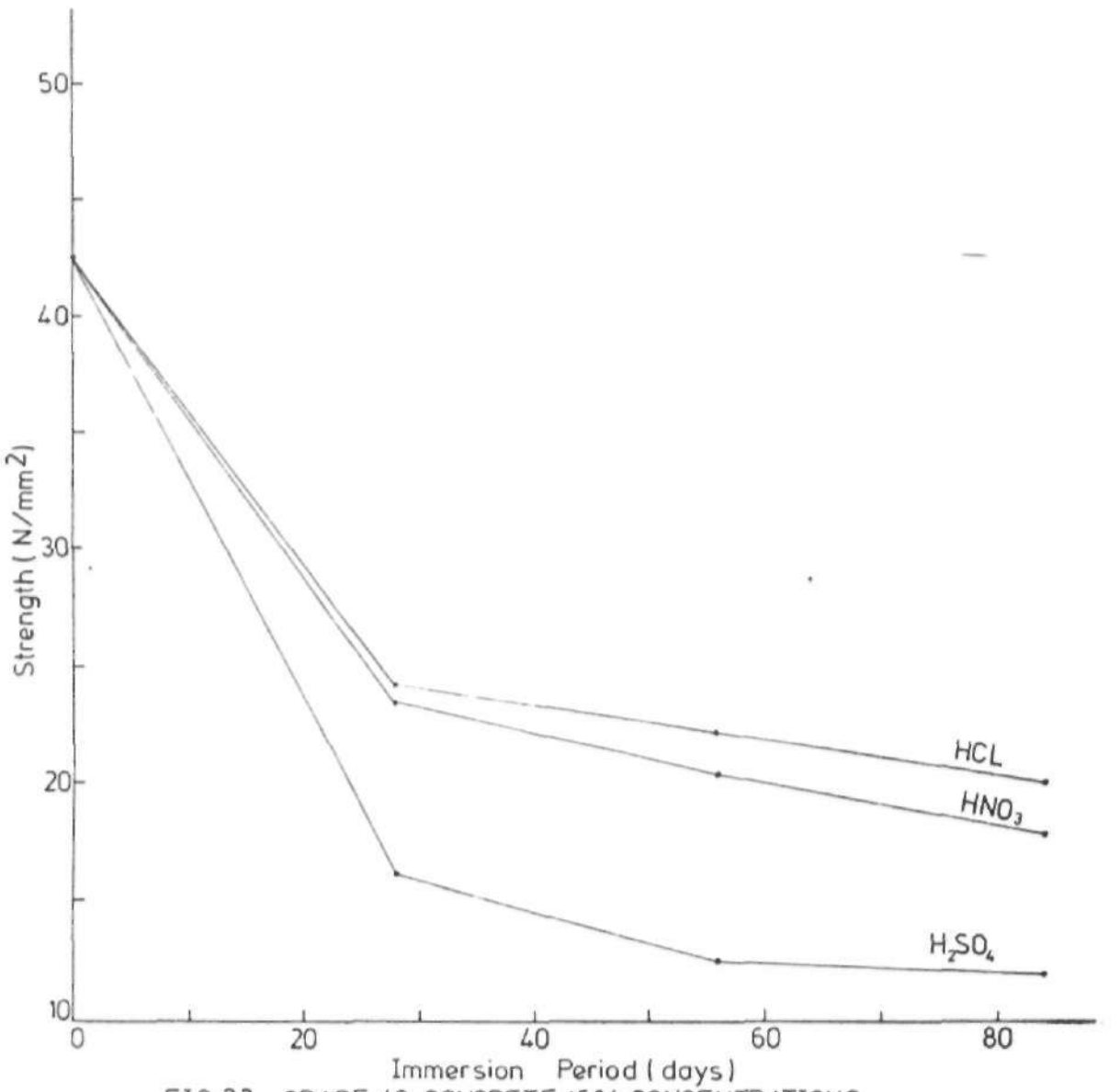


FIG.32 GRADE 40 CONCRETE; 15% CONCENTRATIONS

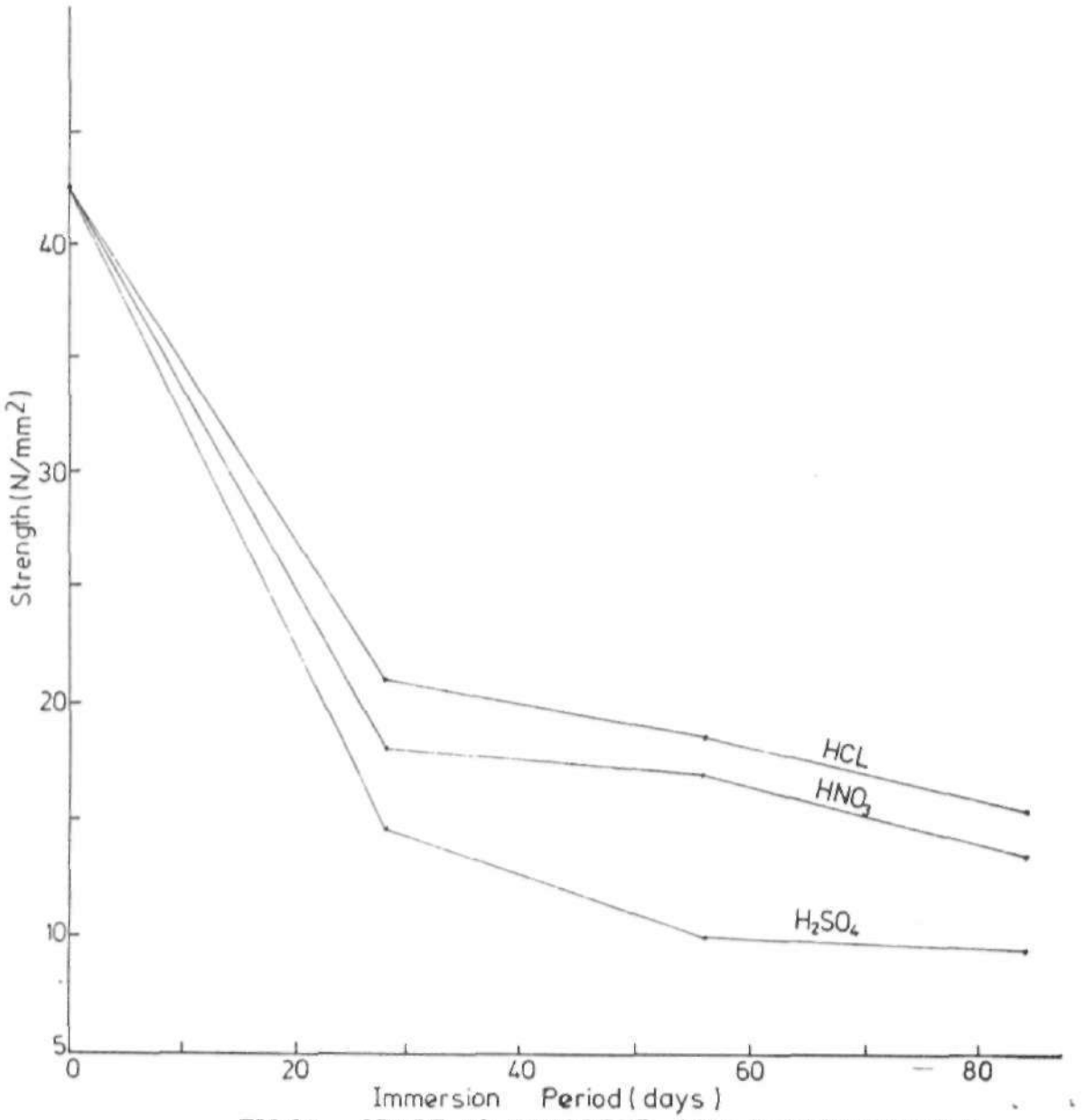


FIG.33 GRADE 40 CONCRETE; 20% CONCENTRATIONS

119

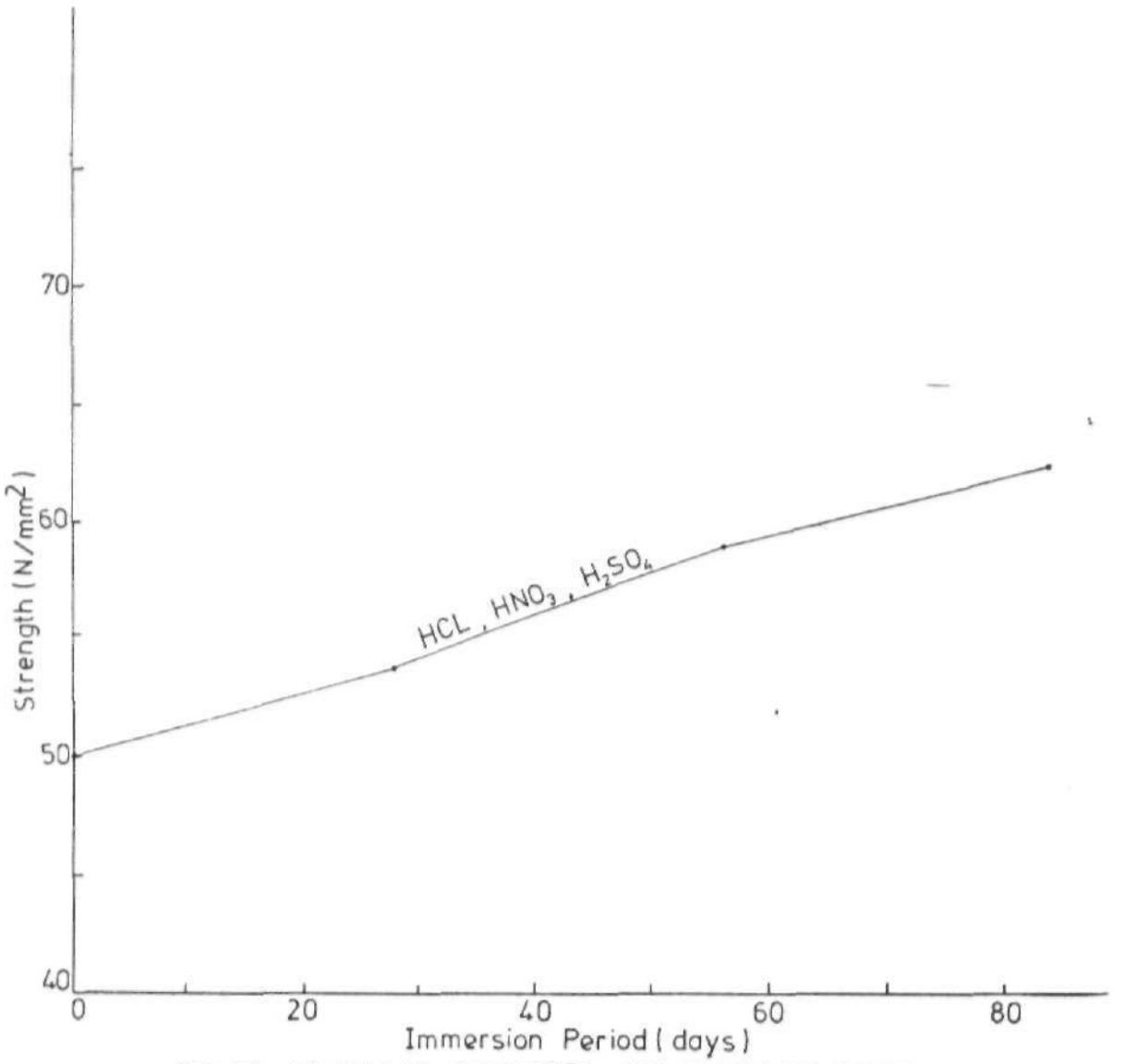


FIG. 34 GRADE 50 CONCRETE; 0% CONCENTRATIONS

120

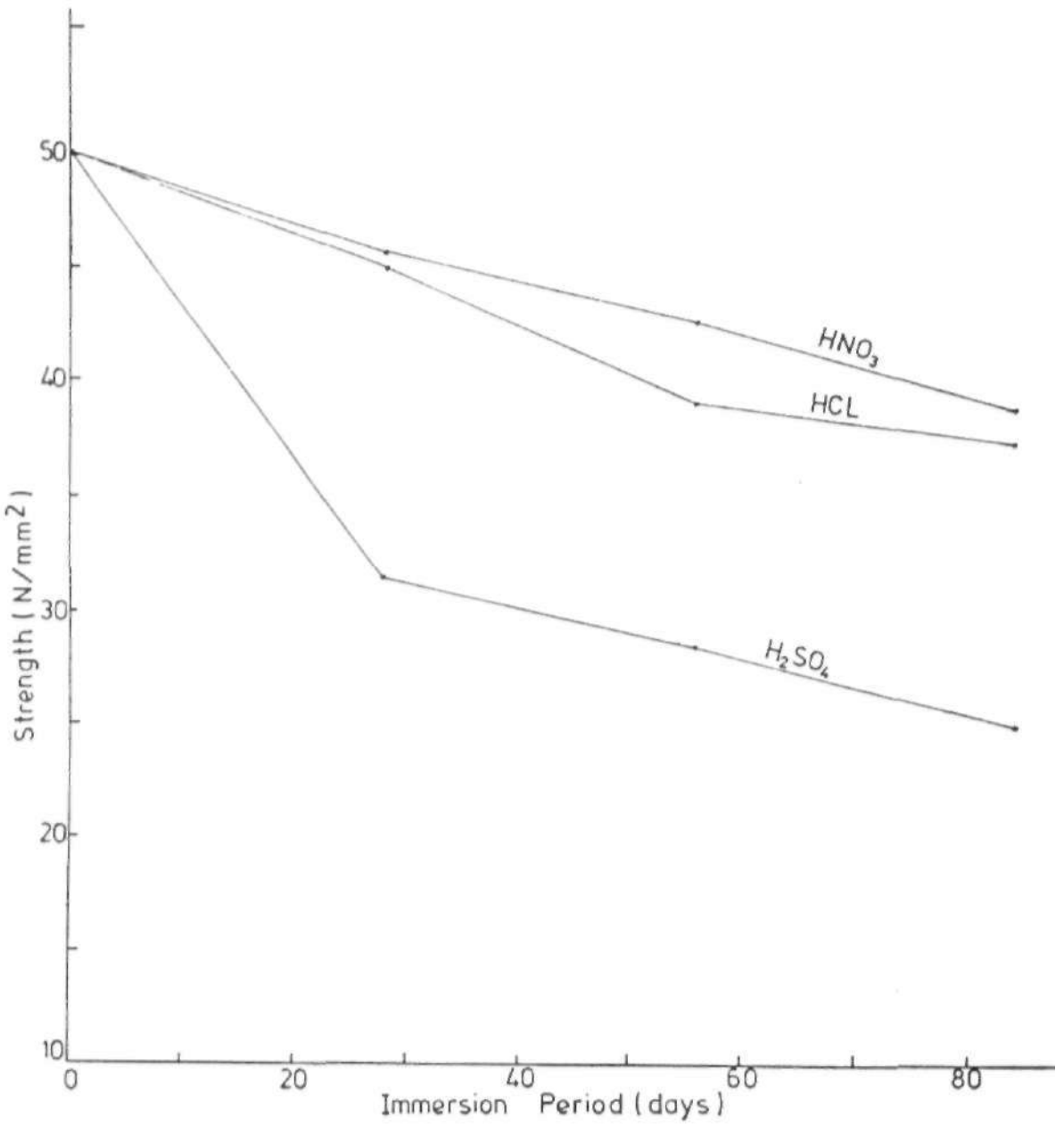


FIG. 35 GRADE 50 CONCRETE; 5% CONCENTRATIONS

121

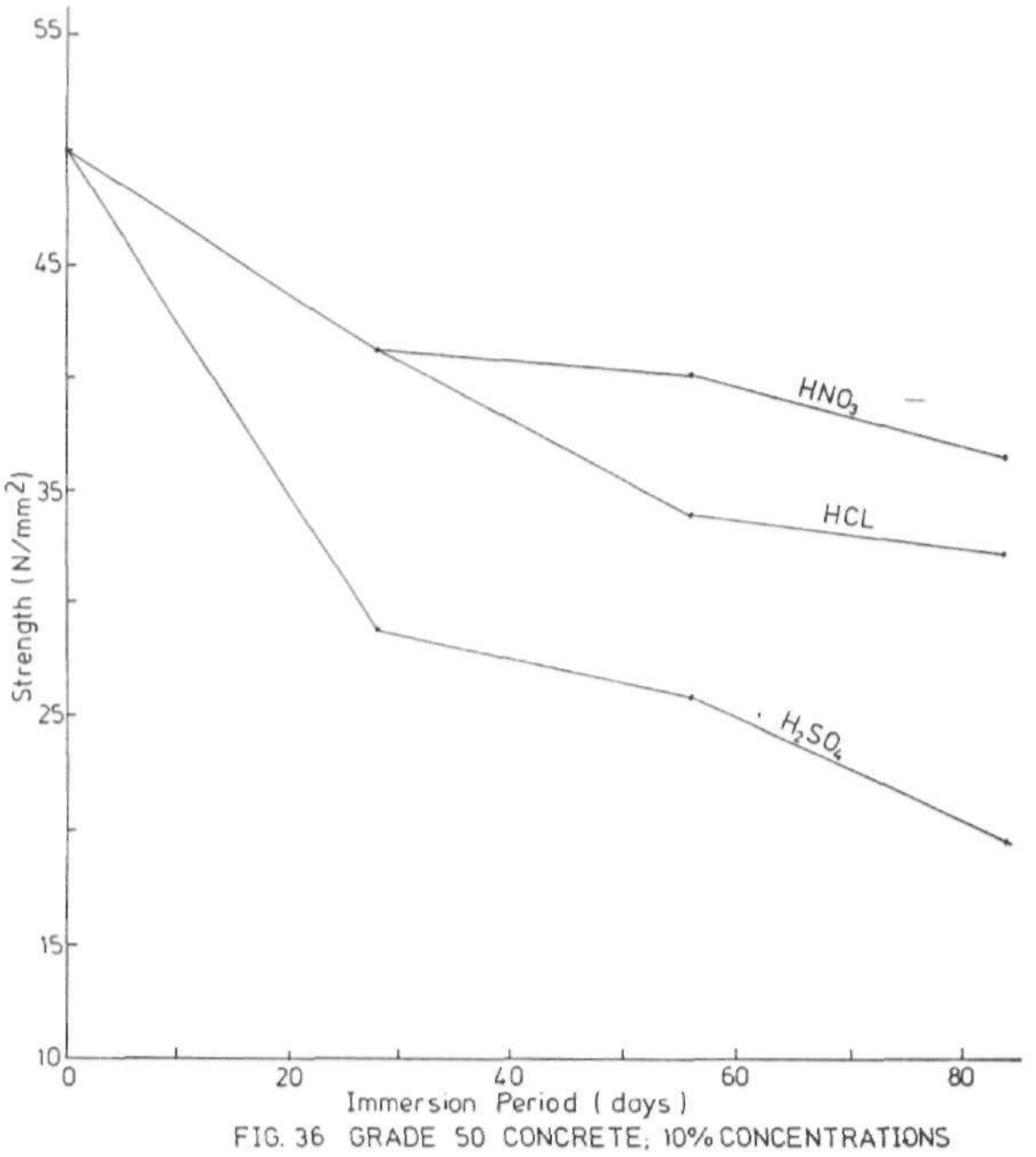


FIG. 36 GRADE 50 CONCRETE; 10% CONCENTRATIONS

122

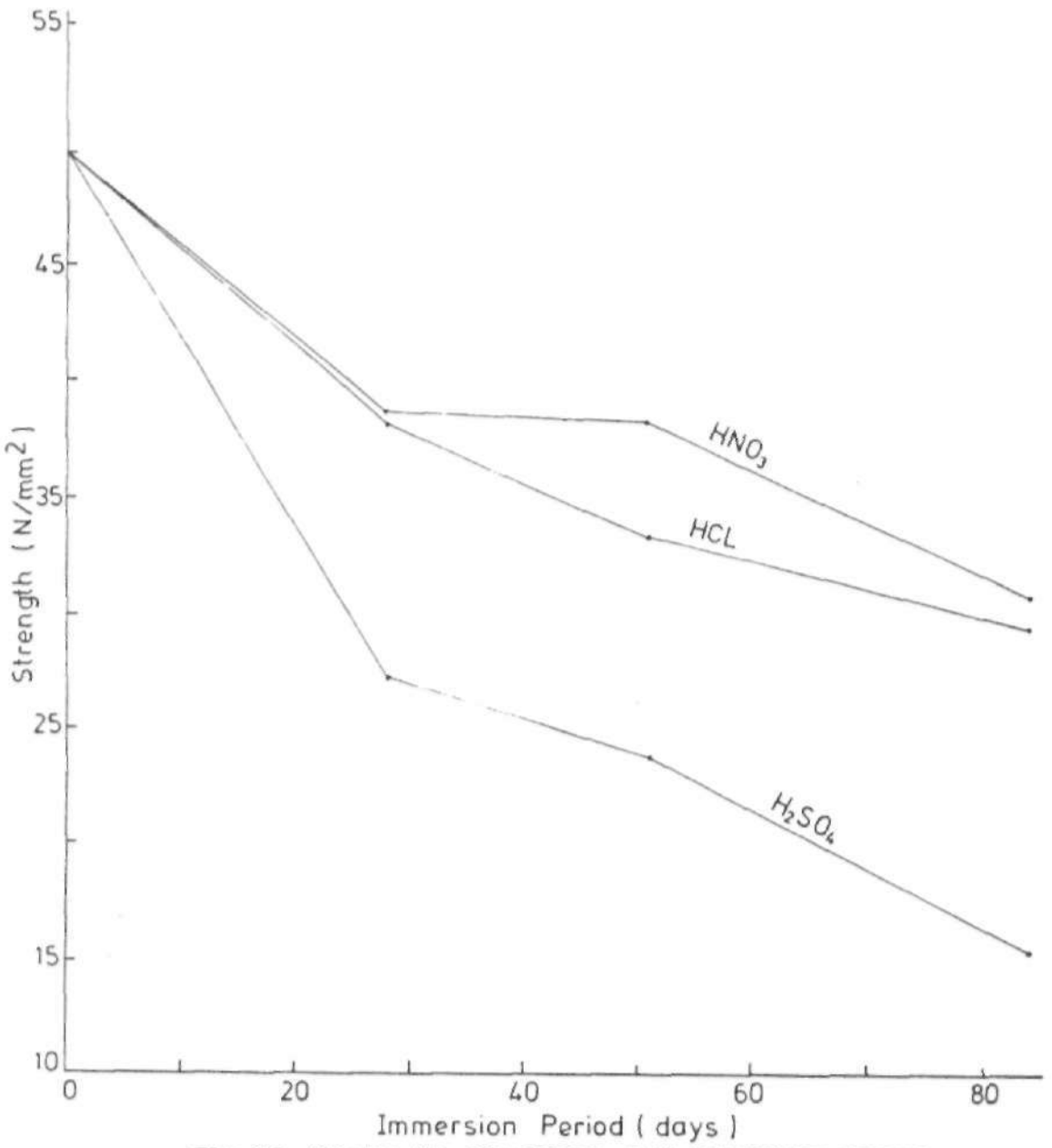


FIG. 37 GRADE 50 CONCRETE; 15% CONCENTRATIONS

123

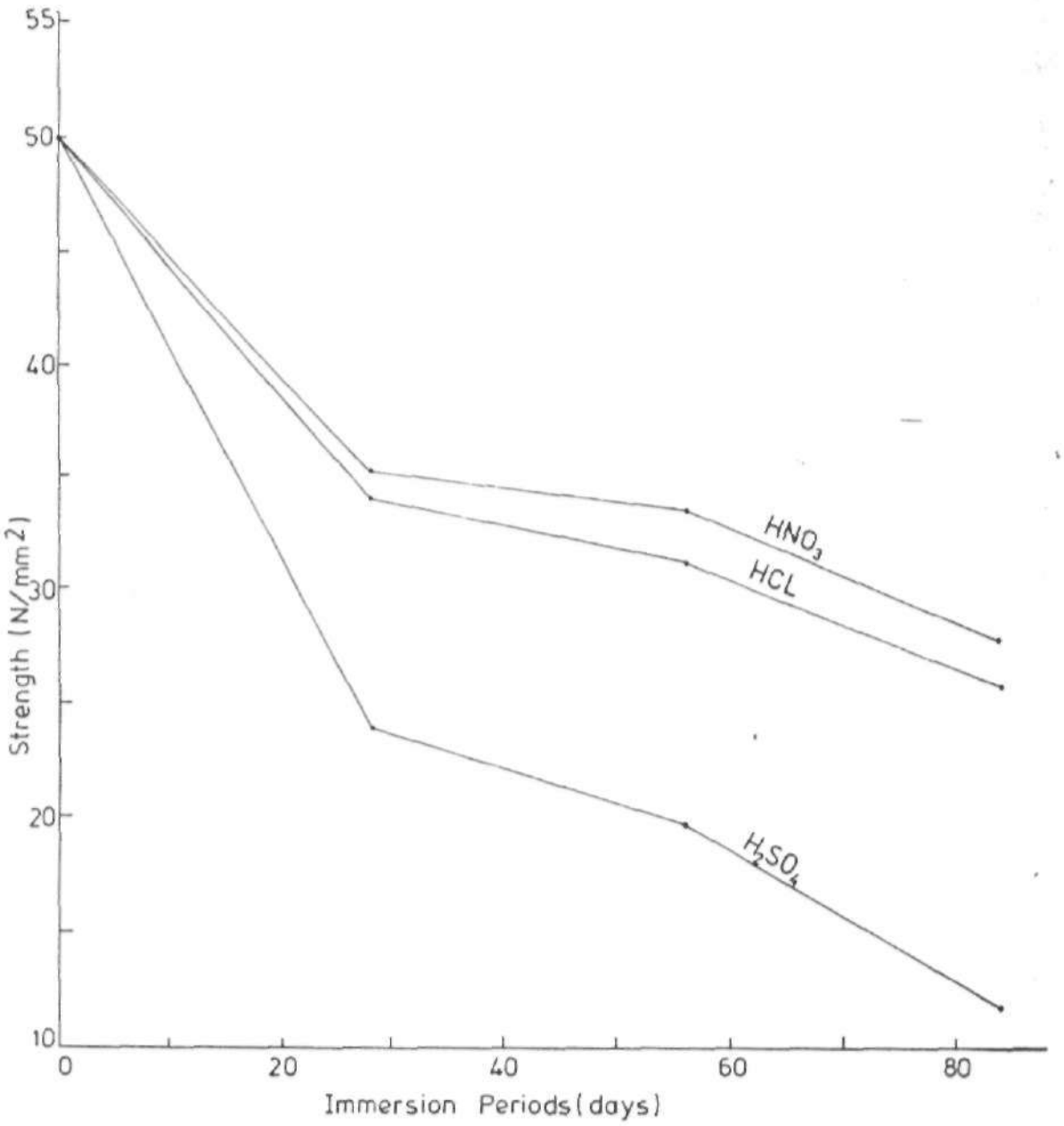


FIG. 38 GRADE 50 CONCRETE; 20% CONCENTRATIONS.

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CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the results of this research, the following conclusions can be drawn.

(1) The concrete cubes immersed in water increased steadily in compressive strength from 35.36 Nmm^{-2} to 41.33 Nmm^{-2} at the end of 84 days of immersion for grade 30; from 42.58 Nmm^{-2} to 51.70 Nmm^{-2} at the end of 84 days of immersion for grade 40; and from 50.18 Nmm^{-2} to 62.81 Nmm^{-2} at the end of 84 days of immersion for grade 50.

On the other hand concrete cubes immersed in the acids decreased steadily in compressive strength. For grade 30 concrete the strength decreased from 35.36 Nmm^{-2} to 11.70Nmm^{-2} from 35.36 Nmm^{-2} to 11.11 Nmm^{-2} and from 35.36 Nmm^{-2} to 3.15Nmm^{-2} at the end of 84 days of immersion in hydrochloric acid, nitric acid and sulphuric acid respectively. For grade 40 concrete the strength decreased from 42.58 Nmm^{-2} to 15.85 Nmm^{-2} from 42.58Nmm^{-2} to 14.08 Nmm^{-2} and from 42.58 Nmm^{-2} to 9.22 Nmm^{-2} at the end of 84 days of immersion in hydrochloric acid, nitric acid and sulphuric

acid respectively. In the case of grade 50 concrete the strength decreased from 50.18 Nmm^{-2} to 25.93 Nmm^{-2}, from 50.18 Nmm^{-2} to 28.14 Nmm^{-2} and from 50.18 Nmm^{-2} to 12.15 Nmm^{-2} at the end of 84 days of immersion in hydrochloric acid, nitric acid sulphuric acid respectively.

2. The decrease in compressive strength increases with increase in concentration of the acids and the duration of immersion periods.
3. With a stagnant and constant-concentration medium, the compressive strength reduction is high in the early days of immersion period and becomes progressively lower thereafter. It might even be possible for the acid attack to stop altogether with time when the acid shall have been completely neutralised.

(4) Sulphuric acid is more aggressive than either the nitric acid or hydrochloric acid, given the same concentration and immersion period. It dessolves the cement-motar content of the concrete, leaving the concrete exposed of coarse aggregate.

(5) It is not very clear which is more aggressive between the nitric acid and the hydrochloric acid. However, they both attack the concrete by diffusion process, softening it and weakening its bonds.

There is no outright washing away of the cement-mortar content of the concrete.

(6) 5% and above concentrations of sulphric acid reduced the compresive strength of concrete grades 30, 40 and 50 to an unsafe value within 28 days of immersion. For the three concrete grades and an equivalent immersion period, it takes 10% or more concentrations by volume of either nitric acid or hydrochloric acid to reduce the compresssive strength to an unsafe value. However, within 56 days of immersion 5% concentration of either nitric acid and hydrochloric acid is enough to cause a significant damage to the three grades of concrete.

(7) It is possible to recognise sulphric acid attack by a whitish colouration on the surface of the concrete and complete exposure of the coarse aggregate as a result of the removal of cement-mortar content of the concrete. Nitric acid attack can be visually observed by a soft concrete surface and a characteristic brownish colouration; while attack due to hydrochloric acid can be recognised by a soft concrete surface and a characteristic greenish colouration.

(8) The grade of concrete did not seem to have had any

appreciable influence on the resistance of the concrete to chemical aggression. This appear to have agreed with the conclusions of some previous researchers that the influence of cement content in the chemical resistance of concrete becomes significant only in the cases of weak mixes.

(9) The depth of penetration of the acids at the end of 84 days of immersion suggests that even 100mm concrete cover, the highest recommend so far, cannot effectively protect the steel against the attack of these acids for an environment with the dimulated % of acid concentration used.

(10) Deterioration becomes first apparent and more intensive at the top surface and the corners and edges of the test cubes which were at the top surface when the cubes were being manufactured. This phenomenon can lead to the logical conclusion that while filling the concrete into the cubes' moulds, the upper part becomes more porous by the rising air bubbles and thus less resistant than the lower layer in the vicinity of the bottom.

5.2 RECOMMENDATIONS

The following recommendation have been made based purely on the findings of this investigation.

(1) Unprotected concrete structures should not be allowed to be subjected to a concentration of 5% or more of any of these three acids.

(2) In formulating conditions for the design and construction of concrete structures to resist sulphric acid, nitric acid or hydrochloric acids the grade of the concrete should be de-emphasized, upon provided that poor concrete mixes and workmanship are not being anticipated.

(3) Industrial chemical manufacturers and dealers should be educated on the dangers inherent in storing industrial chemicals, such as acids, on unprotected concrete floors. The softening and weakening of bonds of the concrete may pass unnoticed which may lead to premature and sudden failure.

(4) To ensure durability and stability as well as the safety of life and properties, sulphric acid, nitric acid and hydrochloric acid should not be manufactured or stored in unprotected concrete structures.

(5) Concrete structures that are likely to come into contact with aggressive chemicals should be better protected by plastic materials or polymer materials that do not dissolve in acids.

5.3 SUGGESTIONS FOR FURTHER RESEARCH

(6) Investigations using percentages of concentrations of the acids lower than 5% might be necessary to help in determining the critical acid content.*

(7) It may also be beneficial to investigate if bituminous materials, or gloss paint, or rubber latex can be successfully employed to protect concrete structures against chemical attack.

* Critical acid content is defined as the lower limit of acid concentration above which protective measures should be specified.

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Appendix 1A

Test Data Sheet 301 — Sieve Analysis on Fine Aggregate

Gross mass of soil (M_o) ...500g..... Mass passing 2mm sieve (M_1) . . . . . .

Mass retained on 2mm sieve ...-..... Mass used in sedimentation analysis (M_2)...-....

Student Name:...M.O.A. Mtallib..... Group No:...-... Date ...15/02/92...

Sample A

Sieve Number	Opening Size (mm)	Mass of Sieve (g)	Mass of Sieve + Soil Retained(g)	Mass of Soil Retained(g)	Corrected Mass Retained (g)	Fraction Retained	Cummulative Fraction Retained	Fraction Passing (%)
7	-	-	-	4.87	-	0.0974	0.0974	93.56
14	-	-	-	183.00	-	0.366	0.4634	56.96
25	-	-	-	85.20	-	0.1704	0.6338	39.92
36	-	-	-	61.50	-	0.123	0.7568	27.62
52	-	-	-	34.10	-	0.0682	0.825	20.80
72	-	-	-	25.80	-	0.516	0.8766	15.64
100	-	-	-	17.60	-	0.0352	0.918	12.12
200				60.60		0.1212	1.033	0.00

Appendix 1B

Test Data Sheet 301 — Sieve Analysis on Fine Aggregate

Gross mass of soil (M_o) 500g ..... Mass passing 2mm sieve (M_1) .....

Mass retained on 2mm sieve ..... Mass used in sedimentation analysis (M_2) .....

Student Name: M.O.A. Mtallib ..... Group No: ... Date 15/02/92 .....

Sample B

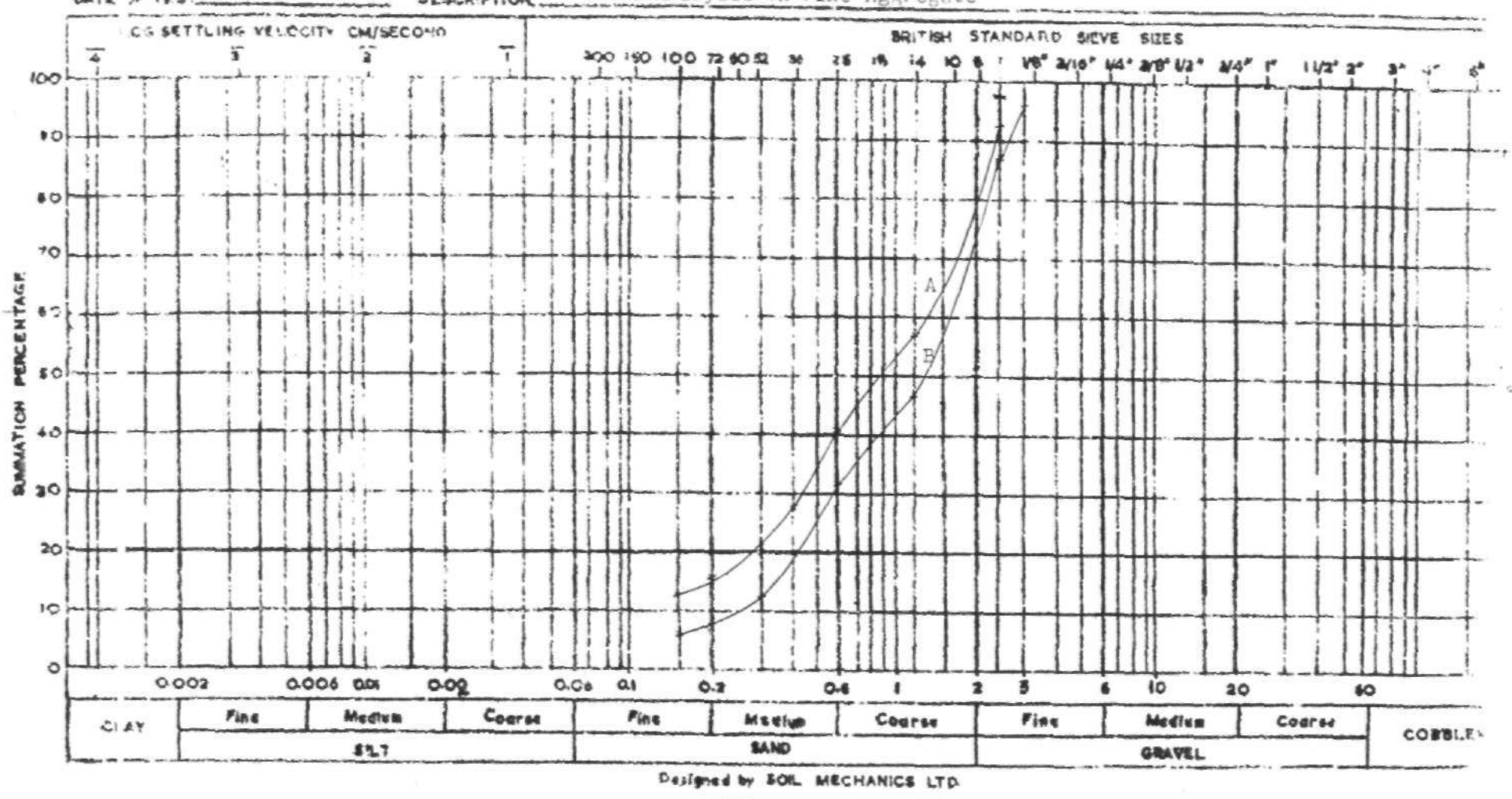
Sieve Number	Opening Size (mm)	Mass of Sieve (g)	Mass of Sieve + Soil Retained(g)	Mass of Soil Retained(g)	Corrected Mass Retained (g)	Fraction Retained	Cummulative Fraction Retained	Fraction Passing (%)
-	10.00	-	-	0	-	0	0	98.90
	5.00	-	-	10.70	-	0.0214	0.0214	96.76
	2.36	-	-	39.90	-	0.0798	0.1012	88.78
	1.18	-	-	212.20	-	0.4244	0.5256	46.34
	0.600	-	-	69.80	-	0.1396	0.0652	32.38
	0.425			62.40		0.1248	0.7900	19.90
	0.300	-	-	33.80	-	0.0676	0.8576	13.14
	0.212	-	-	24.00	-	0.0480	0.9056	8.34
	0.150	-	-	15.20		0.0304	0.9360	5.30
	0.75	-	-	26.50		0.053	0.989	0.00

Appendix 1C (Figure 1)

PARTICLE SIZE DISTRIBUTION

LOCATION: A.B.U., Zaria BORE HOLE No: NIL SAMPLE No: A and B PRETREATMENT DETAILS:

DATE OF TEST: 15/02/92 DESCRIPTION: Sieve Analysis On Fine Aggregate



Designed by SOIL MECHANICS LTD.

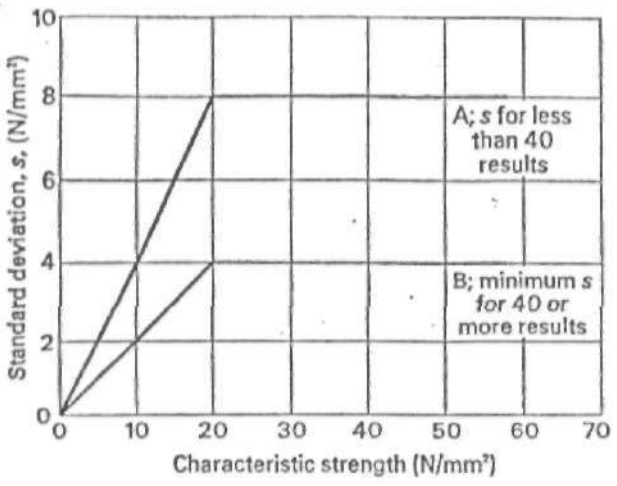


Figure 2 Relationship between standard deviation and characteristic strength

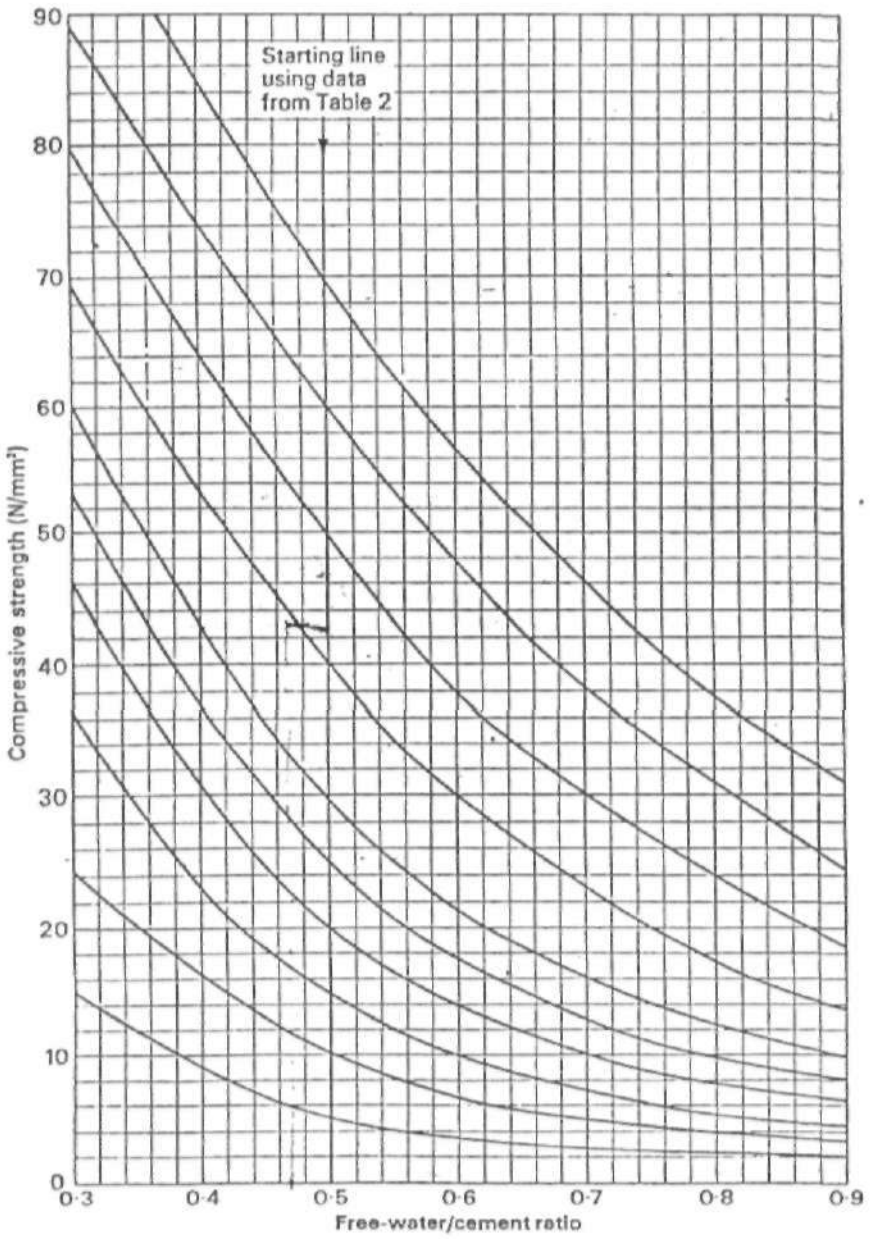


Figure 3 Relationship between compressive strength and free-water/cement ratio

Table 3 Approximate compressive strengths (N/mm²) of concrete mixes made with a free-water/cement ratio of 0·5

Type of cement	Type of coarse aggregate	Compressive strengths (N/mm²) Age (days) 3	7	28	91
Ordinary Portland (OPC) or sulphate-resisting Portland (SRPC)	Uncrushed	18	27	40	48
	Crushed	23	33	47	55
Rapid-hardening Portland (RHPC)	Uncrushed	25	34	46	53
	Crushed	30	40	53	60

1 N/mm² = 1 MN/m² = 1 MPa (see footnote on page 8).

Table 4 Approximate free-water contents (kg/m³) required to give various levels of workability

Slump (mm) / V-B (s)		0–10 >12	10–30 6–12	30–60 3–6	60–180 0–3
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

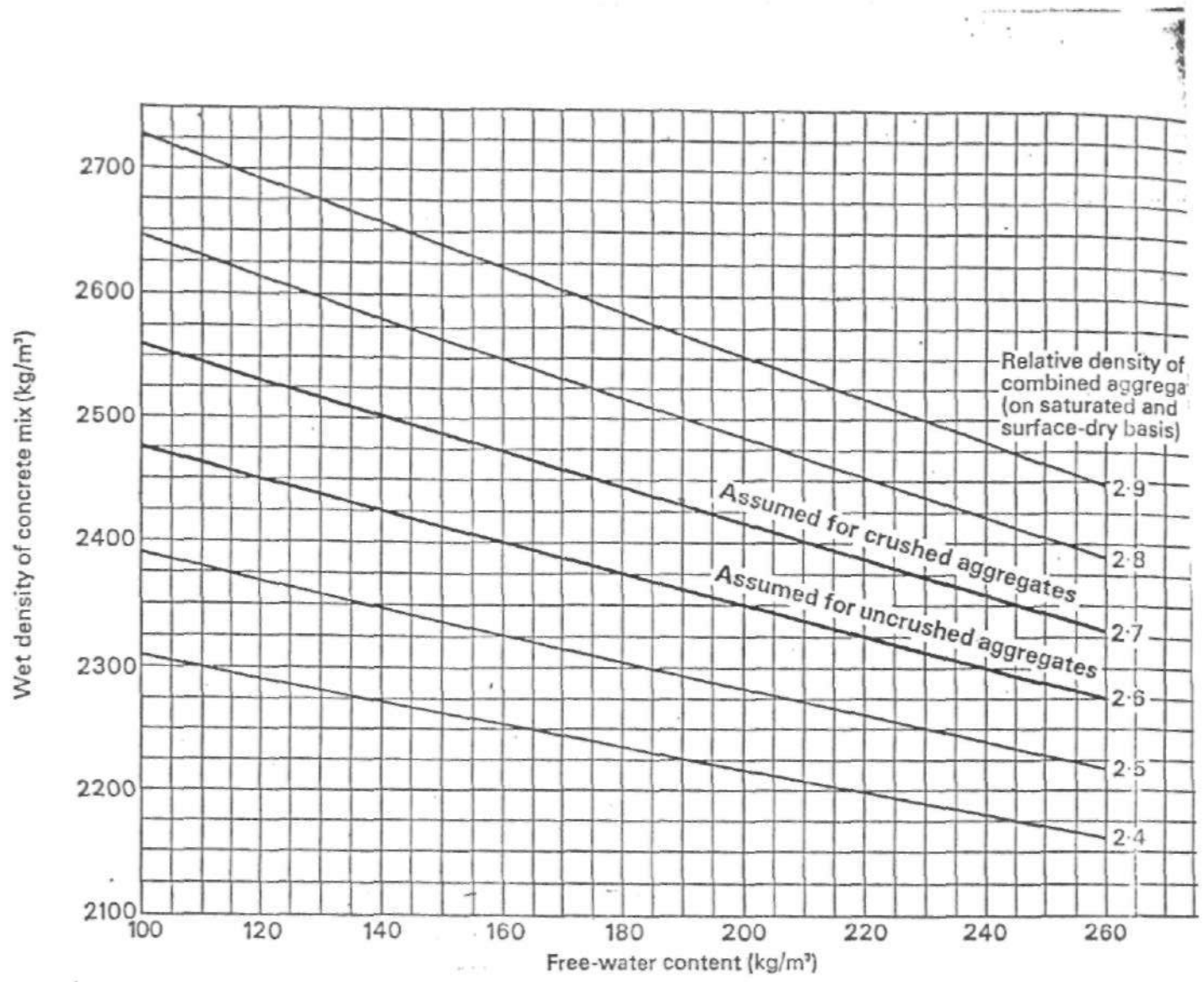


Figure 4 Estimated wet density of fully compacted concrete

Maximum aggregate size: 10mm

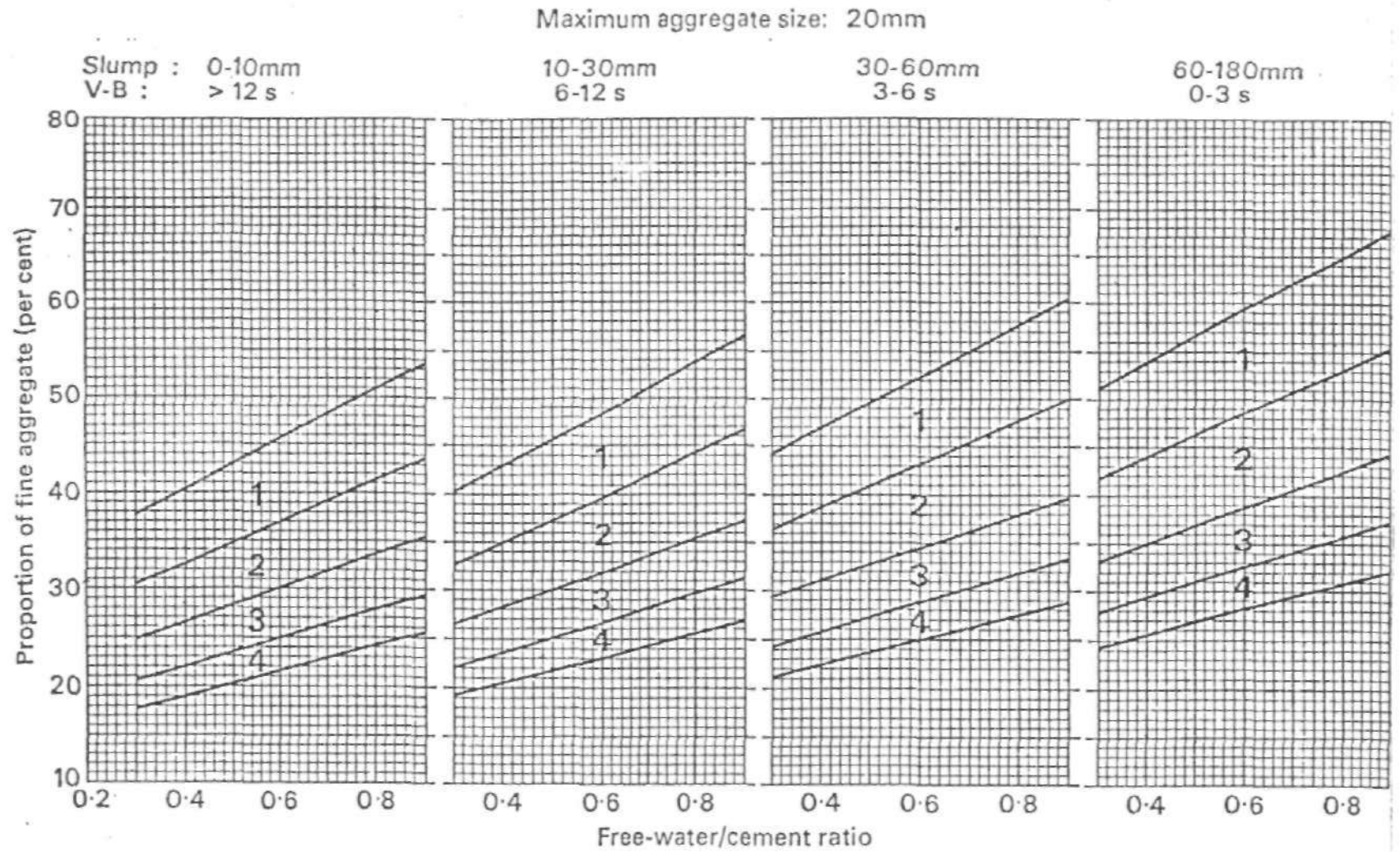

Maximum aggregate size: 20mm
Slump : 0-10mm
V-B : > 12 s
10-30mm
6-12 s
30-60mm
3-6 s
60-180mm
0-3 s
Proportion of fine aggregate (per cent)
80
70
60
50
40
30
20
10
0·2
0·4
0·6
0·8
Free-water/cement ratio
1
2
3
4

Figure 5

Appendix II

Compressive Strength at 28 days Before Immersion

Grade 30

No.	Density (kg/m^3)	Crushing load KN	Comp. Strength N/mm^{-2}
1	8.10	740	32.89
2	8.25	750	33.33
3	8.20	800	35.56
4	8.15	780	34.67
5	8.35	790	35.11
6	8.20	915	40.67
	Average compressive strength	=	35.36

Grade 40

1	8.25	960	42.67
2	8.25	950	42.23
3	8.25	960	42.67
4	8.25	970	43.11
5	8.20	960	42.67
6	8.20	970	43.11
	Average compressive strength	=	42.58

Grade 50

1	8.30	1150	51.11
2	8.30	1120	49.77
3	8.40	1110	49.33
4	8.20	1125	50.00
5	8.40	1130	50.22
6	8.30	1140	50.67
	Average compressive strength	=	50.18

Appendix 111A: Concrete Grade 30 After 28 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/1/C	7.75	7.40	620
5/2/C	8.15	7.90	600
5/3/C	8.00	7.50	610
10/1/C	8.35	7.80	560
10/2/C	8.10	7.60	530
10/3/C	8.25	7.65	570
15/1/C	8.15	7.60	490
15/2/C	8.10	7.60	500
15/3/C	8.15	7.65	470
20/1/C	8.50	7.80	370
20/2/C	8.00	7.40	340
20/3/C	8.30	7.60	350
5/1/N	7.90	7.70	560
5/2/N	8.20	8.00	540
5/3/N	8.00	7.80	580
10/1/N	8.10	7.60	510
10/2/N	8.05	7.60	500
10/3/N	8.15	7.80	520
15/1/N	8.40	7.80	470
15/2/N	8.15	7.60	440
15/3/N	8.20	7.60	460
20/1/N	7.90	7.30	320
20/2/N	8.00	7.30	330
20/3/N	8.20	7.40	330
5/1/S	8.10	7.20	430
5/2/S	8.10	7.10	390
5/3/S	8.10	7.10	420
10/1/S	8.40	6.90	310
10/2/S	8.00	6.40	290
10/3/S	8.20	6.60	280
15/1/S	8.10	6.60	280
15/2/S	8.50	7.00	260
15/3/S	8.30	6.70	300
20/1/S	8.10	6.65	290
20/2/S	8.10	6.60	230
20/3/S	8.10	6.50	260
0/1/0	8.30	8.40	920
0/2/0	8.20	8.30	810
0/3/0	8.20	8.35	770

Appendix 111B: Concrete Grade 30 After 28 days Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/4/C	8.05	8.10	520
5/5/C	8.05	7.80	500
5/6/C	8.10	8.00	520
10/4/C	8.05	7.70	480
10/5/C	8.25	7.80	480
10/6/C	8.20	7.70	460
15/4/C	8.10	7.50	440
15/5/C	8.10	7.50	410
15/6/C	8.20	7.50	420
20/4/C	8.00	7.50	370
20/5/C	8.13	7.50	340
20/6/C	8.15	7.60	360
5/4/N	8.10	7.85	520
5/5/N	8.00	7.80	530
5/6/N	8.20	7.85	510
10/4/N	8.10	7.80	490
10/5/N	8.00	7.70	480
10/6/N	8.30	8.00	490
15/4/N	8.10	7.65	420
15/5/N	8.20	7.70	400
15/6/N	8.20	7.60	380
20/4/N	8.15	7.70	290
20/5/N	7.95	7.60	280
20/6/N	8.20	7.80	300
5/4/S	8.10	7.70	420
5/5/S	8.10	7.30	400
5/6/S	8.10	7.40	380
10/4/S	8.10	6.80	250
10/5/S	8.25	7.00	280
10/6/S	8.20	7.00	260
15/4/S	8.10	6.20	240
15/5/S	8.20	6.30	260
15/6/S	8.20	6.30	220
20/4/S	8.10	6.20	250
20/5/S	8.20	6.30	220
20/6/S	8.20	6.30	210
0/4/0	8.40	8.40	900
0/5/0	8.10	8.20	890
0/6/0	8.20	8.25	930

Appendix 111C: Concrete Grade 30 After 84 days Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/7/C	8.40	8.10	430
5/8/C	8.00	7.80	480
5/9/C	8.20	7.90	450
10/7/C	8.05	7.60	350
10/8/C	8.25	7.80	360
10/9/C	8.10	7.60	380
15/7/C	8.10	7.50	340
15/8/C	8.00	7.40	350
15/9/C	8.20	7.70	330
20/7/C	7.95	7.00	280
20/8/C	8.00	7.30	260
20/9/C	8.10	7.35	250
5/7/N	8.10	7.85	500
5/8/N	8.00	7.75	520
5/9/N	8.15	7.87	500
10/7/N	8.10	7.70	470
10/8/N	8.10	7.65	480
10/9/N	8.10	7.70	450
15/7/N	8.00	7.50	380
15/8/N	8.20	7.60	360
15/9/N	8.15	7.60	380
20/7/N	7.90	7.30	230
20/8/N	8.20	7.50	250
20/9/N	7.85	7.15	270
5/7/S	8.10	6.20	390
5/8/S	8.10	6.25	380
5/9/S	8.30	6.40	380
10/7/S	8.10	5.50	270
10/8/S	8.25	5.45	250
10/9/S	8.20	5.40	240
15/7/S	8.45	5.80	230
15/8/S	8.20	5.30	210
15/9/S	8.10	5.20	220
20/7/S	8.10	5.50	290
20/8/S	7.80	5.20	190
20/9/S	8.25	5.60	170
0/7/0	8.40	8.50	900
0/8/0	8.00	8.00	950
0/9/0	8.05	8.10	940

Appendix 111D: Concrete Grade 40 After 28 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/1/C	8.10	7.85	650
5/2/C	8.20	7.90	690
5/3/C	8.20	7.80	710
10/1/C	8.40	7.85	580
10/2/C	8.10	7.65	600
10/3/C	8.30	7.70	620
15/1/C	8.20	7.65	540
15/2/C	8.10	7.50	550
15/3/C	8.20	7.60	530
20/1/C	8.00	7.40	500
20/2/C	8.20	7.50	480
20/3/C	8.10	7.40	460
5/1/N	8.40	7.90	690
5/2/N	8.40	7.55	700
5/3/N	8.40	7.70	680
10/1/N	8.30	7.80	590
10/2/N	8.00	7.60	600
10/3/N	8.20	7.70	610
15/1/N	8.30	7.75	500
15/2/N	8.10	7.50	520
15/3/N	8.10	7.50	490
20/1/N	8.10	7.40	380
20/2/N	8.10	7.50	440
20/3/N	8.10	7.35	420
5/1/S	8.20	7.40	460
5/2/S	8.30	7.60	490
5/3/S	8.20	7.40	500
10/1/S	8.20	6.80	420
10/2/S	8.20	6.80	400
10/3/S	8.20	6.85	420
15/1/S	8.30	6.85	370
15/2/S	8.25	6.65	340
15/3/S	8.20	6.60	360
20/1/S	8.30	7.00	350
20/2/S	8.10	6.40	320
20/3/S	8.10	6.40	330
0/1/0	8.20	8.20	990
0/2/0	8.30	8.40	1000
0/3/0	8.30	8.35	990

Appendix 111E: Concrete Grade 40 After 56 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/4/C	8.15	7.80	640
5/5/C	8.15	7/75	620
5/6/C	8.10	7.70	600
10/4/C	8.10	7.65	530
10/5/C	8.20	7.80	550
10/6/C	8.20	7.70	520
15/4/C	8.20	7.65	500
15/5/C	8.10	7.60	490
15/6/C	8.20	7.60	480
20/4/C	8.20	7.60	420
20/5/C	8.10	7.50	440
20/6/C	8.10	7.50	410
5/4/N	8.30	7.90	620
5/5/N	8.50	8.15	610
5/6/N	8.30	7.80	630
10/4/N	8.20	7.50	560
10/5/N	8.30	7.60	530
10/6/N	8.30	7.55	540
15/4/N	8.60	7.75	460
15/5/N	8.30	7.40	440
15/6/N	8.40	7.45	440
20/4/N	8.40	7.45	400
20/5/N	8.20	7.20	390
20/6/N	8.20	7.20	380
5/4/S	8.15	7.40	400
5/5/S	8.15	7.65	450
5/6/S	8.15	7.50	430
10/4/S	8.10	6.00	370
10/5/S	8.10	6.30	370
10/6/S	8.10	6.00	320
15/4/S	8.10	6.10	250
15/5/S	8.20	6.30	270
15/6/S	8.20	6.00	290
20/4/S	8.10	6.00	240
20/5/S	8.15	6.15	230
20/6/S	8.10	6.00	230
0/4/0	8.20	8.25	1060
0/5/0	8.00	8.00	1040
0/6/0	8.20	8.20	1050

Appendix 111F: Concrete Grade 40 After 84 days of Immersion

Cube's I.D Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/7/C	8.45	7.70	590
5/8/C	8.20	7.50	580
5/9/C	8.20	7.40	570
10/7/C	8.10	7.50	500
10/8/C	8.20	7.60	500
10/9/C	8.10	7.60	520
15/7/C	8.20	7.40	450
15/8/C	8.10	7.30	450
15/9/C	8.20	7.35	410
20/7/C	8.20	7.40	370
20/8/C	8.10	7.40	360
20/9/C	8.15	7.40	340
5/7/N	8.20	7.70	590
5/8/N	8.00	7.60	570
5/9/N	8.10	7.60	530
10/7/N	8.20	7.60	480
10/8/N	8.10	7.50	500
10/9/N	8.10	7.50	460
15/7/N	8.10	7.50	400
15/8/N	7.90	7.40	400
15/9/N	8.20	7.45	370
20/7/N	8.20	7.60	310
20/8/N	8.10	7.40	310
20/9/N	8.10	7.40	330
5/7/S	8.35	7.60	420
5/8/S	8.20	7.50	400
5/9/S	8.20	7.50	390
10/7/S	8.10	6.20	340
10/8/S	8.10	6.00	320
10/9/S	8.10	6.20	330
15/7/S	8.20	5.30	240
15/8/S	8.20	5.70	280
15/9/S	8.20	5.50	250
20/7/S	8.25	5.60	210
20/8/S	8.10	5.40	230
20/9/S	8.20	5.55	230
0/7/0	8.20	8.30	1160
0/8/0	8.35	8.45	1160
0/9/0	8.30	8.35	1170

Appendix 111G Concrete Grade 50 After 28 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/1/C	8.30	7.90	1020
5/2/C	8.23	7.90	1030
5/3/C	8.26	7.90	1000
10/1/C	8.15	7.80	940
10/2/C	8.35	7.70	900
10/3/C	8.20	7.70	960
15/1/C	8.30	7.60	860
15/2/C	8.30	7.45	820
15/3/C	8.30	7.50	880
20/1/C	8.25	7.60	790
20/2/C	8.10	7.55	750
20/3/C	8.20	7.45	760
5/1/N	8.20	8.00	1020
5/2/N	8.30	8.00	1040
5/3/N	8.20	7.80	1030
10/1/N	8.20	7.70	960
10/2/N	8.45	8.00	930
10/3/N	8.30	7.90	910
15/1/N	8.25	7.70	880
15/2/N	8.20	7.60	850
15/3/N	8.30	7.70	870
20/1/N	8.20	7.70	770
20/2/N	8.30	7.75	790
20/3/N	8.30	7.75	820
5/1/S	8.20	7.70	700
5/2/S	8.20	7.70	730
5/3/S	8.20	7.70	690
10/1/S	8.35	6.80	670
10/2/S	8.30	6.35	650
10/3/S	8.25	6.35	640
15/1/S	8.10	6.60	580
15/2/S	8.15	6.62	610
15/3/S	8.25	6.65	630
20/1/S	8.00	6.50	490
20/2/S	8.25	6.60	540
20/3/S	8.25	6.60	510
0/1/0	8.20	8.30	1215
0/2/0	8.10	8.30	1200
0/3/0	8.20	8.30	1220

Appendix 111H: Concrete Grade 50 After 56 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/4/C	8.30	8.00	900
5/5/C	8.23	7.90	860
5/6/C	8.30	8.00	860
10/4/C	8.10	7.90	780
10/5/C	8.30	7.70	800
10/6/C	8.20	7.70	730
15/4/C	8.25	7.70	750
15/5/C	8.20	7.70	770
15/6/C	8.20	7.70	720
20/4/C	8.35	7.80	700
20/5/C	8.10	7.60	730
20/6/C	8.25	7.60	690
5/4/N	8.20	7.75	970
5/5/N	8.30	8.00	950
5/6/N	8.20	7.70	960
10/4/N	8.20	7.80	900
10/5/N	8.15	7.80	920
10/6/N	8.25	7.80	920
15/4/N	8.30	7.75	860
15/5/N	8.20	7.70	840
15/6/N	8.20	7.70	830
20/4/N	8.40	7.50	800
20/5/N	8.30	7.30	750
20/6/N	8.35	7.30	730
5/4/S	8.15	7.50	640
5/5/S	8.20	7.40	650
5/6/S	8.30	7.40	620
10/4/S	8.10	6.00	610
10/5/S	8.30	7.50	590
10/6/S	8.25	7.00	570
15/4/S	8.30	6.80	530
15/5/S	8.40	6.90	550
15/6/S	8.20	6.60	510
20/4/S	8.25	6.65	440
20/5/S	8.35	6.80	430
29/5/S	8.30	6.70	470
0/4/0	8.31	8.35	1325
0/5/0	8.10	8.10	1345
0/6/0	8.25	8.25	1330

Appendix 111I: Concrete Grade 50 After 84 days of Immersion

Cube's ID Mark	Density B/F Immersion kgm^{-3}	Density A/F Immersion kgm^{-3}	Crushing Load KN
5/7/C	8.30	8.10	820
5/8/C	8.30	8.10	850
5/9/C	8.30	8.10	830
10/7/C	8.30	7.85	760
10/8/C	8.00	8.00	740
10/9/C	8.25	7.80	700
15/7/C	8.15	7.70	650
15/8/C	8.30	7.80	680
15/9/C	8.10	7.60	620
20/7/C	8.15	7.60	610
20/8/C	8.15	7.60	580
20/9/C	8.20	7.70	560
5/7/N	8.25	8.00	900
5/8/N	8.30	8.10	840
5/9/N	8.30	8.00	870
10/7/N	8.25	7.70	800
10/8/N	7.95	7.60	770
10/9/N	8.20	7.70	730
15/7/N	8.25	7.80	710
15/8/N	8.30	7.80	650
15/9/N	8.25	7.70	680
20/7/N	8.10	7.20	640
20/8/N	8.35	7.50	640
20/9/N	8.30	7.50	620
5/7/S	8.25	7.50	560
5/8/S	8.20	7.20	540
5/9/S	8.20	7.20	560
10/7/S	8.30	6.00	450
10/8/S	8.30	6.00	470
10/9/S	8.30	6.10	420
15/7/S	8.40	6.10	330
15/8/S	8.30	6.10	330
15/9/S	8.30	6.10	340
20/7/S	8.10	6.00	250
20/8/S	8.10	6.10	280
20/9/S	8.15	6.10	290

APPENDIX IVA

Grade of concrete 30

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCL 0%	0/1/0	8.30		8.40					34.22			
	0/2/0	8.20	8.20	8.30	8.35	+1.15	+1.83	35.36	36.00	37.04	+1.68	+4.75
	0/3/0	8.20		8.35					40.89			
5%	5/1/C	7.75		7.40					27.56			
	5/2/C	8.15	7.97	7.90	7.6	-0.37	-4.64	35.36	26.67	27.11	-8.25	-23.33
	5/3/C	8.00		7.50					27.11			
10%	10/1/C	8.35		7.80					24.89			
	10/2/C	8.10	8.2	7.60	7.67	-0.53	-6.46	35.36	23.56	24.59	-10.77	-30.46
	10/3/C	8.25		7.65					25.33			
15%	15/1/C	8.15		7.60					21.78			
	15/2/C	8.10	8.13	7.60	7.62	-0.51	-6.27	35.36	22.22	21.63	-13.73	-38.83
	15/3/C	8.15		7.65					20.89			
20%	20/1/C	8.50		7.80					16.44			
	20/2/C	8.00	8.27	7.40	7.60	-0.67	-8.10		15.11	15.70	-19.66	-55.60
	20/3/C	8.30		7.60					15.55			

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APPENDIX IVB

Grade of concrete .....

56 days

Period of Immersion .....

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. strength B/F Immersion (N/mm2)	Comp. Strength A/F Immersion	Average	Change In Strength	% Change in Strength
HCL 0%	0/4/0	8.40		8.40					40.00			
	0/5/0	8.10	8.23	8.2	8.28	+0.05	+0.61	35.36	39.56	40.30	+4.94	+13.97
	0/6/0	8.20		8.25					41.33			
5%	5/4/C	8.05		8.10					23.11			
	5/5/C	8.05	8.07	7.80	7.96	-0.11	-1.36	35.36	22.22	22.81	-12.55	-35.49
	5/6/C	8.10		8.00					23.11			
10%	10/4/C	8.05		7.70					21.33			
	10/5/C	8.25	8.17	7.80	7.73	-0.44	-05.39	35.36	21.33	21.03	-14.33	-40.53
	10/6/C	8.20		7.70					20.44			
15%	15/4/C	8.10		7.50					19.55			
	15/5/C	8.10	8.13	7.50	7.5	-0.63	-7.75	35.36	18.22	18.81	-16.55	-46.80
	15/6/C	8.20		7.50					18.66			
20%	20/4/C	8.0		7.50					16.44			
	20/5/C	8.13	8.09	7.50	7.53	-0.56	-6.92	35.36	15.12	15.85	-19.51	-55.18
	20/6/C	8.15		7.60					16.10			

APPENDIX IVC

Grade of concrete 30

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/7/0	8.40		8.50					40.00			
	0/8/0	8.00	8.15	8.00	8.20	+0.05	+0.61	35.36	42.22	41.33	+5.97	+16.88
	0/9/0	8.05		8.10					41.78			
5%	5/7/C	8.40		8.10					19.11			
	5/8/C	8.00	8.20	7.80	7.93	-0.27	-3.29	35.36	21.33	20.15	-15.21	-43.01
	5/9/C	8.20		7.90					20.00			
10%	10/7/C	8.05		7.60					15.56			
	10/8/C	8.25	8.13	7.80	7.93	-0.46	-5.66	35.36	16.00	17.63	-17.73	-50.14
	10/9/C	8.10		7.60					21.33			
15%	15/7/C	8.10		7.50					15.12			
	15/8/C	8.00	8.10	7.40	7.53	-0.57	-7.04	35.36	15.56	15.12	-20.24	-57.24
	15/9/C	8.20		7.70					14.67			
20%	20/7/C	7.85		7.00					12.44			
	20/8/C	8.00	8.00	7.30	7.23	-0.78	-9.75	35.36	11.56	11.70	-23.66	-66.91
	20/9/C	8.10		7.35					11.11			

Grade of concrete 30

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/1/0	8.30		8.40					34.22			
	0/2/0	8.20	8.23	8.30	8.35	+0.12	+1.46	35.36	36.00	37.04	+1.68	+4.75
	0/3/0	8.20		8.35					40.89			
5%	5/1/N	7.90		7.70					24.89			
	5/2/N	8.20	8.03	8.00	7.83	-0.20	-2.49	35.36	24.00	24.89	-10.47	-29.61
	5/3/N	8.00		7.80					25.78			
10%	10/1/N	8.10		7.6					22.67			
	10/2/N	8.05	8.1	7.6	7.67	-0.43	-5.31	35.36	22.22	22.67	-12.69	-35.89
	10/3/N	8.15		7.8					23.11			
15%	15/1/N	8.40		7.8					20.89			
	15/2/N	8.15	8.25	7.6	7.67	-0.58	-7.03	35.36	19.56	20.30	-15.06	-42.59
	15/3/N	8.20		7.6					20.44			
20%	20/1/N	7.90		7.3					14.22			
	20/2/N	8.00	8.03	7.6	7.33	-0.70	-8.72	35.36	14.64	14.52	-20.84	-58.94
	20/3/N	8.20		7.4					14.67			

APPENDIX IVE

Grade of concrete 30

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/4/0	8.40	8.23	8.40					40.00			
	0/5/0	8.10		8.2	8.28	+0.05	+0.61	35.36	39.56	40.30	+4.94	+13.97
	0/6/0	8.20		8.25					41.33			
5%	5/4/N	8.10		7.85					23.11			
	5/5/N	8.00	8.10	7.80	7.83	-0.27	-3.33	35.36	23.55	23.12	-12.24	-34.62
	5/6/N	8.20		7.85					22.66			
10%	10/4/N	8.10		7.8					21.78			
	10/5/N	8.00	8.13	7.7	7.83	-0.30	-3.69	35.36	21.33	21.63	-13.73	-38.83
	10/6/N	8.30		8.00					21.78			
15%	15/4/N	8.10		7.65					18.66			
	15/5/N	8.20	8.17	7.70	7.65	-0.52	-6.36	35.36	17.78	17.78	-17.58	-49.72
	15/6/N	8.20		7.60					16.89			
20%	20/4/N	8.15		7.70					12.89			
	20/5/N	7.95	8.10	7.60	7.70	-0.40	-4.94	35.36	12.44	12.89	-22.47	-63.55
	20/6/N	8.20		7.80					13.33			

APPENDIX IVF

Grade of concrete 30

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/7/0	8.50		8.50					40.00			
	0/8/0	8.00	8.15	8.00	8.20	+0.05	+0.61	35.36	42.22	41.33	+5.97	+16.88
	0/9/0	8.05		8.10					41.78			
5%	5/7/N	8.10		7.85					22.22			
	5/8/N	8.00	8.08	7.75	7.82	-0.26	-3.22	35.36	23.11	22.52	-12.84	-36.31
	5/9/N	8.15		7.87					22.22			
10%	10/7/N	8.10		7.70					20.89			
	10/8/N	8.10	8.10	7.65	7.68	-0.42	-5.19	35.36	21.33	20.74	-14.62	-14.35
	10/9/N	8.10		7.70					20.00			
15%	15/7/N	8.00		7.50					16.89			
	15/8/N	8.20	8.12	7.60	7.57	-0.55	-6.77	35.36	16.00	16.59	-18.77	-53.08
	15/9/N	8.15		7.60					16.89			
20%	20/7/N	7.90		7.30					10.22			
	20/8/N	8.20	7.98	7.50	7.32	-0.66	-8.27	35.36	11.11	11.11	-24.25	-68.58
	20/9/N	7.85		7.15					12.00			

Grade of concrete 30

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/1/0	8.30		8.40					34.22			
	0/2/0	8.20	8.23	8.30	8.35	+0.12	+1.46	35.36	36.00	37.04	+1.68	+4.76
	0/3/0	8.20		8.35					40.89			
5%	5/1/S	8.10		7.20					19.11			
	5/2/S	8.10	8.10	7.10	7.13	-0.97	-11.97	35.36	17.33	18.37	-16.99	-48.05
	5/3/S	8.10		7.10					18.66			
10%	10/1/S	8.40		6.90					13.78			
	10/2/S	8.00	8.20	6.40	6.63	-1.57	-19.15	35.36	12.89	13.04	-22.32	-63.12
	10/3/S	8.10		6.60					12.44			
15%	15/1/S	8.10		6.60					12.44			
	15/2/S	8.50	8.30	7.00	6.77	-1.53	-18.43	35.36	11.56	12.44	-22.92	-64.82
	15/3/S	8.30		6.70					13.33			
20%	20/1/S	8.10		6.65					12.89			
	20/2/S	8.10	8.10	6.60	6.58	-1.52	-18.77	35.36	10.22	11.56	-23.80	-67.31
	20/3/S	8.10		6.50					11.56			

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Grade of concrete .....

84 days

Period of Immersion .....

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/7/0	8.40		8.50					40.00			
	0/8/0	8.00	8.15	8.00	8.20	+0.05	+0.61	35.36	42.22	41.33	+5.97	+16.88
	0/9/0	8.05		8.10					41.78			
5%	5/7/S	8.10		6.20					17.33			
	5/8/S	8.10	8.17	6.25	6.28	-1.89	-23.13	35.36	16.89	17.04	-18.32	-51.81
	5/9/S	8.30		6.40					16.89			
10%	10/7/S	8.10		5.50					12.00			
	10/8/S	8.25	8.18	5.45	5.45	-2.73	-33.37	35.36	11.11	11.26	-24.12	-68.16
	10/9/S	8.20		5.40					10.67			
15%	15/7/S	8.45		5.80					10.22			
	15/8/S	8.20	8.25	5.30	5.43	-2.82	-34.18	35.36	9.33	9.78	-25.58	-72.34
	15/9/S	8.10		5.20					9.78			
20%	20/7/S	8.10		5.50					8.44			
	20/8/S	7.80	8.05	5.20	5.43	-2.62	-32.55	35.36	8.44	8.15	-27.21	-76.95
	20/9/S	8.25		5.60					7.56			

Grade of concrete 40

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/1/0	8.20		8.20					44.00			
	0/2/0	8.30	8.27	8.40	8.32	+0.05	+0.60	42.58	44.44	44.15	+1.57	+3.69
	0/3/0	8.30		8.35					44.00			
5%	5/1/C	8.10		7.85					28.89			
	5/2/C	8.20	8.16	7.90	7.85	-0.32	-3.92	42.58	30.66	30.37	-12.21	-28.67
	5/3/C	8.20		7.80					31.56			
10%	10/1/C	8.40		7.85					25.78			
	10/2/C	8.10	8.27	7.65	7.73	-0.54	-6.53	42.58	26.67	26.67	-15.91	-37.36
	10/3/C	8.30		7.70					27.55			
15%	15/1/C	8.20		7.65					24.00			
	15/2/C	8.10	8.17	7.50	7.58	-0.59	-7.22	42.58	24.44	24.00	-18.58	-43.64
	15/3/C	8.20		7.60					23.55			
20%	20/1/C	8.00		7.40					22.22			
	20/2/C	8.20	8.10	7.50	7.43	-0.67	-8.27	42.58	21.33	21.33	-21.25	-49.91
	20/3/C	8.10		7.40					20.44			

APPENDIX IVK

Grade of concrete 40

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/4/0	8.20		8.25					47.11			
	0/5/0	8.00	8.13	8.00	8.15	+0.02	+1.25	42.58	46.22	46.67	+4.09	+9.61
	0/6/0	8.20		8.20					46.67			
5%	5/4/C	8.15		7.80					28.44			
	5/5/C	8.15	8.13	7.75	7.75	-0.38	-4.67	42.58	27.55	27.55	-15.03	-35.30
	5/6/C	8.10		7.70					26.66			
10%	10/4/C	8.10		7.65					23.56			
	10/5/C	8.20	8.17	7.80	7.72	-0.45	-5.51	42.58	24.44	23.70	-18.88	-44.34
	10/6/C	8.20		7.70					23.11			
15%	15/4/C	8.20		7.65					22.22			
	15/5/C	8.10	8.17	7.60	7.62	-0.55	-6.73	42.58	21.78	21.78	-20.80	-48.84
	15/6/C	8.20		7.60					21.33			
20%	20/4/C	8.20		7.60					18.66			
	20/5/C	8.10	8.13	7.50	7.53	-0.60	-7.38	42.58	19.56	18.81	-23.77	-55.82
	20/6/C	8.10		7.50					18.22			

Grade of concrete 40

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/7/0	8.20		8.30					51.55			
	0/8/0	8.35	8.28	8.45	8.37	+0.09	+1.09	42.58	51.55	51.70	+9.12	+21.42
	0/9/0	8.30		8.35					52.00			
5%	5/7/C	8.45		7.70					26.22			
	5/8/C	8.20	8.28	7.50	7.53	-0.75	-9.06	42.58	25.78	25.78	-16.80	-39.46
	5/9/C	8.20		7.40					25.33			
10%	10/7/C	8.10		7.50					22.22			
	10/8/C	8.20	8.13	7.60	7.56	-0.57	-7.01	42.58	22.22	22.52	-20.06	-47.11
	10/9/C	8.10		7.60					23.11			
15%	15/7/C	8.20		7.40					20.00			
	15/8/C	8.10	8.17	7.30	7.35	-0.82	-10.04	42.58	20.00	19.41	-23.17	-54.42
	15/9/C	8.20		7.35					18.22			
20%	20/7/C	8.20		7.40					16.44			
	20/8/C	8.10	8.15	7.40	7.40	-0.75	-9.20	42.58	16.00	15.85	-26.73	-62.78
	20/9/C	8.15		7.40					15.11			

APPENDIX IVM

Grade of concrete 40

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/1/0	8.20		8.20					44.00			
	0/2/0	8.30	8.27	8.40	8.32	+0.05	+0.60	42.58	44.44	44.15	+1.57	+3.69
	0/3/0	8.30		8.35					44.00			
5%	5/1/N	8.40		7.90					30.67			
	5/2/N	8.40	8.40	7.55	7.72	-0.68	-8.10	42.58	31.11	30.67	-11.19	-27.97
	5/3/N	8.40		7.70					30.23			
10%	10/1/N	8.30		7.80					26.22			
	10/2/N	8.00	8.16	7.60	7.70	-0.46	-5.64	42.58	26.67	26.67	-15.91	-37.36
	10/3/N	8.20		7.70					27.11			
15%	15/1/N	8.30		7.75					22.22			
	15/2/N	8.10	8.17	7.50	7.58	-0.59	-7.22	42.58	23.11	23.37	-20.21	-47.46
	15/3/N	8.10		7.50					21.78			
20%	20/1/N	8.10		7.40					16.89			
	20/2/N	8.10	8.10	7.50	7.42	-0.68	-8.40	42.58	19.56	18.37	-24.21	-56.86
	20/3/N	8.10		7.35					18.66			

APPENDIX IVN

Grade of concrete 40

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/4/0	8.20		8.25					47.11			
	0/5/0	8.00	8.13	8.00	8.15	+0.02	+0.25	42.58	46.22	46.67	+4.09	+9.61
	0/6/0	8.20		8.20					46.67			
5%	5/4/N	8.30		7.90					27.56			
	5/5/N	8.50	8.37	8.15	7.95	-0.42	-5.02	42.58	27.11	27.56	-15.02	-35.27
	5/6/N	8.30		7.80					28.00			
10%	10/4/N	8.20		7.50					24.89			
	10/5/N	8.30	8.27	7.60	7.55	-0.72	-8.71	42.58	23.56	24.15	-18.43	-43.28
	10/6/N	8.30		7.55					24.00			
15%	15/4/N	8.60		7.75					20.44			
	15/5/N	8.30	8.43	7.40	7.53	-0.90	-10.68	42.58	19.56	19.85	-22.73	-53.38
	15/6/N	8.40		7.45					19.56			
20%	20/4/N	8.40		7.45					17.78			
	20/5/N	8.20	8.27	7.20	7.28	-0.99	-11.97	42.58	17.33	17.33	-25.25	-59.30
	20/6/N	8.20		7.20					16.89			

40

Grade of concrete .....

84 days

Period of Immersion .....

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/7/0	8.30		8.30					51.55			
	0/8/0	8.35	8.28	8.45	8.37	+0.09	+1.09	42.58	51.55	51.70	+9.12	+21.42
	0/9/0	8.30		8.35					52.00			
5%	5/7/N	8.20		7.70					26.23			
	5/8/N	8.00	8.10	7.60	7.63	-0.47	-11.46	42.58	25.33	25.04	-17.54	-41.19
	5/9/N	8.10		7.60					23.56			
10%	10/7/N	8.20		7.60					21.33			
	10/8/N	8.10	8.13	7.50	7.53	-0.60	-7.387	42.58	22.22	21.33	-21.25	-49.91
	10/9/N	8.10		7.50					20.44			
15%	15/7/N	8.10		7.50					17.78			
	15/8/N	7.90	8.07	7.40	7.45	-0.62	-7.684	42.58	17.78	17.33	-25.25	-59.30
	15/9/N	8.20		7.45					16.44			
20%	20/7/N	8.20		7.60					13.78			
	20/8/N	8.10	8.13	7.40	7.47	-0.66	-8.125	42.58	13.78	14.08	-28.51	-66.96
	20/9/N	8.10		7.40					14.67			

Grade of concrete 40

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/1/0	8.20		8.20					44.00			
	0/2/0	8.30	8.27	8.40	8.32	+0.05	+0.60	42.58	44.44	44.15	+1.57	+3.69
	0/3/0	8.30		8.35					44.00			
5%	5/1/S	8.20		7.40					20.44			
	5/2/S	8.30	8.23	7.60	7.47	-0.76	-9.23	42.58	21.78	21.48	-21.10	-49.55
	5/3/S	8.20		7.40					22.22			
10%	10/1/S	8.20		6.80					18.67			
	10/2/S	8.20	8.20	6.80	6.80	-1.40	-17.07	42.58	17.78	18.37	-24.21	-56.86
	10/3/S	8.20		6.80					18.67			
15%	15/1/S	8.30		6.85					16.44			
	15/2/S	8.25	8.25	6.65	6.70	-1.55	-18.78	42.58	15.11	15.85	-26.73	-62.78
	15/3/S	8.20		6.60					16.00			
20%	20/1/S	8.30		7.00					15.55			
	20/2/S	8.10	8.17	6.40	6.60	-1.57	-19.22	42.58	14.22	14.81	-27.77	-65.22
	20/3/S	8.10		6.40					14.67			

Grade of concrete 40

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/4/0	8.20		8.25					47.11			
	0/5/0	8.00	8.25	8.00	8.157	+0.10	+1.21	42.58	46.22	46.67	+4.09	+9.61
	0/6/0	8.20		8.20					46.67			
5%	5/4/S	8.15		7.40					17.78			
	5/5/S	8.15	8.15	7.65	7.527	-0.631	-7.78	42.58	20.00	18.97	-23.61	-55.45
	5/6/S	8.15		7.50					19.11			
10%	10/4/S	8.10		6.00					16.44			
	10/5/S	8.10	8.10	6.30	6.10	-2.02	-24.69	42.58	16.44	15.70	-26.88	-63.13
	10/6/S	8.10		6.00					14.22			
15%	15/4/S	8.10		6.00					11.11			
	15/5/S	8.20	8.17	6.30	6.13	-2.04	-24.97	42.58	12.00	12.00	-30.58	-71.82
	15/6/S	8.20		6.00					12.89			
20%	20/4/S	8.10		6.10					10.67			
	20/5/S	8.15	8.12	6.15	6.05	-2.07	-25.49	42.58	10.22	10.37	-32.21	-75.65
	20/6/S	8.10		6.00					10.22			

Grade of concrete 40

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/7/0	8.20		8.30					51.55			
	0/8/0	8.35	8.28	8.45	8.37	+0.09	+1.09	42.58	51.55	51.70	+9.12	+21.42
	0/9/0	8.30		8.35					52.00			
5%	5/7/S	8.35		7.60					18.67			
	5/8/S	8.20	8.25	7.50	7.53	-0.72	-8.73	42.58	17.78	17.93	-24.65	-57.89
	5/9/S	8.10		7.50					17.33			
10%	10/7/S	8.10		6.20					15.11			
	10/8/S	8.10	8.10	6.00	6.13	-1.97	-24.32	42.58	14.22	14.67	-27.91	-65.55
	10/9/S	8.10		6.20					14.67			
15%	15/7/S	8.20		5.30					10.67			
	15/8/S	8.20	8.20	5.70	5.50	-2.7	-32.93	42.58	12.44	11.41	-31.17	-73.20
	15/9/S	8.20		5.50					11.11			
20%	20/7/S	8.25		5.60					9.33			
	20/8/S	8.10	8.18	5.40	5.52	-2.66	-32.52	42.58	10.22	9.92	-32.66	-76.70
	20/9/S	8.20		5.55					10.22			

Grade of concrete 50

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/1/0	8.20		8.30					54.00			
	0/2/0	8.10	8.17	8.30	8.30	+0.13	+1.59	50.18	53.33	53.85	+3.67	+7.31
	0/3/0	8.20		8.30					54.22			
5%	5/1/C	8.30		7.90					45.33			
	5/2/C	8.23	8.26	7.90	7.90	-0.36	-4.36	50.18	45.77	45.18	-5.00	-9.97
	5/3/C	8.26		7.90					44.44			
10%	10/1/C	8.15		7.80					41.78			
	10/2/C	8.35	8.23	7.70	7.73	-0.5	-6.08	50.18	40.00	41.48	-8.70	-17.34
	10/3/C	8.20		7.70					42.67			
15%	15/1/C	8.30		7.60					38.22			
	15/2/C	8.30	8.30	7.45	7.52	-0.78	-9.40	50.18	36.44	37.92	-12.26	-24.43
	15/3/C	8.30		7.50					39.11			
20%	20/1/C	8.25		7.60					35.11			
	20/2/C	8.10	8.18	7.55	7.53	-0.65	-7.95	50.18	33.33	34.07	-16.11	-32.10
	20/3/C	8.20		7.45					33.78			

Grade of concrete 50

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl 0%	0/4/0	8.31		8.35					58.88			
	0/5/0	8.10	8.22	8.10	8.25	+0.03	0.36	50.18	59.77	59.25	+9.07	18.07
	0/6/0	8.25		8.30					59.11			
5%	5/4/C	8.30		8.00					40.00			
	5/5/C	8.23	8.28	7.90	7.97	-0.31	-3.74	50.18	38.22	38.81	-11.37	-22.66
	5/6/C	8.30		8.00					38.22			
10%	10/4/C	8.10		7.90					34.67			
	10/5/C	8.20	8.20	7.70	7.78	-0.42	-5.12	50.18	35.56	34.22	-15.96	-31.81
	10/6/C	8.20		7.70					32.44			
15%	15/4/C	8.25		7.70					33.33			
	15/5/C	8.20	8.22	7.70	7.70	-0.52	-6.33	50.18	34.22	33.18	-17.00	-33.88
	15/6/C	8.20		7.70					32.00			
20%	20/4/C	8.35		7.80					31.11			
	20/5/C	8.10	8.23	7.60	7.67	-0.56	-6.80	50.18	32.44	31.41	-18.77	-37.41
	20/6/C	8.25		7.60					30.67			

Grade of concrete 50

Period of Immersion ..... 84 days

Acid/concentration		Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HCl	0%	0/7/0	8.20		8.30					63.33			
		0/8/0	8.15	8.18	8.20	8.23	+0.05	+0.61	50.18	62.22	62.81	+12.63	+25.17
		0/9/0	8.20		8.20					62.88			
	5%	5/7/C	8.30		8.10					36.44			
		5/8/C	8.30	8.30	8.10	8.10	-0.20	-2.41	50.18	37.78	37.03	-13.15	-26.21
		5/9/C	8.30		8.10					36.88			
	10%	10/7/C	8.30		7.85					33.78			
		10/8/C	8.00	8.18	8.00	7.89	-0.29	-3.54	50.18	32.89	32.59	-17.59	-35.05
		10/9/C	8.25		7.80					31.11			
	15%	15/7/C	8.15		7.70					28.89			
		15/8/C	8.30	8.18	7.80	7.70	-0.48	-5.86	50.18	30.22	28.89	-21.29	-42.43
		15/9/C	8.10		7.60					27.56			
	20%	20/7/C	8.15		7.60					27.11			
		20/8/C	8.15	8.17	7.60	7.63	-0.54	-6.61	50.18	25.78	25.93	-24.25	-48.33
		20/9/C	8.20		7.70					24.89			

Grade of concrete 50

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/1/0	8.20		8.30					54.00			
	0/2/0	8.10	8.17	8.30	8.30	+0.13	+1.59	50.18	53.33	53.85	+3.67	+7.31
	0/3/0	8.20		8.30					54.22			
5%	5/1/N	8.30		8.00					45.33			
	5/2/N	8.30	8.27	8.00	7.95	-0.32	-3.87	50.18	46.22	45.78	-4.40	-8.77
	5/3/N	8.20		7.85					45.78			
10%	10/1/N	8.20		7.70					42.66			
	10/2/N	8.45	8.32	8.00	7.87	-4.50	-5.41	50.18	41.33	41.48	-8.70	-17.34
	10/3/N	8.30		7.90					40.44			
15%	15/1/N	8.25		7.70					39.11			
	15/2/N	8.20	8.25	7.60	7.67	-0.58	-7.03	50.18	37.78	38.52	-11.66	-23.24
	15/3/N	8.30		7.70					38.67			
20%	20/1/N	8.20		7.70					34.22			
	20/2/N	8.30	8.27	7.75	7.73	-0.54	-6.53	50.18	35.11	35.26	-14.92	-29.73
	20/3/N	8.30		7.75					36.44			

Grade of concrete 50

Period of Immersion ..... 56 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/4/0	8.31		8.35					58.88			
	0/5/0	8.10	8.22	8.10	8.25	+0.03	0.36	50.18	59.77	59.25	+9.07	18.07
	0/6/0	8.25		8.30					59.11			
5%	5/4/N	8.20		7.75					43.11			
	5/5/N	8.30	8.23	8.00	7.82	-0.41	-4.98	50.18	42.22	42.66	-7.52	-14.99
	5/6/N	8.20		7.70					42.66			
10%	10/4/N	8.20		7.80					40.00			
	10/5/N	8.15	8.20	7.80	7.80	-0.40	-4.88	50.18	40.88	40.58	-9.60	-19.13
	10/6/N	8.25		7.80					40.88			
15%	15/4/N	8.30		7.75					38.22			
	15/5/N	8.20	8.23	7.70	7.72	-0.51	-6.20	50.18	37.33	38.15	-12.03	23.97
	15/6/N	8.20		7.70					38.89			
20%	20/4/N	8.40		7.50					35.56			
	20/5/N	8.30	8.35	7.30	7.37	-0.98	-11.74	50.18	33.33	33.78	-16.40	-32.68
	20/6/N	8.35		7.30					32.44			

Grade of concrete 50

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
HNO_3 0%	0/7/0	8.20		8.30					63.33			
	0/8/0	8.15	8.18	8.20	8.23	+0.05	+0.61	50.18	62.22	62.81	+12.63	+25.17
	0/9/0	8.20		8.20					62.86			
5%	5/7/N	8.25		8.00					40.00			
	5/8/N	8.30	8.28	8.10	8.03	-0.25	-3.02	50.18	37.33	38.67	-11.51	-22.94
	5/9/N	8.30		8.00					38.67			
10%	10/7/N	8.25		7.70					35.55			
	10/8/N	7.95	8.13	7.60	7.67	-0.46	-5.65	50.18	34.22	34.07	-16.11	-32.10
	10/9/N	8.20		7.70					32.44			
15%	15/7/N	8.28		7.80					31.55			
	15/8/N	8.30	8.28	7.80	7.77	-0.51	-6.16	50.18	28.89	30.22	-19.96	-39.78
	15/9/N	8.25		7.70					30.22			
20%	20/7/N	8.10		7.20					28.44			
	20/8/N	8.35	8.25	7.50	7.40	-0.85	-10.30	50.18	28.44	28.14	-22.04	-43.92
	20/9/N	8.30		7.50					27.55			

APPENDIX IVY

Grade of concrete 50

Period of Immersion ..... 28 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/1/0	8.20		8.30					54.00			
	0/2/0	8.10	8.17	8.30	8.30	+0.13	+1.59	50.18	54.33	53.85	+3.67	+7.31
	0/3/0	8.20		8.30					54.22			
5%	5/1/S	8.20		7.70					31.11			
	5/2/S	8.20	8.20	7.70	7.70	-0.50	-6.10	50.18	32.44	31.40	-18.78	-37.43
	5/3/S	8.20		7.70					30.66			
10%	10/1/S	8.35		6.65					29.78			
	10/2/S	8.30	8.30	6.35	6.45	-1.85	-22.29	50.18	28.89	29.04	-21.14	-42.13
	10/3/S	8.25		6.35					28.44			
15%	15/1/S	8.10		6.60					25.78			
	15/2/S	8.15	8.17	6.62	6.62	-1.55	-18.97	50.18	27.11	27.00	-23.18	-46.19
	15/3/S	8.25		6.65					28.00			
20%	20/1/S	8.00		6.50					21.78			
	20/2/S	8.25	8.17	6.60	6.57	-1.60	-19.58	50.18	24.00	24.15	-26.03	-51.87
	20/3/S	8.25		6.60					26.67			

Grade of concrete 50

Period of Immersion ..... 56 days

APPENDIX IVZ1

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/4/0	8.31		8.35					58.88			
	0/5/0	8.10	8.22	8.10	8.25	+0.03	+0.36	50.18	59.77	59.25	+9.07	18.07
	0/6/0	8.25		8.30					59.11			
5%	5/4/S	8.55		7.50					28.44			
	5/5/S	8.20	8.35	7.40	7.43	-0.92	-11.02	50.18	28.89	28.30	-21.88	-43.60
	5/6/S	8.30		7.40					27.56			
10%	10/4/S	8.10		6.00					27.11			
	10/5/S	8.30	8.22	7.50	6.83	-1.39	-16.91	50.18	26.22	26.22	-23.96	-47.75
	10/6/S	8.25		7.00					25.33			
15%	15/4/S	8.30		6.80					23.55			
	15/5/S	8.40	8.30	6.90	6.77	-1.53	-18.43	50.18	24.44	23.55	-26.63	-53.07
	15/6/S	8.20		6.60					22.66			
20%	20/4/S	8.25		6.65					19.55			
	20/5/S	8.35	8.30	6.80	6.72	-1.58	-19.04	50.18	19.11	19.85	-30.33	-60.44
	20/6/S	8.30		6.70					20.89			

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APPENDIX IV/2

Grade of concrete 50

Period of Immersion ..... 84 days

Acid/concentration	Cube's ID Mark	Density B/F Immersion (kg/m^3)	Average	Density A/F Immersion (kg/m^3)	Average	Change in Density (kg/m^3)	% Change In Density	Average Comp. Strength B/F Immersion (N/mm^2)	Comp. Strength A/F Immersion (N/mm^2)	Average	Change In Strength	% Change in Strength
H_2SO_4 0%	0/7/0	8.20		8.30					63.33			
	0/8/0	8.15	8.18	8.20	8.23	+0.05	+0.61	50.18	62.22	62.81	+12.63	+25.17
	0/9/0	8.20		8.20					62.88			
5%	5/7/S	8.25		7.50					24.89			
	5/8/S	8.20	8.22	7.20	7.30	-0.92	-11.19	50.18	24.00	24.59	-25.59	-51.00
	5/9/S	8.20		7.20					24.89			
10%	10/7/S	8.30		6.00					20.00			
	10/8/S	8.30	8.30	6.00	6.03	-2.27	-27.35	50.18	20.87	19.85	-30.33	-60.44
	10/9/S	8.30		6.10					18.67			
15%	15/7/S	8.40		6.10					14.67			
	15/8/S	8.30	8.33	6.10	6.10	-2.23	-26.77	50.18	14.67	14.82	-35.36	-70.47
	15/9/S	8.30		6.10					15.11			
20%	20/7/S	8.10		6.00					11.11			
	20/8/S	8.10	8.12	6.10	6.07	-2.05	-25.25	50.18	12.44	12.15	-38.03	-75.79
	20/9/S	8.15		6.10					12.89			

Appendix VA: Grade 30 Concrete in HCl

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
28 days	HCL 0%		37.04	4.75	
	5%		27.11		23.33
	10%		24.59		30.46
	15%		21.63		38.83
	20%		15.70		55.60
56 days	0%		40.30	13.97	
	5%		22.81		35.49
	10%		21.03		40.53
	15%		18.81		46.80
	20%		15.85		55.18
84 days	0%		41.33	16.88	
	5%		20.15		43.01
	10%		17.63		50.14
	15%		15.12		57.24
	20%		11.70		66.91

Appendix VB: Grade 30 Concrete in HNO_3

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
28 days	HNO_3 0%		37.04	4.75	
	5%		24.89		29.61
	10%		22.67		35.89
	15%		20.30		42.59
	20%		14.52		58.94
56 days	0%		40.30	13.97	
	5%		23.12		34.62
	10%		21.63		38.83
	15%		17.78		49.72
	20%		12.89		63.55
84 days	0%		41.33	16.88	
	5%		22.52		36.31
	10%		20.74		41.35
	15%		16.59		53.08
	20%		11.11		65.58

Appendix VC: Grade 30 Concrete in H_2SO_4

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
28 days	H_2SO_4 0%		37.04	4.76	
	5%		18.37		48.05
	10%		13.04		63.12
	15%		12.44		64.82
	20%		11.56		67.31
56 days	0%		40.30	13.97	
	5%		17.78		49.72
	10%		11.70		66.91
	15%		10.67		69.82
	20%		10.07		71.52
84 days	0%		41.33	16.88	
	5%		17.04		51.81
	10%		11.26		68.16
	15%		9.78		72.34
	20%		8.15		76.95

Appendix V0: Grade 40 Concrete in HCl

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
28 days	HCl 0%		44.15	3.69	
	5%		30.37		28.67
	10%		26.67		37.38
	15%		24.00		43.64
	20%		21.33		49.91
56 days	0%		46.67	9.61	
	5%		27.55		35.30
	10%		23.70		44.34
	15%		21.78		48.84
	20%		18.81		55.82
84 days	0%		51.70	21.42	
	5%		25.78		39.46
	10%		22.52		47.11
	15%		19.41		54.42
	20%		15.85		62.78

Appendix VE: Grade 40 Concrete in HNO_3

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
28 days	HNO_3 0%		44.15	3.69	
	5%		30.67		27.97
	10%		26.67		37.36
	15%		23.37		47.46
	20%		18.37		56.86
56 days	0%		46.67	9.61	
	5%		27.56		35.27
	10%		24.15		43.28
	15%		19.85		53.38
	20%		17.33		59.30
84 days	0%		51.70	21.42	
	5%		25.04		41.19
	10%		21.33		49.91
	15%		17.33		59.30
	20%		14.08		66.93

Appendix Vf: Grade 40 Concrete in H_2SO_4

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
28 days	H_2SO_4 0%		44.15	3.69	
	5%		21.48		49.55
	10%		18.37		56.86
	15%		15.85		62.78
	20%		14.81		65.22
56 days	0%		46.67	9.61	
	5%		18.97		55.45
	10%		15.70		63.13
	15%		12.00		71.82
	20%		10..37		75.65
84 days	0%		51.70	21.42	
	5%		17.93		57.89
	10%		14.67		65.55
	15%		11.41		73.20
	20%		9.92		76.70

Appendix VG: Grade 50 Concrete in HCl

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
28 days	HCl 0%		53.85	7.31	
	5%		45.18		9.97
	10%		41.48		17.34
	15%		37.92		24.43
	20%		34.07		32.10
56 days	0%		59.25	18.07	
	5%		38.81		22.66
	10%		34.22		31.81
	15%		33.18		33.88
	20%		31.41		37.41
84 days	0%		62.81	25.17	
	5%		37.03		26.21
	10%		32.59		35.05
	15%		28.89		35.05
	20%		25.93		48.33

Appendix VH: Grade 50 Concrete in HNO_3

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
28 days	HNO_3 0%		53.85	7.31	
	5%		45.78		8.77
	10%		41.48		17.34
	15%		38.52		23.24
	20%		35.26		29.93
56 days	0%		59.25	18.07	
	5%		42.66		14.99
	10%		40.58		19.13
	15%		38.15		23.97
	20%		33.78		32.68
84 days	0%		62.81	25.17	
	5%		38.67		22.94
	10%		34.07		32.10
	15%		30.22		39.78
	20%		28.14		43.92

Appendix VI: Grade 50 Concrete in H_2SO_4

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
28 days	H_2SO_4 0%		53.85	7.31	
	5%		31.40		37.43
	10%		29.04		42.13
	15%		27.00		46.19
	20%		24.15		51.87
56 days	0%		59.25	18.07	
	5%		28.30		43.60
	10%		26.22		47.75
	15%		23.55		53.07
	20%		19.85		60.44
84 days	0%		62.81	25.17	
	5%		24.59		51.00
	10%		19.85		60.44
	15%		14.82		70.47
	20%		12.15		75.79

Appendix VIA: Grade 30 Concrete at 28 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
28 days	0% (All acids)		37.04	4.75	
	5% : HCl		27.11		23.33
	HNO_3		24.89		29.61
	H_2SO_4		16.99		48.05
	10%: HCl		24.59		30.46
	HNO_3		22.67		35.89
	H_2SO_4		13.04		63.12
	15% HCl		21.63		38.83
	HNO_3		20.30		42.59
	H_2SO_4		12.44		64.82
	20% HCl		15.70		55.60
	HNO_3		14.52		58.94
	H_2SO_4		11.56		67.31

Appendix VIB: Grade 30 Concrete at 56 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
56 days	0% (All acids)		40.30	13.97	
	5% : HCl		22.81		35.49
	HNO_2		23.12		34.62
	H_2SO_4		17.78		49.72
	10%: HCl		21.03		40.53
	HNO_3		21.63		38.83
	H_2SO_4		11.70		66.91
	15% HCl		18.81		46.80
	HNO_3		17.78		49.72
	H_2SO_4		10.67		69.82
	20% HCl		15.85		55.81
	HNO_3		12.89		63.55
	H_2SO_4		10.07		71.52

Appendix VIC: Grade 30 Concrete at 84 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		35.36			
84 days	0% (All acids)		41.33	16.88	
	5% : HCl		20.15		43.01
	HNO_3		22.52		36.31
	H_2SO_4		17.04		51.81
	10%: HCl		17.63		50.14
	HNO_3		20.74		41.35
	H_2SO_4		11.26		68.16
	15% HCl		15.12		57.24
	HNO_3		16.59		53.08
	H_2SO_4		9.78		72.34
	20% HCl		11.70		66.91
	HNO_3		11.11		68.58
	H_2SO_4		8.15		76.95

Appendix VID: Grade 40 Concrete at 28 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
84 days	0% (All acids)		44.15	3.69	
	5% : HCl		30.37		28.67
	HNO_3		30.67		27.97
	H_2SO_4		21.48		49.55
	10%: HCl		26.67		37.36
	HNO_3		26.67		37.36
	H_2SO_4		18.37		56.86
	15% HCl		24.00		43.64
	HNO_3		23.37		47.46
	H_2SO_4		15.85		62.78
	20% HCl		21.33		49.91
	HNO_3		18.37		56.86
	H_2SO_4		14.81		65.22

Appendix VIE: Grade 40 Concrete at 56 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
56 days	0% (All acids)		46.67	9.61	
	5% : HCl		27.55		35.30
	HNO_3		27.56		35.27
	H_2SO_4		18.97		55.45
	10%: HCl		23.70		44.34
	HNO_3		24.15		43.28
	H_2SO_4		15.70		63.13
	15% HCl		21.78		48.84
	HNO_3		19.85		53.38
	H_2SO_4		12.00		71.82
	20% HCl		18.81		55.82
	HNO_3		17.33		59.30
	H_2SO_4		10.37		75.65

Appendix VIF: Grade 40 Concrete at 84 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		42.58			
84 days	0% (All acids)		51.70	21.42	
	5% : HCl		25.78		39.46
	HNO_3		25.04		41.19
	H_2SO_4		17.93		57.89
	10%: HCl		22.52		47.11
	HNO_3		21.33		49.91
	H_2SO_4		14.67		65.55
	15% HCl		19.41		54.42
	HNO_3		17.33		59.30
	H_2SO_4		11.41		73.20
	20% HCl		15.85		62.78
	HNO_3		14.08		66.96
	H_2SO_4		9.92		76.70

Appendix VIG: Grade 50 Concrete at 28 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
28 days	0% (All acids)		53.85	7.31	
	5% : HCl		45.18		9.97
	HNO_3		45.78		8.77
	H_2SO_4		31.40		37.43
	10%: HCl		41.48		17.34
	HNO_3		41.48		17.34
	H_2SO_4		29.04		42.13
	15% HCl		37.92		24.43
	HNO_3		38.52		23.24
	H_2SO_4		27.00		46.19
	20% HCl		34.07		32.10
	HNO_3		35.26		39.73
	H_2SO_4		24.15		58.87

Appendix VIH: Grade 50 Concrete at 56 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
56 days	0% (All acids)		59.25	18.07	
	5% : HCl		38.81		22.66
	HNO_3		42.66		14.99
	H_2SO_4		28.30		43.60
	10%: HCl		34.22		31.81
	HNO_3		40.58		19.13
	H_2SO_4		26.22		47.75
	15% HCl		33.18		33.88
	HNO_3		38.15		23.97
	H_2SO_4		23.55		53.07
	20% HCl		31.41		37.41
	HNO_3		33.78		32.68
	H_2SO_4		19.85		60.44

Appendix VII: Grade 50 Concrete at 84 days of Immersion

Period of Immersion	Acid/ Concentration	Original Strength (N/mm^2)	New Strength (N/mm^2)	Increase (%)	Decrease (%)
		50.18			
84 days	0% (All acids)		62.81	25.17	
	5% : HCl		37.03		26.21
	HNO_3		38.67		22.94
	H_2SO_4		24.59		51.00
	10%: HCl		32.59		35.05
	HNO_3		34.07		32.10
	H_2SO_4		19.85		60.44
	15% HCl		28.89		42.43
	HNO_3		30.22		39.78
	H_2SO_4		14.82		70.47
	20% HCl		25.93		48.33
	HNO_3		28.14		43.92
	H_2SO_4		12.15		75.79