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خلد أحمد جاسم عبد الواحد البياتي

إشراف

أ.م.د. مهدي صالح عيسى
أ.م.د. ماهر بهنام السمعاني

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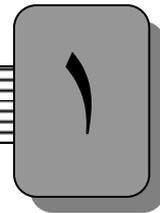
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CHAPTER



INTRODUCTION

General

The ability of structural concrete to retain its original form, quality and serviceability when exposed to corrosive environments is nowadays a subject of considerable world wide concern and study. In general, degradation of concrete structures may result from the environment to which the concrete is exposed or by internal causes within the concrete. However, acidic attack is probably one of the most common causes of deterioration at the present time.

Acidic solutions containing hydrogen ions are frequently encountered in industrial practice. For example, hydrochloric, sulfuric or nitric acids may be present in effluents of the chemical industry. Acetic, formic or lactic acids are found in many food products. Carbonic acid, H_2CO_3 presents in soft drinks, high CO_2 concentrations are also found in natural waters.

The exchange reaction between the acidic solutions and the constituents of Portland cement paste gives rise to soluble salts of calcium, such as calcium chloride, calcium acetate, and calcium bicarbonate, which are removed by leaching. In natural ground waters, only sulphuric acid is likely to be found as a result of the oxidation of sulfides minerals such as pyrites and marcasite. When concrete is in

contact with such acidic waters, the calcium hydroxide reacts with the sulphuric acid to form gypsum. Which can be readily washed away^(r0,r1,r2,r3,r4). However, on a wider scale, acid rain, in which sulfuric acid is an important component can affect the long-term durability of concrete structures exposed to the atmosphere. Another form of sulfuric acid attack on concrete, which is especially severe in hot climates, occurs in sewage systems. Much higher concentrations of sulfuric acid attack on concrete can occur in industrial environments. The most common forms of such attack are random spillage^(r5). Leakage or irresponsible dumping of chemical waste from industrial processes can also lead to sulfuric acid attack on concrete.^(r6)

Sulfuric acid is formed under natural conditions when iron sulfide minerals, pyrite for example, undergo oxidative weathering in the presence of air and water by processes which may be both chemical and biochemical. The first stage is a chemical reaction and is the oxidation of the iron disulfide to ferrous sulfate and sulfuric acid.^(r7)

1.2 Research Significance

Acidic solutions are among the most aggressive solutions to concrete and mortar and include both mineral acids such as sulphuric, hydrochloric, nitric, phosphoric and organic acids such as lactic, citric, formic and tannic. With all the Portland cement compounds being susceptible but the free lime is attacked most readily. The attacking acid can usually be identified by the salt of the acid deposited in the concrete. For example, sulphuric acid reacts with calcium hydroxide or calcium silicate hydrate resulting gypsum which is deposited in solution or reacts with calcium aluminate phase in cement to form calcium silphoaluminate (ettringite). The product at crystallisation can cause expansion disruption

of the concrete .Hydrochloric acid reacts with all compounds of portland cement resulting calcium chloride . Nitric acid reacts with all compounds of portland cement resulting calcium nitrate, which is readily washed away. The use of chemical admixtures and finely divided mineral admixtures may be advantageous in maintaining the high PH level inside the concrete which reduce the penetration rate of the acidic solutions. These admixtures react slowly to give the insoluble or soluble salts of calcium. Hence, reduction in compressive strength was occurs substantially with time.

It is necessary to investigate another cementing material which can not be affected so much with acids such as sulphur cement. There is a very definite need for low cost / high performance binder materials. Sulphur bound system appears to be a very promising answer to this need. Sulphur mortar is used in special cases like floors with bed joint where Portland cement concrete is not completely satisfactory. Since sulfur concrete and mortar can be formulated to resist acid and salt corrosion, hence, they are being tested to be used for tanks, electrolytic cells, thickeners, bridged jacking, industrial flooring, bricks and pipes.^(१,२,३)

The sulphur mix reaches its full strength in hours, which has practical and economic advantages particularly for precast industry. Sulphur mixes possess many useful characteristics exhibited by Portland cement concrete as well as some unique properties which make them suitable for many special applications. Sulphur – sand mixes promise excellent structural and mechanical properties at low relative cost. However, heat susceptibility and effect of water and temperature cycling still need to be examined very carefully to overcome the problem of long – term durability.^(४)

For these reasons sulphur sand mixes have been thoroughly investigated to determine the mix design, the best method for preparation of mixture and the behavior particularly when subjected to temperature variation and the effect of acids at different concentrations.

1.3 Objective and Scope

The objective of this work is to produce mortar or concrete with high resistance to acidic solution.

The degree of deterioration was assessed by the change in compressive strength, modulus of rupture, absorption and change in weight. The performance of specimens prepared with various types of mortar under the effect of sulphuric, nitric and hydrochloric acid solutions for different concentrations were also investigated. Such acidic concentrations may be encountered in effluents of chemical industry.

For the purpose of this investigation, compressive strength, change in weight and absorption were carried out on 3312 cubes. On the other hand, modulus of rupture tests were conducted on 1066 prisms, which were exposed to 1% concentrations of acid solutions for a period of 28 days, to 5% concentrations for a period of 24 hours.

Linear shrinkage and coefficient of thermal expansion were measured from 48 specimens tested for a period of two days.

1.4 Research Layout

The research work in the present thesis is covered in five chapters. Chapter one is the introduction of the research. Chapter two demonstrates the review of previous works on different types of sulphur mortar and concrete and also, demonstrates the chemical resistance of them.

Chapter three deals with the materials, mix proportion, method of testing. Further, it includes the experimental program and information about the acidic solutions.

The results of all test specimens under the effect of acidic solution with their discussion are presented in chapter four.

Chapter five is devoted to the conclusions of this work and suggestions for further research.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

The literature review presented in this chapter covers the following aspects:-

1. Sulphur.
2. Sulphur mortar and Concrete.
3. Chemical Resistance of Sulphur mortar and concrete.

2.2 Sulphur

2.2.1 Specifications and Standards:

Mark, Othmer, Overberger, and Seaborg ⁽⁶⁾, reported that the Sulphur, S, was a nonmetallic element and is the second element of group VIA below oxygen and above Selenium. In massive elemental form, Sulphur is often referred to as brimstone. Sulphur is one of the most important raw materials of the chemical industry.

Although the modern history of Sulphur may have begun with proof in the late 18th century by Lavoisier that Sulphur is an element, Sulphur recovered as a by-product, ie, involuntary Sulphur, accounts for a larger portion of world supply than the voluntary material. It was obtained from hydrogen sulfide, which evolves with natural gas, crude

petroleum, tar sands, oil shales, and coal which are desulfurized. Other sources of Sulphur include metal sulfides, e.g., pyrites; sulfate materials, e.g., gypsum; and elemental Sulphur in native and volcanic deposits mined in the traditional manner.

Sulphur constitutes 0.03 wt %, of the earth's crust. The forms in which it is ordinary found include elemental or native Sulphur in unconsolidated volcanic rocks, in anhydrite over salt - dome structures, and in bedded anhydrite or gypsum evaporate basin formations, combined Sulphur in metal sulfide ores and mineral sulfates; hydrogen sulfide in natural gas; organic compounds in petroleum and tar sands; and a combination of both pyretic and organic compounds in coal.

Anon., (1970) (as cited by **Jurjees**⁽²¹⁾) reported that the Sulphur abundant in the subsoil at different levels from the ground surface in many parts of the world, such as the Gulf Coast in the United States, in Poland and Mishraq in Iraq. The main impurities in elemental Sulphur are air inclusions, water, hydrosulphides, heavy metal sulphides, sulfoxy acids and some arsenic, selenium and tellurium.

Commercial Sulphur is derived from two principle sources. It can originate from the huge natural deposits of the element in the world and it can be formed generally as a by product from oil and gas refining.

Sulphur is mined by open pit method or by Frasch hot water process from deeper deposits. The Frasch operation contributes about three quarters of the native Sulphur in the United States, Poland, Mexico and USSR. Iraq began its production from extensive reserves and undoubtedly would become a major producer.

A super heated water was pumped into underground stratum of porous limestone impregnated with Sulphur. Melted Sulphur was then pumped to the surface and allowed to solidify in large open vats.

Several other methods for detecting small amounts of elemental Sulphur have been developed.

Quantitatively, Sulphur in a free or combined state is generally determined by oxidizing it to a soluble sulfate, by fusion with an alkali, carbonate if necessary, and precipitating it as insoluble barium sulfate. Oxidation could be effected with such agents as concentrated or fuming nitric acid, bromine, sodium peroxide, potassium nitrate, or potassium chlorate.

2.2.2 Allotropy

Sulphur crystallizes in at least two distinct systems: the rhombic and monoclinic forms. Rhombic sulphur, S_{α} , was stable at atmospheric pressure up to 90.0°C , at which transition to monoclinic sulphur, S_{β} , takes place. Monoclinic sulphur was then stable up to its natural melting point of 114.0°C . The basic molecular unit of both of these crystalline forms of sulphur is the octatomic sulphur ring S_8^R . Other forms of solid sulphur included hexatomic sulphur, as well as modifications of catenapolysulfur⁽⁶⁾.

Wiewiorowski., Touro. (1909) and **Meyer** (1977) (as cited by **Mark., Othmer., Overburger.** And **Seaborg.**⁽⁶⁾) reported that the molecular constitution of liquid sulphur undergoes significant and reversible changes with temperature variations. These changes were evidenced by characteristic temperature dependence of the physical properties of sulphur. In most studies of liquid sulphur, some striking changes in its physical properties were observed at 16.0°C . For example, the viscosity of purified sulphur at 12.0°C which was about 11 MPa.s (=cP) dropped to a minimum of 6.7 Mpa.s at 10.7°C , and then began to rise. At $(10.9-16.0)^{\circ}\text{C}$ the viscosity of liquid sulphur rised very sharply to 30 MPa.s at 16.0°C and reached a maximum of 93 Pa.s (930 P) at 18.7

°C. above this temperature, the viscosity gradually dropped off again to 2 Pa.s (2·P) at 3·6 °C.

A qualitative exploration of these viscosity changes in terms of the allotropy of sulphur implies that, below 109 °C sulphur consists mainly of S₈ rings, and a normal decrease of viscosity with rising temperature is observed. The sudden increase in the viscosity of sulphur above 109 °C is attributed to the formation of polymeric sulphur chain molecules. Then, as the temperature is raised further, the concentration of polymeric sulphur continues to increase, but the opposing effect of chain length resulting from thermal sulphur-sulphur bond scission causes a gradual decrease in viscosity in the temperature range between 187 °C and the boiling point of sulphur⁽⁶⁾.

Coethales., Moss. And Schmidt ⁽⁷⁾. studied the inorganic polymers and reported that the simplest sulphur-containing polymer was sulphur itself. The stable structures of elemental sulphur consist of eight-membered rings (α -sulphur or rhombic, and β -sulphur or monoclinic forms). When molten sulphur is heated above 109 °C, a viscous melt is formed which consists of an equilibrium mixture of linear chains and eight-membered rings. By rapid cooling, the polymeric structure was maintained and the product obtained was insoluble in carbon disulfide, in contrast to ordinary sulphur. The yield of polymer depended on the temperature of the melt, the speed of the cooling, and the temperature to which it has been cooled. When the polymer was obtained from a melt which has been heated above 200 °C and when the obtained product was stretched, new properties appeared.

At room temperature, polymeric sulphur is unstable and slowly degraded to the stable eight-membered ring structure (α - sulphur). This transformation occurs less rapidly in the stretched form than in the unstretched.

Allotropic forms of sulphur has been studied also by other investigators. Their results are summarized in **Jurjees**^(r) thesis.

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Sulphur Mortar and Concrete

A number of attempts investigated the guide for mixing and placing sulphur mortar and concrete in construction. This sulphur mortar and concrete have been made to improve the resistance of mortar and concrete to various types and concentrations of acids.

Bacon and Davis as cited by **Fontana, Farrell, and Yuan**^(r) used sulphur as a construction material to utilize the surplus sulphur. They tested many suggested additives for modifying the properties of sulphur for specific applications and found that almost all of these additives were unsuitable.

Duecker as cited by **Fontana, Farrell, and Yuan**^(r), found that the ۷۰% sand and ۳۰% sulphur mixture of **Bacon and Davis** increases in volume on thermal cycling with a loss in flexural strength. He was able to retard both the tendency for volume increase and the resulting loss of strength on thermal cycling by modifying the sulphur with an olefin polysulfied. He used additives to prepare more stable cements and produced more industrial acceptance. More research and development were achieved by means of improving sulphur products to be used as acid-resistant mortars and grouts.

Mckinney as cited by **Fontana, Farrell, and Yuan**^(r), outlined testing methods for sulphur materials that had been found satisfactory at the **Mellon** Institute. Many of these methods have been adopted and were found in ASTM specifications for chemical resistant sulphur mortar. The developments that led to the ability to modify sulphur and produce a more durable product brought increased interest in research towards commercial activities.

Fontana, Farrell, and Yuan ⁽⁷⁾ found that a mixture of 10% sand and 4% sulphur produces an acid resistant material with excellent strength. An accelerated laboratory test program was conducted by them to evaluate the response of sulphur cement concrete cylinders to acidic solutions. The response of the specimens, made using sulphur cement and having design compressive strength of 20.5 N/mm² to 51.5 N/mm², was evaluated through visual examination.

Samarai, Laquerbe and Hadithi ⁽⁸⁾ concluded that the structural and physical properties of sulphur sand mixes vary widely depending on mix design used and sand grading. Maximum strengths were achieved using a dense graded sand with sulphur level chosen to just fill the voids. They found that compressive strength of the range 30-50 MPa and flexural strength of 5.0 MPa have been obtained with these mixes.

They found also that no loss of strength with time occurred, and compared it with normal portland cement concrete and found that sulphur and sand mix gains strength very rapidly and reaches about 90% of ultimate strength in about (9) hours under ambient temperature and humidity condition.

Khan and Al-Tayyib ⁽⁹⁾ reported that the sulphur concrete is a thermoplastic mixture of sulphur, coarse aggregate, sand and usually filler powder. They identified this product as an acid and salt-resistant construction material which can be used in certain situations where conventional portland cement concrete (PCC) has limited life span, such as in floors, sumps and drainage ditches of chemical and metallurgical plants. Also, they studied reinforcing steel corrosion. The reinforced specimens were partially immersed in 5 percent sodium chloride solution for a period of (7) years and were subjected to corrosion measurement. The test results indicated that the time to corrosion initiation of reinforcing steel in sulphur concrete is longer than that in portland

cement concrete. But, once the corrosion initiates, the corrosion rate of reinforcing steel in sulphur concrete is higher than that in a good-quality portland cement concrete.

McBee, Weber and Ward⁽¹⁾ studied the chemical resistance of sulphur concrete to typical agents for industrial uses. The sulphur concrete was prepared with proper mix proportions by mixing molten sulphur polymer cement with mineral aggregates, producing a high strength concrete product with an average compressive strength of 7000 psi (48 Mpa) upon cooling. Because of its thermoplastic nature, the mechanical strength properties of sulphur concrete (Sc) were achieved rapidly upon solidification, with 80% of the ultimate strength achieved after few hours. Sulphur concretes that have been developed were essentially impervious to moisture permeation and extremely resistant to most mineral acid and salt solutions.

The materials were evaluated in over 60 industrial process environments in a cooperative testing program in the sulphur institute and industry and were showing superior performance characteristics to portland cement concrete in special industrial applications where corrosive environments exist⁽¹⁾.

Samarai. and Hadithi⁽¹⁾ studied the effect of temperature on sulphur cement and its molten point is (119 °C). The relation between heat and behavior of sulphur as a building material is very important to be known whether this material is good or not. The research contained a study of the effect of temperature on the resistance of sulphur mortar between (-30 - 100) °C. Results proved that the effect of temperature would be 60% among natural temperature circumstances and 100 °C. On the other hand, research work has been done about the changes with temperature. Two kinds of changes were studied between (0-70) °C and (-30-100) °C. Results showed that the effect of the first change did not

exist and no changes regarding the outside of the material can be recognized. The effect of the second change is clear on the outside shape of the material. There is also a decrease in resistance about 10% after 40 ring of changes.

Ho, J.L.K. and **Woodhams, R.T.** ⁽¹⁹⁾ studied the influence of chopped rovings on fracturing, i.e.; the flexural and compressive strength of sulphur concrete. Fracture energy was found to be sensitive to the length and concentration of the added rovings. Under optimum conditions the fracture toughness could be increased by more than a factor of 20 at fiber concentration approaching 10% by weight of the sulphur content. For optimum performance the chopped rovings should be near their critical pullout length. The preferred length was between 4 and 6 cm for ease of mixing and dispersion. Two types of fibers were compared: a polyester type (polyethylene terephthalate) and a glass fiber type (alkali-resistant). The glass fibers increased maximum flexural load by a factor of 3.6 and the compressive strength by 60% whereas the polyester fibers increased maximum flexural load marginally by a factor of 1.3 and compressive strength by 33% at the optimum fiber length and concentration. Incorporation of a minor quantity of these chopped fibers or rovings into sulphur concrete offers a convenient and simple technique for improving the fracture toughness and ductility of this material. They reported also, that the sulphur concrete used is modified molten sulphur as a binder for graded aggregate to produce a concrete-like construction material with high early compressive strength, good corrosion resistance to strong acids and salt solutions, excellent fatigue resistance, low moisture penetration and excellent freeze-thaw resistance.

Czarnecki, B. and **Gillott, J.E.** ⁽²⁰⁾, reported that the strength of sulphur concrete was affected by factors such as type of aggregate, aggregate particle shape and texture, amount of sulphur binder in the

mix, and type of admixture used. The density of this concrete is also affected by these factors. Some of these concretes perform poorly in moist conditions, as shown by loss of more than 30% strength. Increased amounts of sulphur binder adversely affect the strength of concrete; however, loss of strength of such mixes upon immersion in water was smaller. Type of aggregate influences the strength of concrete, but no correlation was found between the petrography and mineralogy of aggregates and the strength of concrete; the strongest aggregate did not always produce the strongest concrete.

Four types of admixtures were employed: glycerin, crude oil, and two types of silanes. Glycerin and crude oil generally decreased the strength of sulphur concrete. Silane admixtures act as adhesive promoters and were capable of rendering the concrete hydrophobic. Concrete made with aggregate that was pretreated with silanes generally showed a dramatic increase in strength under both dry and wet conditions.

They reported also, that the sulphur concretes are materials in which coarse and fine aggregates are bounded together by elemental sulphur. The concrete was cast in the molten state and bonding occurs on cooling when the sulphur crystallizes. The physical properties of elemental sulphur affected the properties of sulphur concretes, which in some respects were superior to those of portland cement concretes. These properties included rapid strength development, high strength, low permeability, and excellent resistance to strong acids and salts. Sulphur concrete reaches ultimate strength after a few hours, making it a very good choice for low-temperature concreting.

The strength of sulphur concrete varied in the range from 30 to 40 MPa and was comparable to that of portland cement concrete.

Several factors influence the strength of sulphur concrete, such as age of the specimen, size of the specimen, H₂S (Hydrogen Sulfide)

content, mix casting temperature, type and strength of the aggregate, gradation of the aggregate, and amount of sulphur used in the mix. A major draw back to the use of sulphur concrete in construction is that it sometimes shows poor durability due to excessive expansion and cracking in the presence of moisture. This has been found to occur with only certain aggregates ⁽¹⁴⁾.

Samarai, and **Hadithi** ⁽¹⁵⁾, outlined the effect of some factors on the resistance of sulphur mortar as follows:

- Effect of temperature of the mix on its behavior and its mechanical resistance. The suitable temperature for making sulphur mortar is 140 °C and not to exceed 150 °C under all conditions because at this degree oxygen and hydrogen with sulphur would make dangerous and asphyxiated gases (SO₂, SO₃, H₂S).
- Effect of temperature of mould and its fast cooling: if the used mould is hot it will give results better than using cold mould. Results showed that resistance of pressure is not affected by the cooling method after casting.
- Effect of method and circumstances of casting: several experiments showed that the most suitable method to cast the sulphur concrete cubes is by vibration, so the necessary time for vibration was studied also.

Jurjees, T., A;R. ⁽¹⁶⁾ reported that the mix proportions for preparing sulphur concrete were 20% sulphur, 44% sand, 30% coarse aggregate and 1% air voids.

Diehl (1976) (as cited by **Beat Mayer** ⁽¹⁷⁾) discussed the influence of reaction temperature and reaction time on the compressive strength of sulphur concrete with sulphur to sand ratios of 20:80 to 40:60, and of a sulphur foam with a density of 0.3 g/cm³ obtained by adding talcum and an organic blowing agent, "Porofor D33", to sulphur DCPD mixtures. He

discusses in detail the weathering properties and the erosion by organic solvents, salts, acids, and alkalis.

Platou (1981) as cited by **Mark., Othmer., Overberger.** and **Seaborg.**⁽⁶⁾, reported that the sulphur concrete is a mixture of sulphur with fine and coarse aggregates. These materials are heated to 140 °C, placed, and then allowed to cool and solidify into a rigid concrete material. Concrete prepared with sulphur as the binder has mechanical properties comparable to portland cement concrete.

A modified sulphur binder, i.e., sulphur containing 3-5 wt% organic material, has been developed for aggregates. The resultant sulphur concrete products maintain substantially all their initial strength, even after 300-freeze- thaw cycles.

Sulphur concrete was used in many special cases where portland concrete is not completely satisfactory. Since sulphur concrete can be formulated to be resistant to acid and salt corrosion, sulphur concrete is used for tanks, electrolytic cells, thickeners, bridged decking, industrial flooring, and pipes⁽⁶⁾.

Barnes (1967) (as cited by **Mark., Othmer., Overberger.** and **Seaborg.**⁽⁶⁾), reported that the sulphur mortar is used as bricks, blocks, and similar materials. They were stacked one upon the other and since the blocks are dry, they can be moved and adjusted until the desired wall configuration is achieved. The blocks were bonded by applying the coating to the wall surfaces only.

Neville, ⁽⁷⁾ reported that the sulphur concrete consists of sulphur, fine and coarse aggregate, but contains no water or cement. The powdered sulphur and aggregate were mixed in a conventional mixer equipped with a heater so as rapidly to raise the temperature of the mix to 140 °C. At that temperature, the ingredients form a uniform mixture which can be cast into moulds. An alternative procedure was to pre-heat

the coarse aggregate slowly to about 180 °C, and then feed it into a tilting –drum mixer. A sufficient amount of sulphur was added to coat the coarse aggregate, then fine aggregate was added, followed by the remaining sulphur and a workability agent (such as silica flour). On casting, the moulds or forms were over filled to allow for the contraction of sulphur on cooling, after which the surplus concrete was removed by sawing.

The mix proportions (by mass) for optimum strength and workability were, typically 20% sulphur, 32% fine aggregate, 48% coarse aggregate and 0% silica flour. The grading of the aggregate should be selected so as to give a minimum void content. Compared with portland cement concrete, sulphur concrete gains strength very rapidly and attains about 90% of its ultimate strength in 6 to 8 hours under normal temperature and humidity conditions. The high early –age strength made sulphur concrete suitable for use in precast units for outdoor applications. Its good chemical durability made it appropriate for industrial plant use. The disadvantages of sulphur concrete were its brittleness, high creep and the corrosive effect on reinforcing steel under wet or humid conditions. Also, sulphur concrete has a low melting point of 119 °C with a consequential loss of strength. However, sulphur concrete cannot be used where there is a risk of temperature above 100 °C⁽²⁹⁾.

2.4 Chemical Resistance of Sulphur Mortar and Concrete

2.4.1 General Guide

American Society for Testing and Materials C (386-83)⁽¹³⁾ specifies standard practice for [use of chemical – resistant sulphur mortar] as a general guide to the resistance of sulphur mortars in immersed service at ambient temperature, and may usually be upgraded for spillage only.

Specific recommendations can be obtained from this standard for the manufacture of sulphur mortar⁽¹⁷⁾. Table (2-1) was intended for use as a general guide as shown below:

Table (2-1):General guide to chemical resistance of sulphur mortar

Substance	Chemical Resistance
Acids, mineral (nonoxidizing)	R
Acids, mineral (oxidizing)	R
Acids, organic	L
Alkalies, inorganic	N
Bleaches	N
Wet gases, oxidizing	R
Wet gases, reducing	R
Gases, nonoxidizing and nonreducing	R
Organic solvents	L

R = generally recommended

L = limited use

N = not recommended

2.4.2 Chemical Resistance of Sulphur Mortar and Concrete to Acids

McBec, Weber and ward ⁽¹⁾ studied the chemical resistance of sulphur concrete to typical reagents for industrial uses. The sulphur concrete specimens were tested for chemical resistance to twenty six reagents such as acids and salts. The results showed that the sulphur concrete has a good resistance to sulphuric, nitric, hydrochloric acids.

Also, they showed no sign of corrosion or deterioration for a test period of 7 to 9 years.

Some industrial testing results of sulphur concrete were given in table (2-2).

Table (2-2): Industrial testing results of sulphur concrete materials

Environment	Performance
Sulphuric acid	NR
Copper sulphate-sulphuric acid	NR
Magnesium chloride	NR
Hydrochloric acid	NR
Nitric acid	NR
Zinc sulphate-sulphuric acid	NR
Copper slimes	Attacked by organics Used in processing
Nickel sulphate	NR
Vanadium sulphate – sulphuric acid	NR
Uranium sulphate – sulphuric acid	NR
Potash brines	NR
Manganese oxide-sulphuric acid	NR
Hydrochloric acid – nitric acid	NR
Mixed nitric – citric acid	NR
Ferric chloride – sodium	NR
Chloride – hydrochloric acid	NR
Boric acid	NR
Sodium hydroxide	Attacked by > 10% NaOH

Citric acid	NR
Acidic and biochemical	NR
Sodium chlorate – hypochlorite	Attacked by solution at 0. to 7. °C
Ferric – chlorate ion	NR
Sewege	NR
Hydrofluoric acid	NR – with graphite aggregate
Glyoxal – acetic acid formaldehyde	NR
Chromic acid	Deteriorated at 8. °C and 9. % concentration, marginal at lower temperature and concentration

Test results showed no sign of corrosion or deterioration for test period of 7 to 9 years

NR – Non reactive

The element which is closely related to sulphur is selenium, which has a similar group of valences and analogous allotropy. Sulphur was between phosphorus and chlorine horizontally in the periodic table, and its properties are generally those to be expected from its position in that table. An exception is that its melting point is higher than would be expected, probably because of its complex molecular structure.

Tuller (1904) (as cited by **Mark.**, **Othmer.**, **Overberger.** and **Seaborg.**⁽⁶⁾), reported that the sulphur is insoluble in water but is soluble to varying degrees in many organic solvents, eg., carbon disulfide,

benzene, warm aniline, warm carbon tetrachloride, and liquid ammonia-carbon disulfide is the most commonly used solvent for sulphur

Mellor (1930) (as cited by **Mark.**, **Othmer.**, **Overberger.** and **Seaborg.**⁽⁶⁾) reported that sulphur combines directly and usually energetically with almost all of the elements; exceptions include gold, platinum, iridium, and the inert gases. In the presence of oxygen or dry air, sulphur is very slowly oxidizes to sulphur dioxide. When burned in air, it forms predominantly sulphur dioxide with small amounts of sulphur trioxide. In the presence of moist air, sulphurous acid and sulphuric acids were slowly generated.

Hydrochloric acid reacts with sulphur only in the presence of iron to form hydrogen sulfide. Sulphur dioxide forms when sulphur was heated with concentrated sulphuric acid at 200 °C. Dilute nitric acid up to 40% concentration has little effect, but sulphur oxidizes by concentrated nitric acid in the presence of bromine with a strongly exothermic reaction.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Introduction

The aim of this work is to study the resistance of sulphur mortar and concrete to acidic solutions. And also to investigate the mechanical properties of such mortar. This chapter includes the materials used, proportioning of mixes, mixing procedure, casting and curing processes.

It includes also, the testing procedures adopted throughout this investigation.

3.2 Materials

3.2.1 Fine Aggregate

The fine aggregate used throughout this work is glass sand. Tests are carried out to determine the grading, fineness modulus, sulphate content and chemical composition. Results showed that the grading and sulphate content are conformed to Iraqi specifications No. ٤٥:١٩٩٨^(٩), zone (٤) as shown in table (٣-١) and fig (٣-١). The chemical composition is presented in table (٣-٢).

* **Table (٣-١):** Grading and physical properties of fine aggregate

Sieve size (mm)	Cumulative passing %	Limit of Iraqi specification ٤٥:١٩٩٨ ^(١) zone (٤)
٢.٣٦ mm	١٠٠	٨٠ - ١٠٠
١.١٨ mm	١٠٠	٧٠ - ١٠٠
٦٠٠ um	٩٦	٥٥-١٠٠
٣٠٠ um	٦٩.٨٩	٥-٧٠
١٥٠ um	٢.٢٥	-

Bulk Sp.Gr. (Dry basis) = ٢.٦١

Sulfate content = ٠.١٣% max = ٠.٥ %

Fineness modulus = ١.٣١٩

*Physical tests were conducted in the National Center for Construction Laboratories (NCCL).

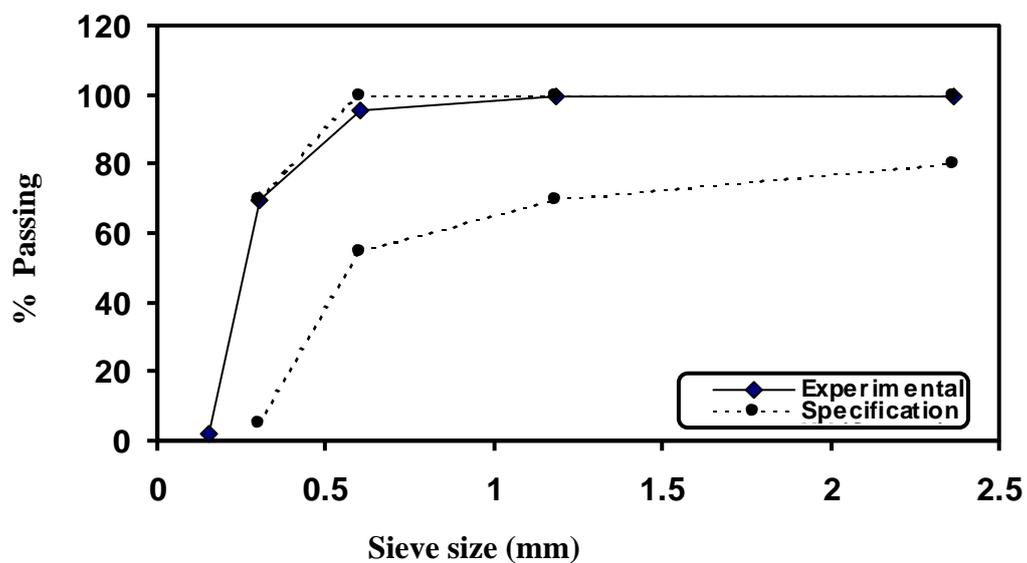


Fig (٣-١): Grading curve for fine aggregate with grading limits of zone (٤)
sand

***Table (۳-۲):** Chemical composition of glass sand

Oxide Composition	Oxide Content
SiO _۲	۹۸.۴۰
Al _۲ O _۳	۱.۲۰
Fe _۲ O _۳	۰.۰۷
CaO	۰.۰۱
MgO	۰.۰۲
L.O. I	۰.۳۰

*Chemical tests were conducted by the office of geological survey and metallurgy.

۳.۲.۲ Sulphur Cement

Sulphur, used throughout this work is agricultural sulphur which was brought from Al-Mishraq Sulphur State Company. The chemical composition and physical properties of sulphur cement are presented in table (۳-۳) and table (۳-۴) respectively.

***Table (۳-۳):** Chemical composition of sulphur cement

Technical Description	Tests Results
۱- Sulphur content (S), (Purity)	۹۷.۹۰
۲- Ash	۰.۰۵
۳- Hydrocarbon	۰.۰۲
۴- Acidity (H _۲ SO _۴)	۰.۰۱
۵- Humidity	۰.۰۲
۶- Calcium Carbonate	۱.۹۰

*Chemical tests were conducted by the office of geological survey and metallurgy.

*Table (۳-۴): Physical properties of sulphur cement

Physical Properties	Test Results
Specific gravity of rhombic sulphur	۲.۱ gm/cm ^۳
Atomic number	۱۶
Atomic weight	۳۲.۰۶۰
Colour	Astraw yellow
State	Agricultural

* Physical tests were conducted by the office of the geological survey and metallurgy.

۳.۳ Mix Proportions

Six basic mixes were prepared in the experimental work of present study. The proportions by total weight of mix were as shown in table (۳-۵).

The procedure of mix design mainly dependeds on modulus of fineness for sand, sulphur cement content and mix casting temperature.

۳.۴ Experimental Procedure

۳.۴.۱ Precautions

Sulphur mortar must be heated and molten in order to be used. If overheated, it ignites and burns with a low blue flame that creates sulphur dioxide. If this happened, heating must be stopped and the vessel must be covered with a tight-fitting lid to smother the flame. When using sulphur mortar in a confined area, each pail of molten material must be checked before entering the area to be sure that the mortar is not burning. The surfaces that molten sulphur mortar will contact to must be dry. All

workmen must be equipped with suitable eye protection and gloves to protect them from spills and splashes of the molten mortar. It is recommended that workmen wear flame retardant clothing. Water should not be used to extinguish ignited sulphur mortar.

۳.۴.۲ Sulphur Cement Specimens

The reference sulphur cement specimens (REF.) prepared for acidic activity test are made from elemental sulphur. They are gave a (۷days) characteristic average compressive strength of ۲۹.۶ MPa and average modulus of rupture of ۱.۳۴ MPa.

After solidification shrinkage with a large concentration drop void appear on the top surface of the cube. Before immersing the elemental specimens in the acidic solutions, the large contraction drop at the top surface of cube is filled with molten sulphur at the same temperature of placing to produce a plane surface cube. Fig (۳-۲) shows a picture that is typically obtained after (۱ day) age.

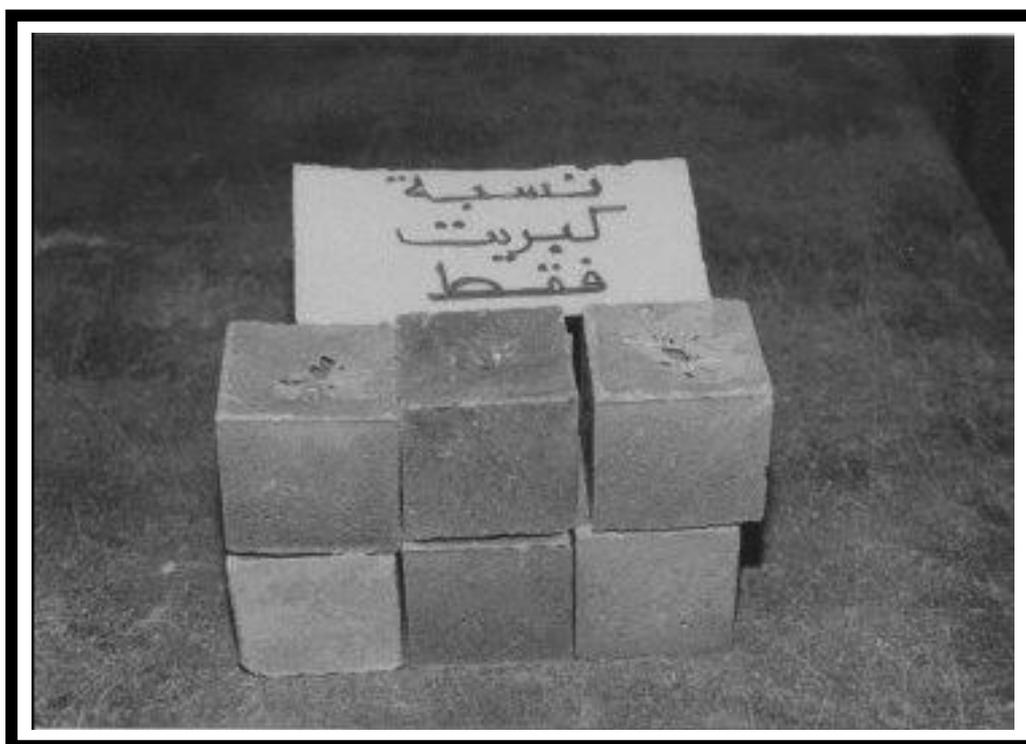


Fig (۳-۲): The reference sulphur cement mixture

3.4.3 Sulphur Mortar Mixtures

The objective of mixture design for sulphur mortar is to determine sulphur cement content, in combination with specific sand, that provides desirable balance between mechanical strength, high specific gravity, low absorption and good workability. Table (3-5) contains data illustrating the properties obtained in developing mixture design for sulphur mortar prepared with varying amount of sulphur cement in combination with glass sand of fineness modulus of 1.319. Trial mixes were found to be necessary to fix the sulphur cement content to the optimum. Figs. (3-3) and (3-4) show the effect of sulphur cement content on the strength of mixtures. The ratio of (37.5%) sulphur is the maximum and should not be exceeded to prevent formation of a skin of sulphur on the sample surface.

Figs (3-5) through (3-9) show pictures that are typically obtained after (1 day) age for reference and sulphur mortar mixtures.

Table (3-5): Proportions of reference and sulphur mortar mixtures

Series	Glass sand % by weight	Sulphur cement % by weight	Average density gm/cm ³	Average (√) days	
				compressive strength (MPa)	Modulus of rupture (MPa)
REF.	-	100	2.100	29.7	1.340
D	70	20	2.224	27.7	2.370
C	71.4	28.6	2.239	22.8	2.474
B	66.0	33.0	2.278	27.7	2.809
E	62.0	37.0	2.300	31.2	3.110
A	60	40	2.209	29.2	2.970

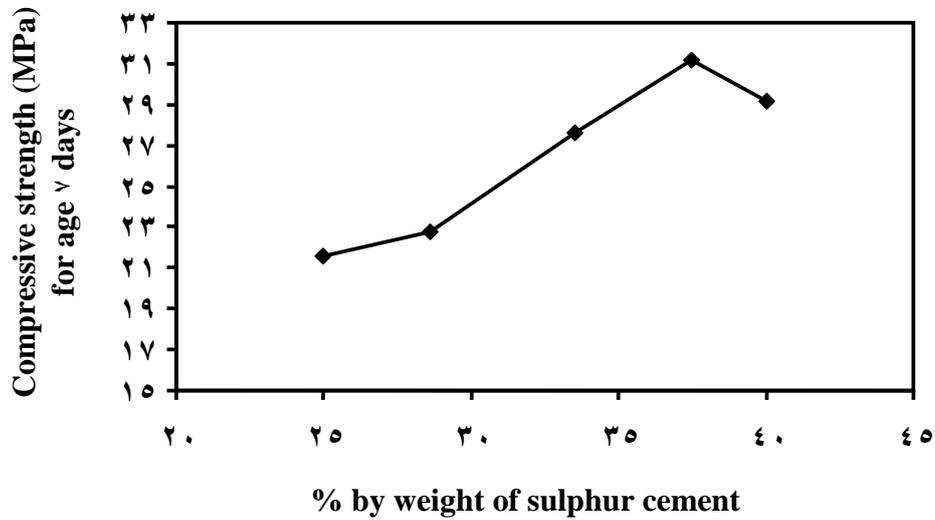


Fig (3-3): Relationship between cement content and modulus of rupture for different studied mixtures

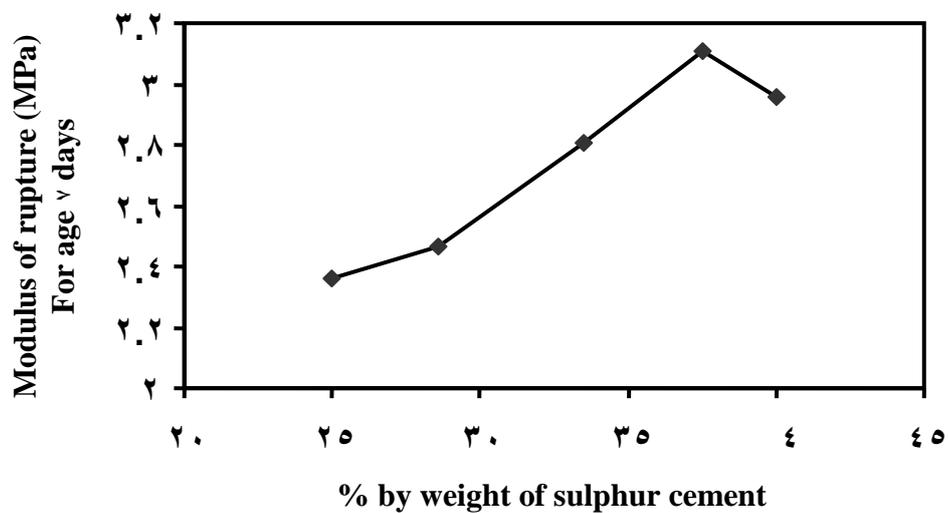


Fig (3-4): Relationship between cement content and compressive strength for different studied mixtures

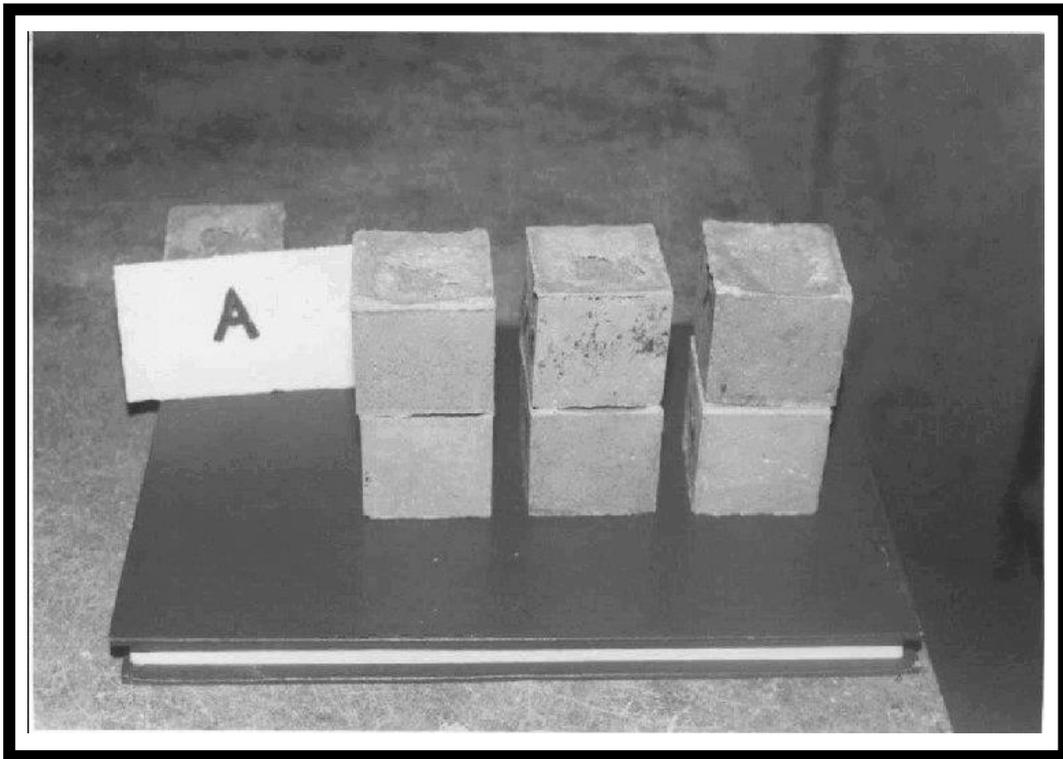


Fig (۳-۵): The Specimens of series (A) sulphur mortar mixture

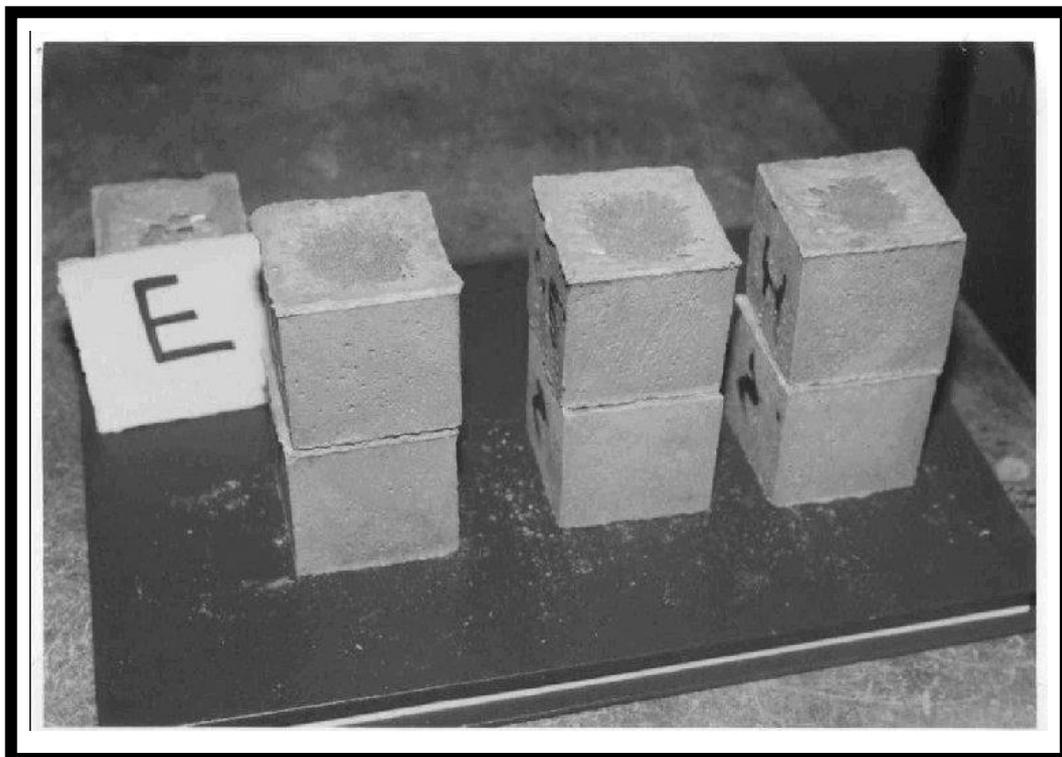


Fig (۳-۶): The Specimens of series (E) sulphur mortar mixture

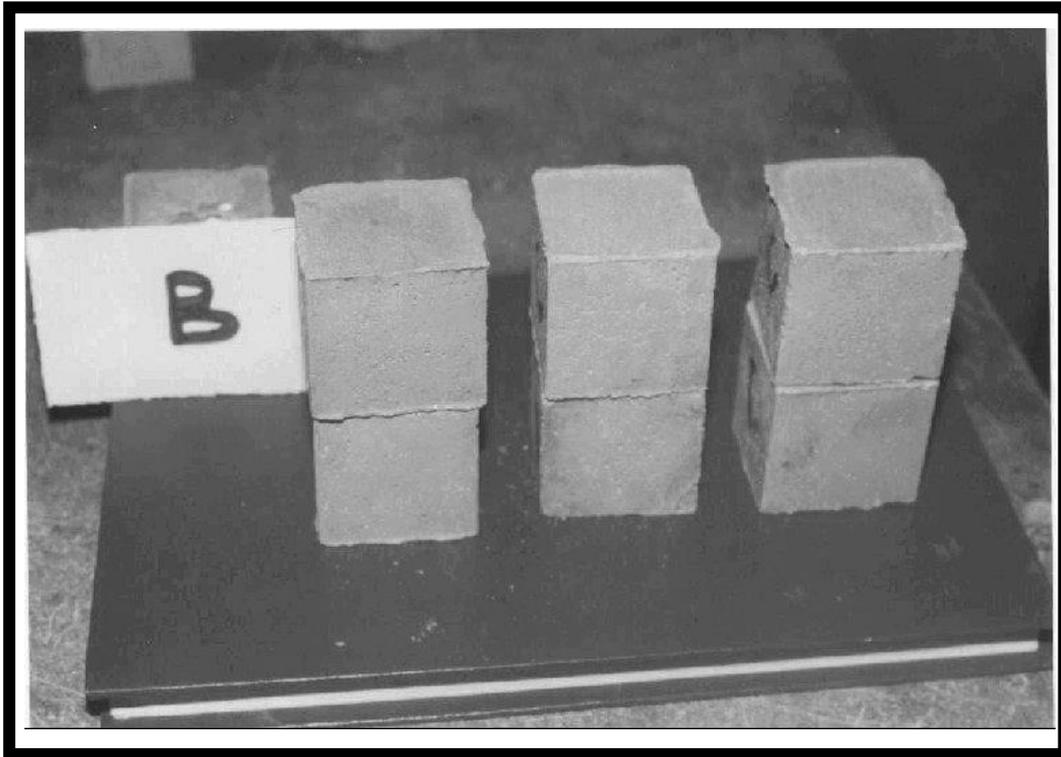


Fig (۳-۷): The Specimens of series (B) sulphur mortar mixture

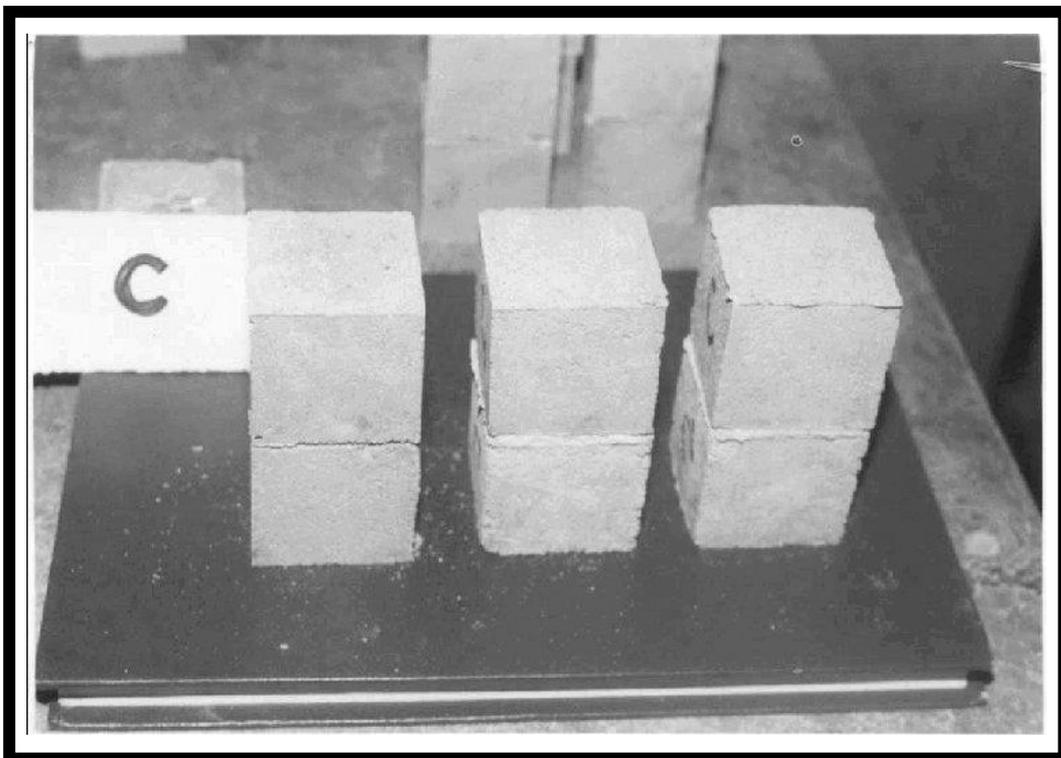


Fig (۳-۸): The Specimens of series (C) sulphur mortar mixture

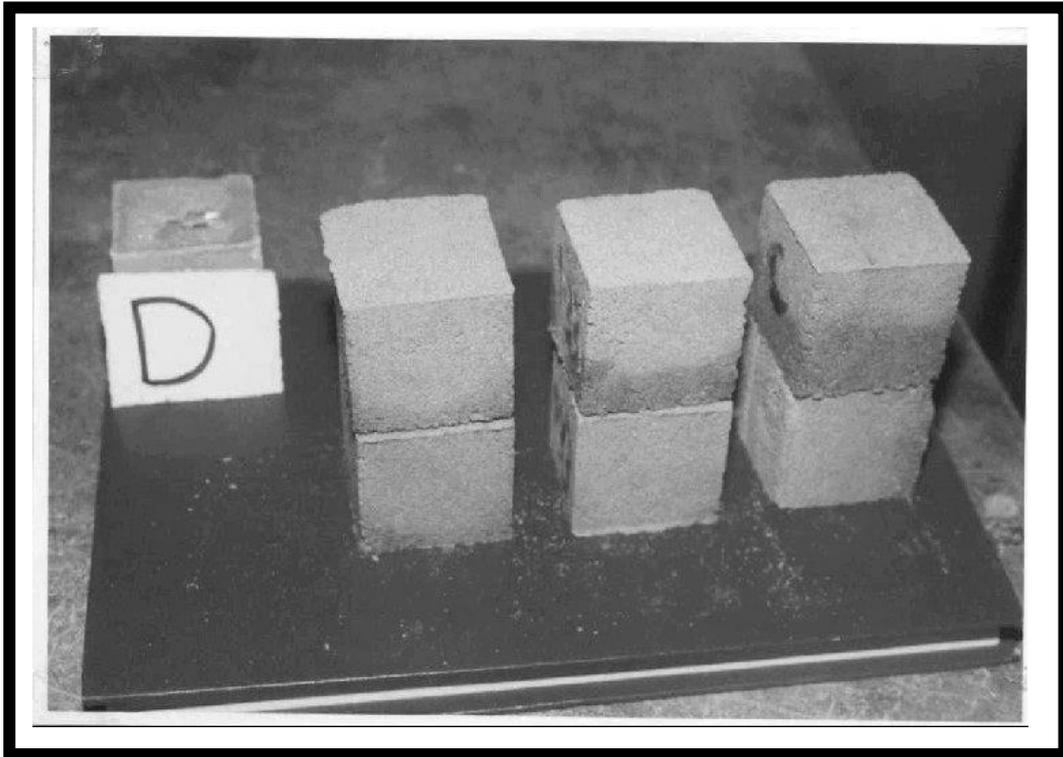


Fig (۳-۹): The Specimens of series (D) sulphur mortar mixture

۳.۵ Specimens Preparation

۳.۵.۱ Mixing

The mixing method which was applied to achieve homogenous mix consists of the following steps:

۱. Putting the sand in a vessel made of aluminium under a heating source.
۲. Heating the sand and mixing it by a trowel until a homogenous a temperature of ۱۴۳°C is attained.
۳. Adding the desired quantity of sulphur and mixing it until the molten sulphur and sand is blended to ensure thorough mixing to give homogenous mix, so that the final sulphur mortar mixture temperature is $(۱۲۹ \text{ to } ۱۴۳)^{\circ}\text{C}$.

۳.۵.۲ Casting

After mixing, the sulphur mortar was poured into hot metallic molds, the molds were well cleaned and the interior surfaces were oiled to prevent adhesion with sulphur mortar after hardening. The molds must be preheated to approximately (143°C) before adding the mixture.

The mixture was compacted in the mold by a heated tamper or by vibration. Samples were cast in an upright position and were finished before solidification.

۳.۵.۳ Curing, Storage and Age of Testing

After casting, the sulphur mortar specimens were allowed to cool at room temperature before being removed from the mold. And should be allowed to cool for a period of (۹ hours) at room temperature. Prior to testing the sulphur mortar shall be stored in closed containers and in a clean, dry place to prevent contamination of the product. The mortar is not found to deteriorate in storage. The compressive strength and flexural strength were investigated at ages ۹h, ۱,۳,۷,۱۴,۲۸ and ۹۰ days before exposure to acidic solutions.

۳.۶ Acid Preparation

According to program of work the following steps were done:

1. Fifteen separate solutions were prepared by adding the ۹۸% concentration of nitric acid, ۹۸% concentration of sulphuric acid and ۳۲% concentration of hydrochloric acid to tap water at three steps to avoid the evolution of toxic gases due to the reaction between the acid and water.

٢. The specimens were then completely immersed in the solutions, which were stored in hard plastic tubes to a depth sufficient to cover the mixture specimens. The PH level of the acidic solutions are monitored every ٣ weeks by means of a portable PH meter.

٣.٦.١ Sulphuric Acid (H_2SO_4)

This acid was brought from Al-Kaaka'a company at a concentration of ٩٨%. Five separate solutions were prepared by adding concentrated sulphuric acid to tap water. They were prepared at concentrations of (٢٠%, ٤٠%, ٦٠%, ٨٠% and ٩٨%). Parallel PH levels and specific gravities are demonstrated in table (٣-٦).

٣.٦.٢ Nitric Acid (HNO_3)

This acid was brought from the Al-Kaaka'a company at a concentration of ٩٨%. Five separate solutions were prepared by adding concentrated nitric acid to tap water. They were prepared at concentration of (٢٠%, ٤٠%, ٦٠%, ٨٠% and ٩٨%). Parallel PH levels and specific gravities are demonstrated in table (٣-٦).

٣.٦.٣ Hydrochloric Acid (HCl)

This acid was brought from the Al-Kaaka'a company at a concentration of ٣٢%. Five separate solutions were prepared by adding concentrated hydrochloric acid to tap water. They were prepared at concentration of (١٠%, ١٥%, ٢٠%, ٢٥% and ٣٢%). Parallel PH levels and specific gravities are demonstrated in table (٣-٦).

Table (٣-٦): Specific gravities and PH levels for acidic solutions

Type of acid	Concentrations %	PH Levels	Specific gravities
Sulphuric	٢٠	٣.٥	١.١٧٠
	٤٠	٢.٦	١.٣٤٠
	٦٠	٢.٢	١.٥١٢
	٨٠	١.٤	١.٦٨٣
	٩٨	٠.٠	١.٨٣٦
Nitric	٢٠	٢.٥	١.٠٨٦
	٤٠	١.٨٦	١.١٧١
	٦٠	٢.٠	١.٢٥٧
	٨٠	١.٦	١.٣٤٣
	٩٨	٠.٠	١.٤٢٠
Hydrochloric	١٠	٣.٥	١.٠٤٠
	١٥	٣.٠٥	١.٠٦١
	٢٠	٢.٦	١.٠٨١
	٢٥	٢.١٥	١.١٠١
	٣٢	١.٥٢	١.١٣٠

٣.٧ Testing Hardened Sulphur Mortar Specimens

٣.٧.١ Compressive Strength Test

The compressive strength tests were performed according to ASTM C (١٠٩-٨٠)^(١٥) and ASTM C (٥٧٩-٨٢)^(١٤) using ٥٠ mm cubes and a testing machine of ٢٠٠ KN capacity.

The load was applied, without interruption, to failure at such a rate of maximum load will be reached is not less than ٢٠ nor more than ٨٠

seconds from start of loading. The tests were performed at the ages of 1h, 1, 3, 7, 14, 28 and 90 days.

3.7.2 Flexural strength (Modulus of Rupture)

The modulus of rupture test was carried out in accordance with ASTM C(39-10) specification. The molds used for casting prisms were (40 by 40 by 160 mm).

One point load method was used in determining flexural strength of the prism specimens. The load was applied at the rate of (264 ± 11 N/min). The flexural strength is equal to the maximum stress at the moment of crack or break. It was calculated as follows:

$$S = \frac{3PL}{2bd^2}$$

Where

S : Flexural strength, MPa

P : Total maximum load, N

L : Span length, mm

b : Width of specimens mm

d : Depth of specimen, mm

3.7.3 Absorption Test

This test was conducted in accordance with B.S 1881- part 6. The specimens were immersed in the acidic solutions until age of test. Each specimen was taken out of the acid and swept by a piece of cloth to remove the acid on the surface and to dry. Each specimen was weighted and the absorption was calculated as follows:

$$A = [(W-D) / (D*G)] * 100$$

Where:

A : absorption %

W : saturated weight of specimen, g

D :Dry weight of specimen before immersed in the acidic solutions, g

G : specific gravity of acid.

Absorption shall be known as the corrected absorption and the result shall express to the nearest 0.1 %.

3.7.4 Weight Change Test

This test was carried out according to ASTM C(267-89)⁽¹²⁾. The 50 mm sulphur mortar cube specimens were immersed in the acidic solution up to the age of the test, then the specimen was extracted from the acidic tank washed by tap water and dried with a cloth as rapidly as possible until all free water is removed from surface. All the specimen were allowed to dry for (1/2 hour). The specimen is weighted to the nearest 0.01 g the change in weight is given by the following equation:

$$\text{weight change \%} = [(W - C) / C] * 100$$

where:

C : The weight of dry specimen before immersion, g

W : Weight of dry specimen after immersion, g

The result showing plus (+) sign indicates gain in weight and the result showing a minus (-) sign indicates a loss in weight.

3.7.5 Density of Specimens

This test was done according to the ASTM C(905-80)⁽⁹⁾. Apparent density of specimens were measured by the weight of a unit

volume of specimens in air and water at specified temperature to nearest 0.01 g. The age of test was (24 hour). Dry (cured) density of the test specimen was calculated as follows:

$$D_d = S / (S - I)$$

Where:

D_d : apparent dry (cured) density, g/cm³

S : weight of specimen in air, g

I : weight of specimen while immersed in water, g

3.7.6 specific Gravity of Acids

This test was carried out according the ASTM E 12-76⁽¹⁴⁾. Apparent specific gravity of liquids was measured by dividing the weight in air of a unit volume of liquid at a stated temperature to the weight in air of equal density of an equal volume of gas free distilled water of a stated temperature.

3.7.7 Linear Coefficient of thermal Expansion Test

This test was carried out according to ASTM C(031-80)⁽¹⁵⁾. The (2.0*2.0*20) cm prisms were placed in the drying oven to attain a constant length and condition at (22 °C) for a minimum period of (16 hours). The length of each bar at (22 °C) was measured with the length comparator. Then they were placed in an oven heated to (70 °C) for (24 hours). The prisms were removed at a rate that did not permit the temperature of the oven to drop below the established temperature. Then they were placed into a desiccator for cooling immediately after the reading is taken at the elevated temperature. The linear coefficient of

thermal expansion per (C^o), C, of the four prisms were calculated as follows:

$$C = (Z - Y - W) / T (W - X)$$

where:

Z : length of bar, including studs, at elevated temperature, mm

Y : length of stud expansion, mm = X * T * K

K : The linear coefficient of thermal expansion per (C^o) of the studs)

W : length of bar, including studs, at initial temperature, mm

T : temperature change, (C^o) and

X : length of the two studs at initial temperature, mm

Table (3-4): Linear coefficient of thermal expansion of reference and sulphur mortar mixtures

Series	Glass sand % by weight	Sulphur cement % by weight	Coefficient of thermal expansion per °C at 70°C
REF.	0.0	100	8.7×10^{-6}
D	70	20	Insignificant
C	71.4	28.6	Insignificant
B	66.0	33.0	Insignificant
E	62.0	37.0	Insignificant
A	60	40	Insignificant

3.7.8 Linear Shrinkage Test

This test was carried out according to ASTM C(031-80)⁽¹⁾. The (2.0*2.0*20) cm prisms were placed in the drying oven to attain a constant temperature and condition at (22 °C) for a minimum period of (16 hours). The length of each bar at (22 °C) was measured with the length comparator. Then they were placed in an oven heated to (70 °C) for (24 hours). To induce cure, cool over night at (22 °C) before measuring, the linear shrinkage for the four prisms were calculated as follows:

$$\text{Percent Shrinkage} = [(L_0 - L) / L_0] * 100$$

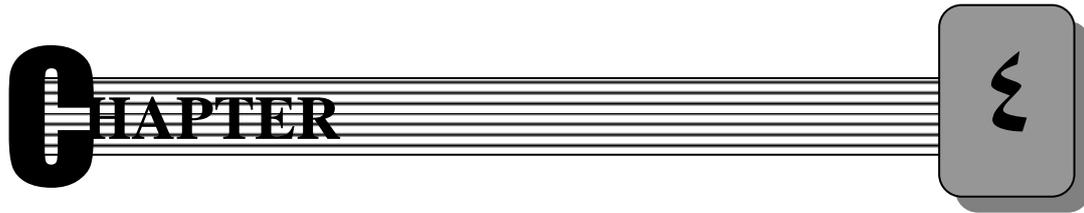
Where:

L_0 : original length (length of standard bar), mm

L : length as measured during or after cure, mm excluding studs.

Table (3-1): Percent linear shrinkage of reference and sulphur mortar mixtures

Series	Glass sand % by weight	Sulphur cement % by weight	Shrinkage %
REF.	0.0	100	0.672
D	70	20	0.163
C	71.4	28.6	0.206
B	76.0	33.0	0.289
E	72.0	37.0	0.303
A	60	40	0.008



RESULTS AND DISCUSSION

4.1 Results:

4.1.1 Compressive Strength Results

The average compressive strength and flexural strength with time before exposure to acidic solutions are demonstrated in table (4-1) and figs (4-1a) through (4-1b). Each value represents the average of three test specimens.

The average compressive strength with time of exposure to (10%, 15%, 20%, 25% and 32%) concentrations of Hydrochloric acid, (20%, 40%, 60% and 80%) concentrations of nitric acid, and (20%, 40%, 60%, 80% and 98%) concentrations of sulphuric acid for reference, sulphur mortar mixtures are demonstrated in table (4-2 to 4-4). Each value represents the average of two test specimens. The graphical representation of these relations is illustrated in figs. (4-2 to 4-4).

4.1.2 Flexural Strength Results

The variation of average flexural strength with exposure time to Hydrochloric acid, nitric and sulphuric acid for various types of sulphur mortar is shown in tables (4-5 to 4-7) and Figs (4-5 to 4-7). Every data

point in these tables represents an average value recorded for two sulphur mortar specimens.

4.1.3 Absorption Results

The absorption of various types of sulphur mortar and reference mixtures after exposure to Hydrochloric acid, Nitric acid and sulphuric acid for periods of (1, 2, 4 and 8 days) are shown in tables (4- 14 to 16) and Figs (4- 18 to 21). Every data point in these tables represents an average value recorded for two sulphur mortar specimens.

4.1.4 Weight Loss Results

The weight loss of reference, sulphur mortar mixtures after exposure to Hydrochloric acid, Nitric acid and sulphuric acid for periods of 1, 2, 4, 8 and 16 days are shown in tables (4- 17 to 19) through (4- 20 to 22) and Figs. (4- 23 to 25).

The corresponding percentages of weight loss for specimens exposed to various concentrations of three types of acids after heating to 40°C, 60°C and 80°C are given in tables (4- 23 to 25). Every data point in these tables represents an average value recorded for two sulphur mortar specimens.

Table (4-1): Compressive strength and flexural strength of reference and sulfur mortar mixtures with time before exposure to acidic solution

Series	Glass sand % by weight	Sulphur Cement % by weight	Average Density _r gm /cm ³	Compressive strength before exposure to acidic solutions (MPa)							Flexural strength (MPa)	
				Age							9 hour	1 day
				9 hour	1 day	3 days	7 days	14 days	28 days	90 days		
REF.	0.0	100	2.1	28	29.2	29.6	29.6	29.7	29.8	29.9	1.1	1.2
D	70	20	2.22 _ε	20	20.3	20.8	21.6	21.4	21.0	21.6	2.0	2.1
C	71.4	28.6	2.23 _ρ	21.2	22.0	22.8	22.8	23.2	23.2	23.7	2.1	2.2
B	66.0	33.0	2.27 _λ	26.8	27.2	27.4	27.6	27.8	28	28	2.0	2.7
E	62.0	37.0	2.30 ₁	30	30.0	30.7	31.2	31.0	31.6	31.7	2.8	3.01
A	60	40	2.20 _ρ	28	28.8	28.9	29.2	29.3	29.7	29.7	2.7	2.80

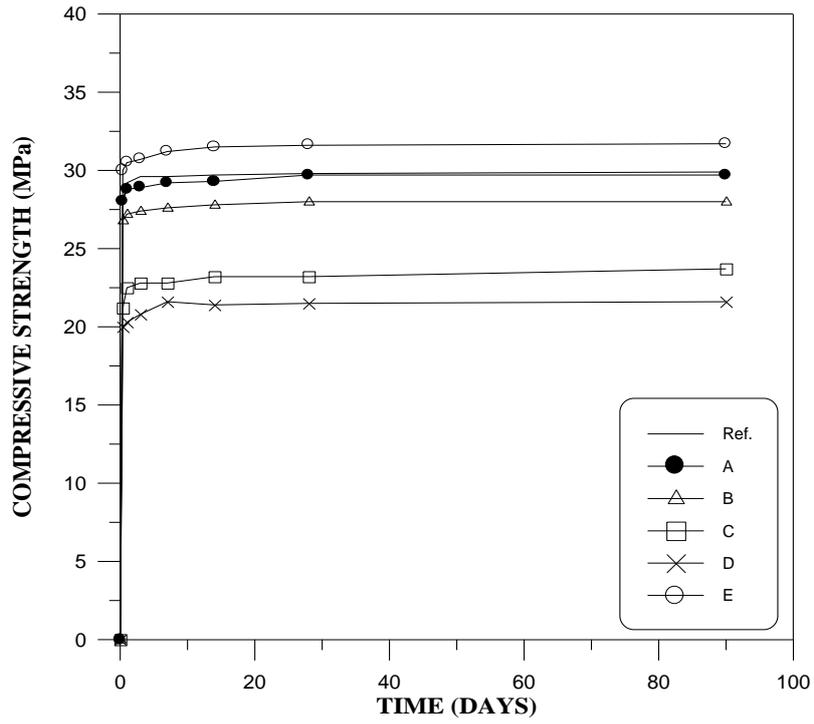


Fig. (4-1a): Compressive strength development with time

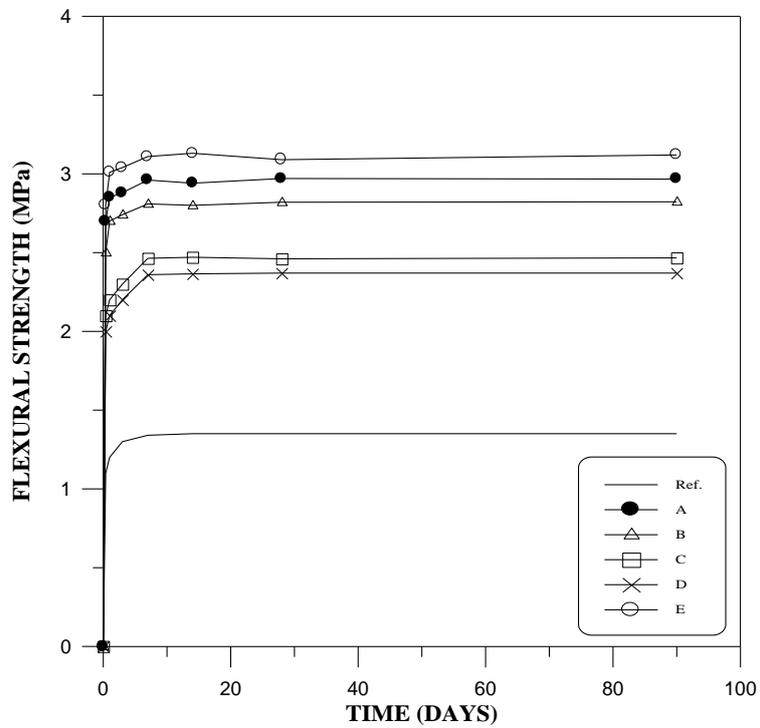


Fig. (4-1b): Flexural strength development with time

Table (4-2): Compressive strength of reference and sulphur mortar mixtures after exposure to hydrochloric acid solutions

Series	Glass sand % by weight	Sulphur Cement % by weight	Compressive strength of dry samples after exposure to acidic solutions (MPa)																				
			Before exposure				22 % concentration				20 % concentration				20 % concentration				10 % concentration				
			10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days					
REF.	00	100	21.6	29.06	29.02	29.44	29.24	29.03	29.46	29.32	29.04	29.0	29.4	29.4	29.48	29.36	29.12	29.64	29.46	29.32	29.04	29.48	
D	20	70	21.6	21.44	21.28	21.96	21.42	21.42	21.22	21.84	21.08	21.37	21.14	21.68	19.76	21.3	21.6	19.6	21.32	21.2	21.04	19.36	21.36
C	28.6	71.4	22.8	22.7	22.00	22.2	22.63	22.46	22.46	22.12	22.4	22.09	22.38	21.96	21.12	22.07	22.34	21.88	22.04	22.28	21.76	22.02	21.72
B	33.0	66.0	22.6	22.49	22.30	22.4	22.48	22.46	22.49	22.1	22.4	22.42	22.44	22.88	22.28	22.4	22.7	22.6	22.6	22.6	22.4	22.6	22.68
E	32.0	62.0	31.2	31.3	31.0	31.08	31.1	31.096	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02
A	40	60	29.2	29.10	29.04	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88	29.88

Table (4-3): Compressive strength of reference and sulphur mortar mixtures after exposure to hydrochloric acid solutions

Series	Glass sand % by weight	Sulphur Cement % by weight	Compressive strength of wet samples after exposure to acidic solutions (Mpa)															
			Before exposure				10 % concentration				20 % concentration				30 % concentration			
			10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days	10 days	20 days	30 days	40 days
REF.	100	100	29.7	29.30	29.1	28.7	29.7	29.38	29.16	28.77	29.84	29.41	29.17	28.78	29.41	29.22	29.84	29.41
D	70	20	21.7	21.4	20.4	19.7	21.8	20.44	19.48	17.8	21.1	20.0	19.4	17.7	21.1	20.8	19.5	17.7
C	71.4	28.7	22.8	22.3	21.8	20.8	21.8	22.33	21.87	20.92	19.4	22.3	21.89	20.99	19.19	22.3	21.89	20.99
B	77.0	33.0	27.7	27.10	27.7	20.8	24.0	27.18	27.77	20.92	24.4	27.7	27.8	24.4	27.7	27.22	27.8	24.4
E	72.0	37.0	31.7	30.8	30.4	29.4	28.7	30.44	29.77	28.78	28.8	30.4	30.0	29.8	28.8	30.4	29.8	28.8
A	70	40	29.7	28.84	28.8	28.4	27.77	28.8	28.77	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8

Table (4-4): Compressive strength of reference, and sulphur mortar mixtures after exposure to nitric acid solutions.

Series	Sulphur Cement % by weight	Glass sand % by weight	Compressive strength of dry samples after exposure to acidic solutions (MPa)																
			Before exposure	2. % concentration				4. % concentration				6. % concentration				8. % concentration			
				1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days
REF.	100	100	29.7	29.03	29.40	29.3	29.0	29.4	29.4	29.1	28.7	29.2	29.2	29.2	29.4	28.47	28.3	28.1	
D	20	70	21.7	21.12	20.71	19.8	18.0	20.9	20.21	18.80	17.1	20.8	20.11	18.40	10.22	19.02	17.42	13.27	
C	28.7	71.4	22.8	22.4	22.0	21.2	19.06	22.2	21.72	20.06	18.3	22.11	21.47	17.22	21.82	20.9	18.98	10.26	
B	33.0	67.0	27.7	27.2	27.8	27.0	24.42	27	27.0	20.01	23.2	27.90	27.30	20.32	22.77	20.77	23.72	19.89	
E	37.0	63.0	31.2	30.89	30.7	30.0	28.60	30.7	30.2	29.21	27.22	30.7	29.9	28.42	27.41	30.20	27.43	23.48	
A	4.0	7.0	29.2	28.92	28.72	28.09	27.98	28.70	28.33	27.41	20.23	28.77	28.11	27.07	24.87	28.3	27.00	20.0	

Table (4-5): Compressive strength of reference and sulphur mortar mixtures after exposure to nitric acid solutions.

Series	Sulphur Cement % by weight	Glass sand % by weight	Compressive strength of wet samples after exposure to acidic solutions (MPa)																
			Before exposure	1. % concentration				3. % concentration				5. % concentration				8. % concentration			
				1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days
REF.	0	100	29.7	29.37	29.10	28.7	27.78	29.2	28.81	27.99	27.39	29.1	28.71	27.74	25.73	28.89	28.17	27.70	23.9
D	20	70	21.7	20.8	19.99	18.38	10.17	20.09	19.08	17.71	13.03	20.0	19.4	17.2	12.81	20.29	18.99	16.37	11.7
C	28	71	22.8	21.98	21.17	19.02	17.23	21.80	20.89	18.99	10.19	21.73	20.77	18.04	14.3	21.06	20.31	17.93	12.94
B	33	66	27.7	27.83	27.7	24.07	21.37	27.79	20.92	23.90	20.3	27.72	29.73	23.87	19.7	27.32	20.3	22.47	17.31
E	37	62	31.2	30.49	29.78	28.02	20.09	30.34	29.0	27.82	24.32	30.3	29.30	27.09	23.7	29.91	28.72	27.04	20.88
A	40	60	29.2	28.07	27.90	27.78	24.2	28.44	27.70	27.1	22.99	28.34	27.02	20.77	22.3	28.01	27.83	24.47	19.71

Table (4-1): Compressive strength of reference and sulphur mortar mixtures after exposure to sulphuric acid solutions.

Series	Glass sand % by weight	Sulphur Cement % by weight	Compressive strength of dry samples after exposure to acidic solutions (MPa)																				
			20 % concentration				40 % concentration				60 % concentration				80 % concentration				98 % concentration				
			Before exposure	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days
REF.	100	100	29.4	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
D	70	70	21.4	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
C	50	50	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
B	30	30	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
E	10	10	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
A	0	0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Table (4-5): Compressive strength of reference and sulphur mortar mixtures after exposure to sulphuric acid solutions.

Series	Glass sand % by weight	Sulphur Cement % by weight	Compressive strength of wet samples after exposure to acidic solutions (MPa)																			
			20 % concentration				40 % concentration				60 % concentration				80 % concentration				98 % concentration			
			Before exposure	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days	80 days	10 days	20 days	40 days
REF.	100	100	29.4	29.4	29.4	28.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4
D	70	70	21.4	21.4	20.4	19.4	18.4	21.4	21.4	20.4	19.4	18.4	21.4	21.4	20.4	19.4	18.4	21.4	21.4	20.4	19.4	18.4
C	50	50	22.4	22.4	22.4	21.4	20.4	22.4	22.4	22.4	21.4	20.4	22.4	22.4	22.4	21.4	20.4	22.4	22.4	22.4	21.4	20.4
B	30	30	27.4	27.4	27.4	26.4	25.4	27.4	27.4	27.4	26.4	25.4	27.4	27.4	27.4	26.4	25.4	27.4	27.4	27.4	26.4	25.4
E	10	10	31.4	31.4	31.4	30.4	29.4	31.4	31.4	31.4	30.4	29.4	31.4	31.4	31.4	30.4	29.4	31.4	31.4	31.4	30.4	29.4
A	0	0	29.4	29.4	28.4	27.4	26.4	29.4	29.4	28.4	27.4	26.4	29.4	29.4	28.4	27.4	26.4	29.4	29.4	28.4	27.4	26.4

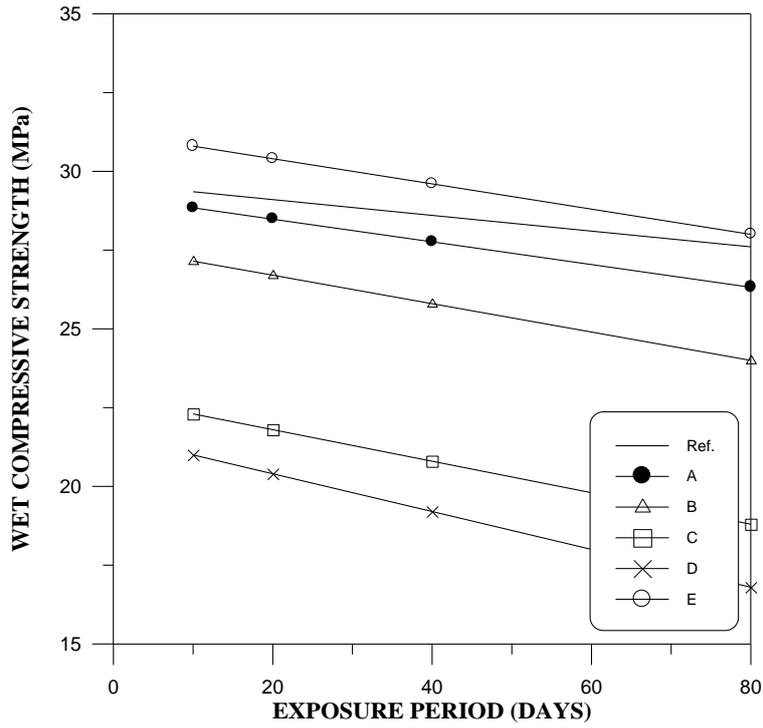


Fig. (4-2): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric acid solution

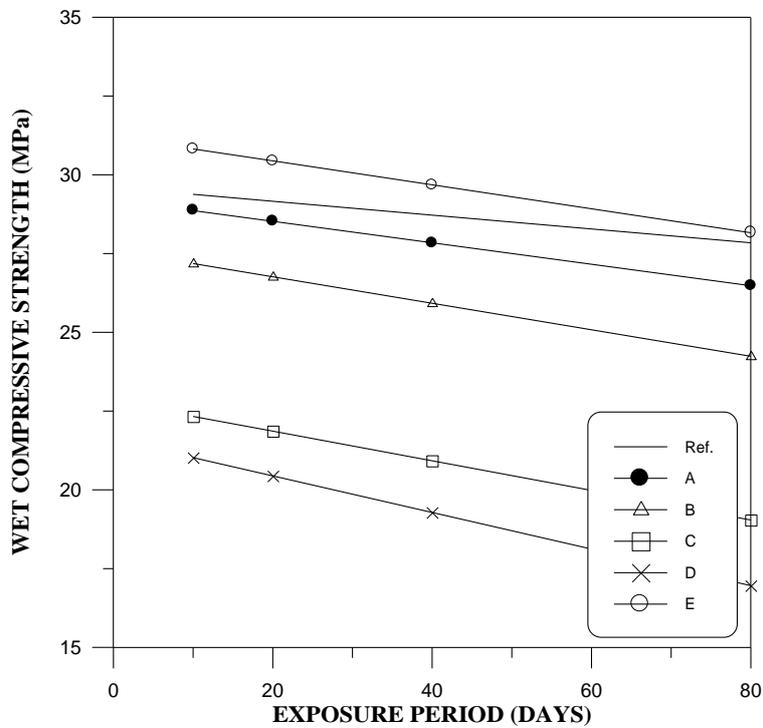


Fig. (4-3): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric acid solution

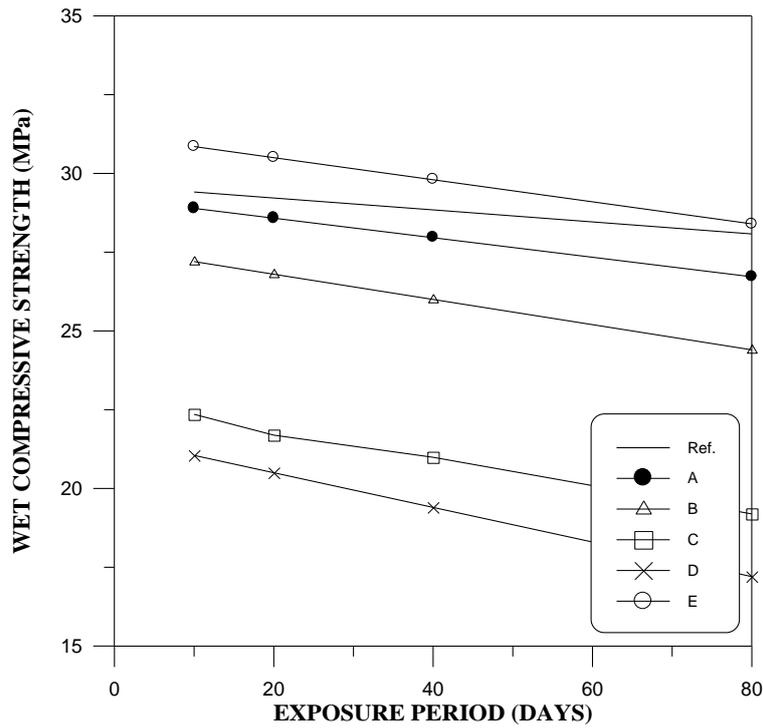


Fig. (4-4): Compressive strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

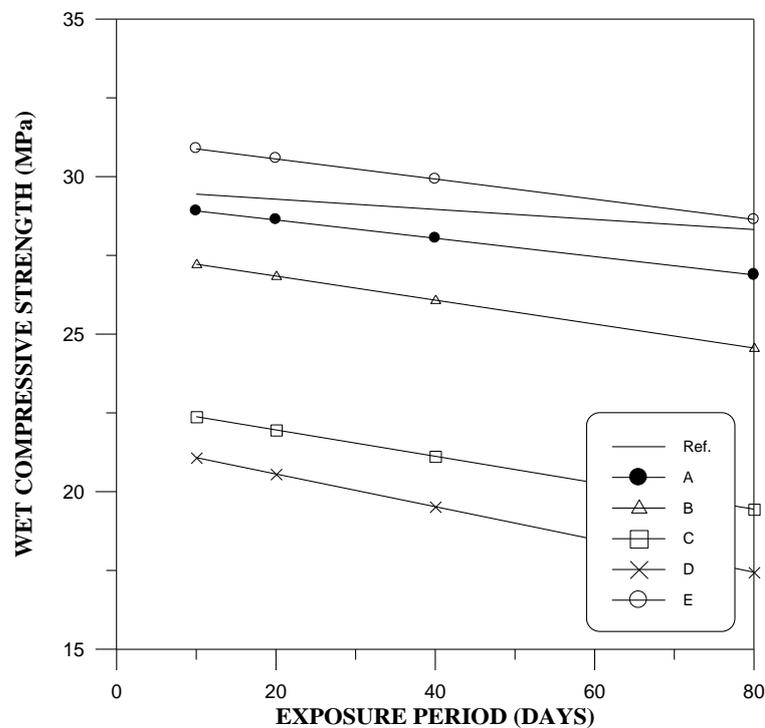


Fig. (4-5): Compressive strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

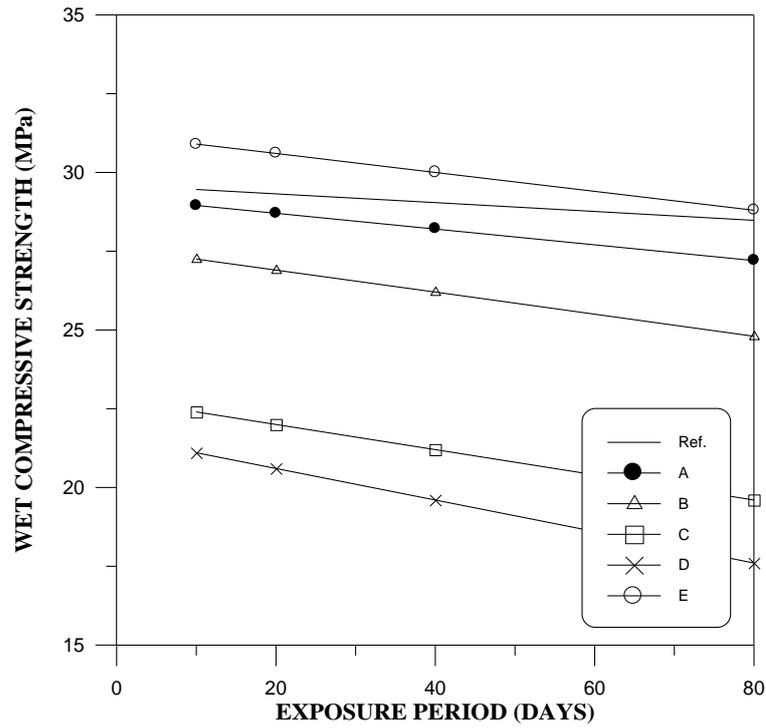


Fig. (4-6): Compressive strength of reference and sulphur mortar specimens after exposure to 32% concentration of hydrochloric Acid Solution

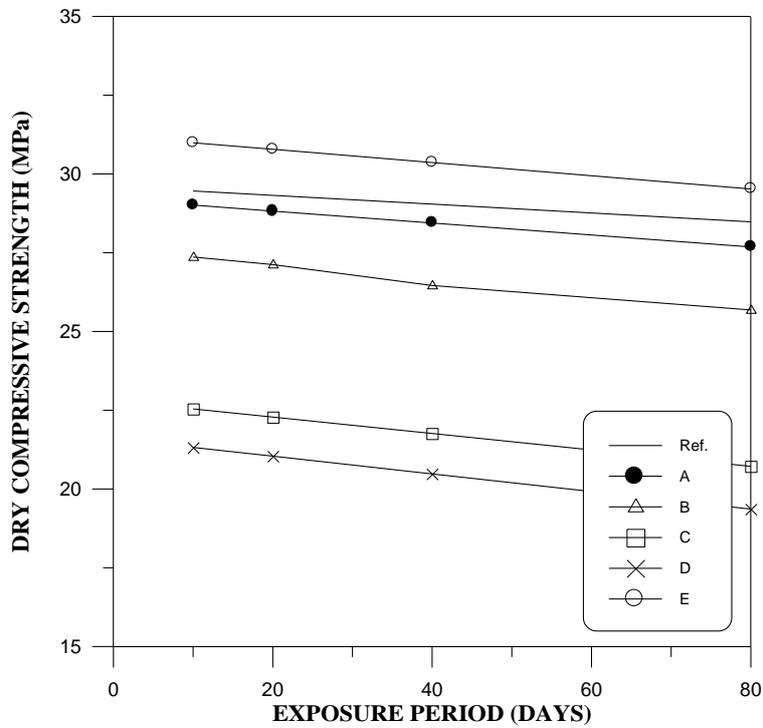


Fig. (4-7): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric Acid solution

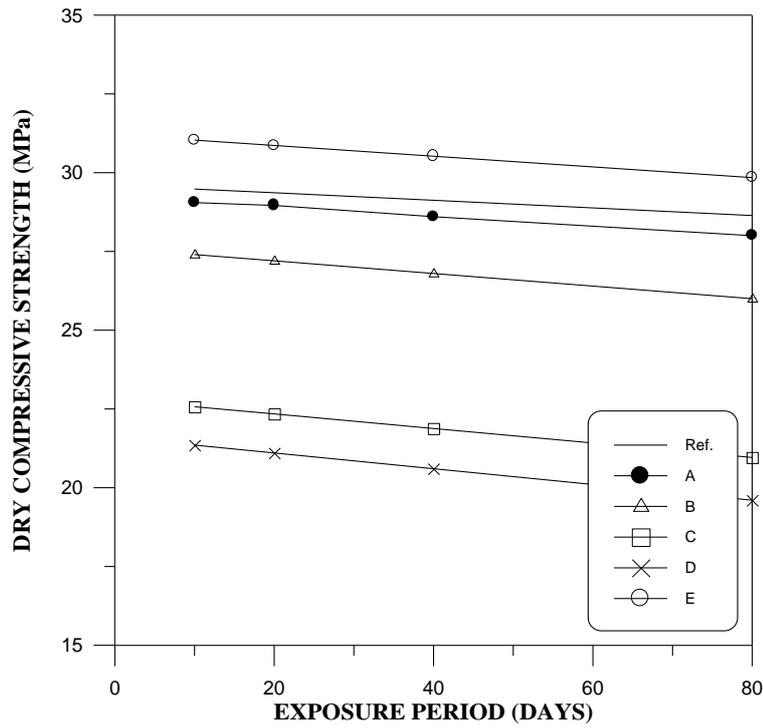


Fig. (4-8): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric Acid solution

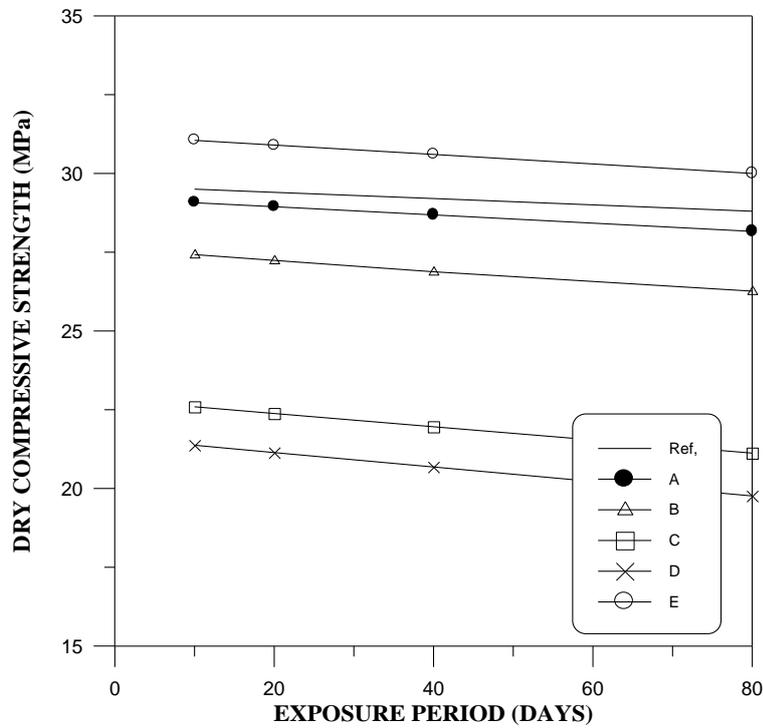


Fig. (4-9): Compressive strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric Acid solution

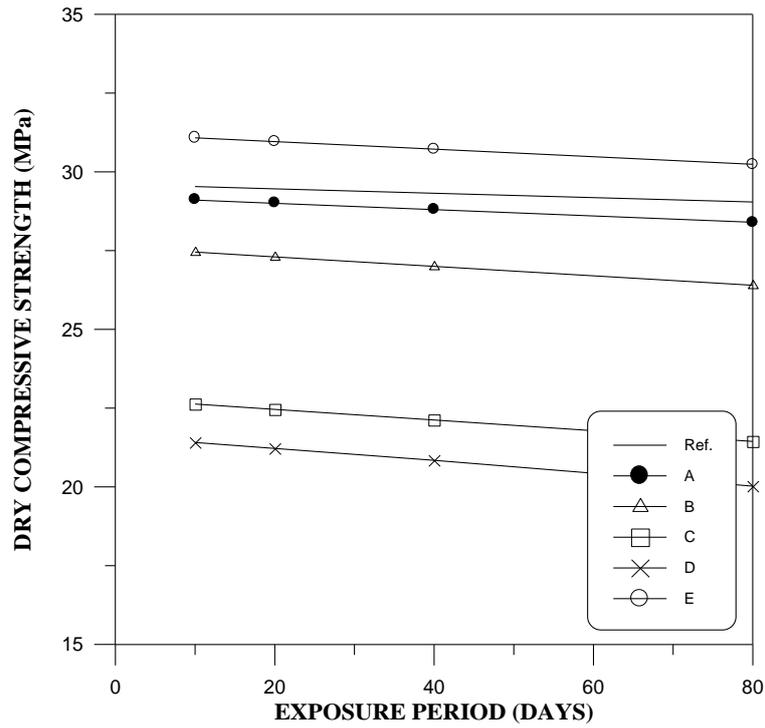


Fig. (4-10): Compressive strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

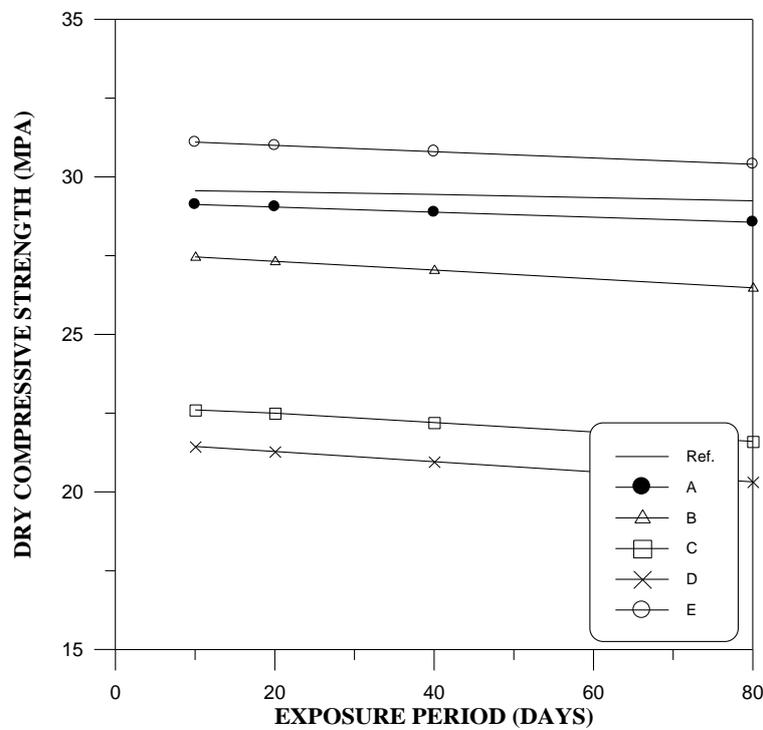


Fig. (4-11): Compressive strength of reference and sulphur mortar specimens after exposure to 32% concentration of hydrochloric acid solution

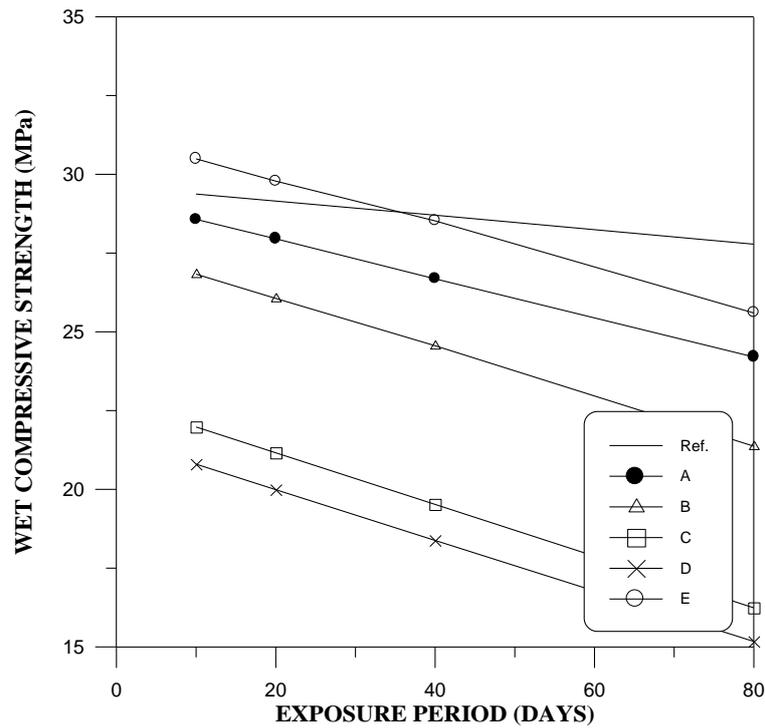


Fig. (4-12): Compressive strength of reference and sulphur mortar specimens after exposure to 2% concentration of nitric acid solution

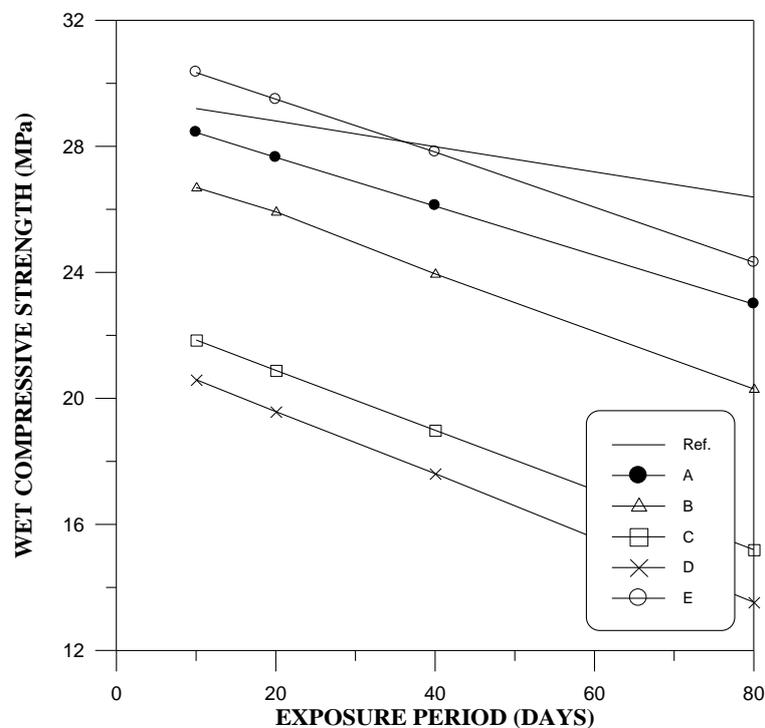


Fig. (4-13): Compressive strength of reference and sulphur mortar specimens after exposure to 4% concentration of nitric acid solution

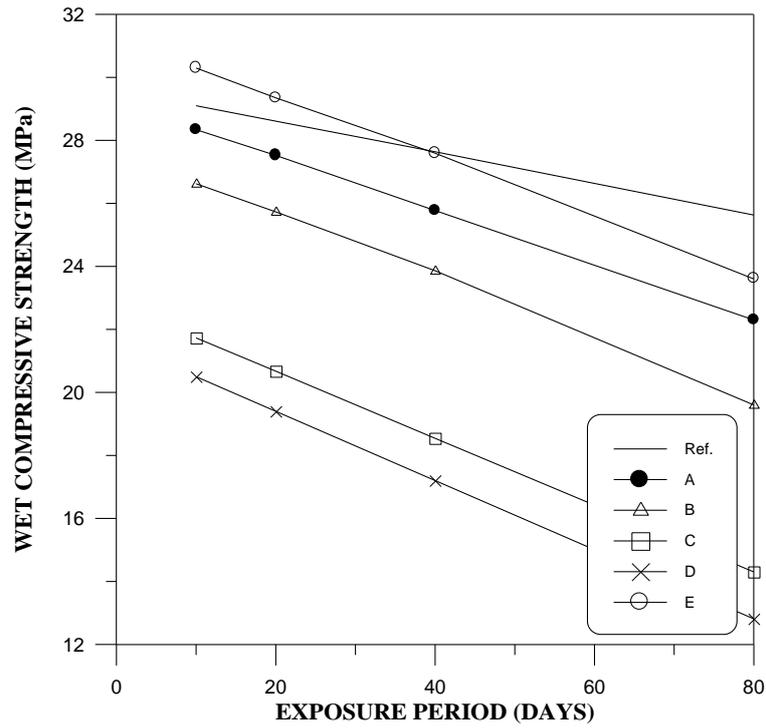


Fig. (4-14): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of nitric acid solution

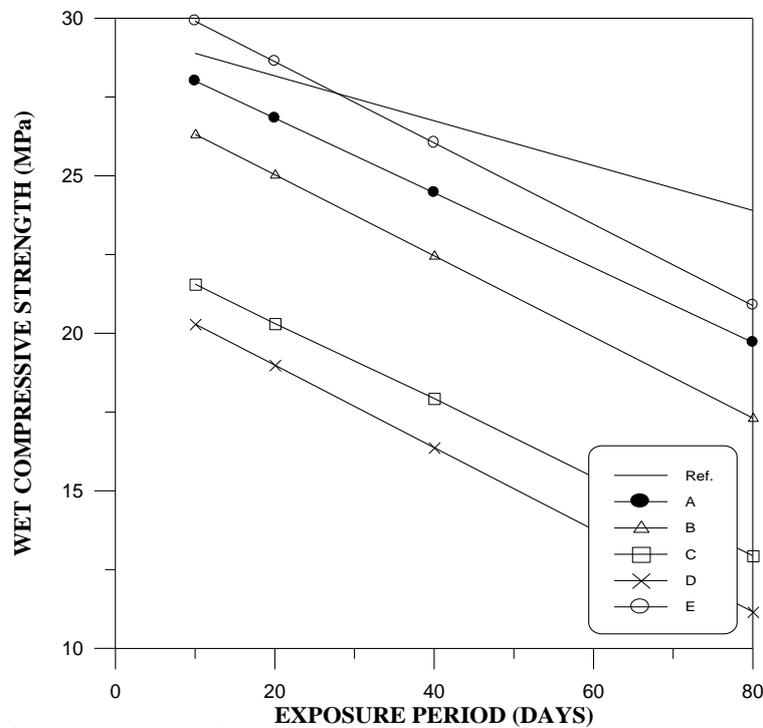


Fig. (4-15): Compressive strength of reference and sulphur mortar specimens after exposure to 8% concentration of nitric acid solution

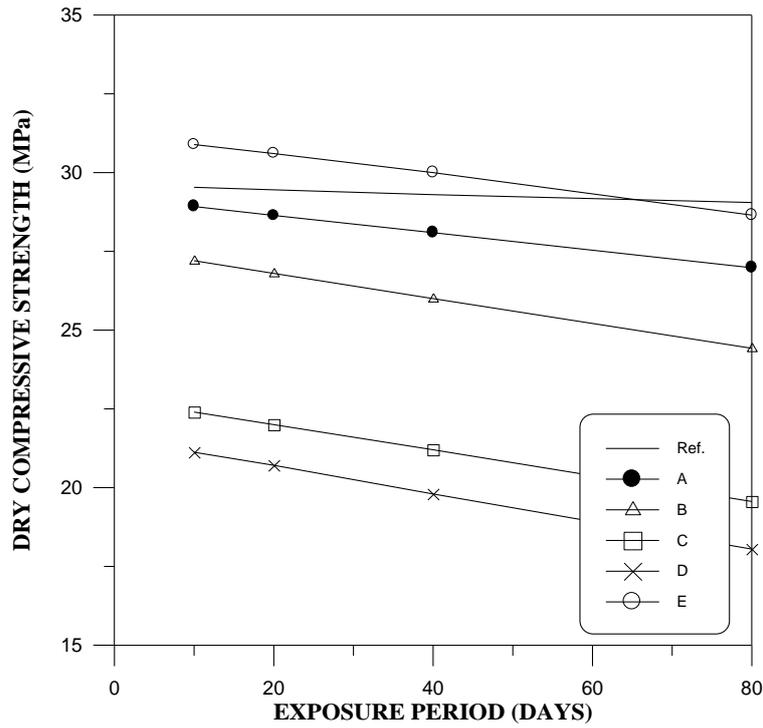


Fig. (4-16): Compressive strength of reference and sulphur mortar specimens after exposure to 2.0% concentration of nitric acid solution

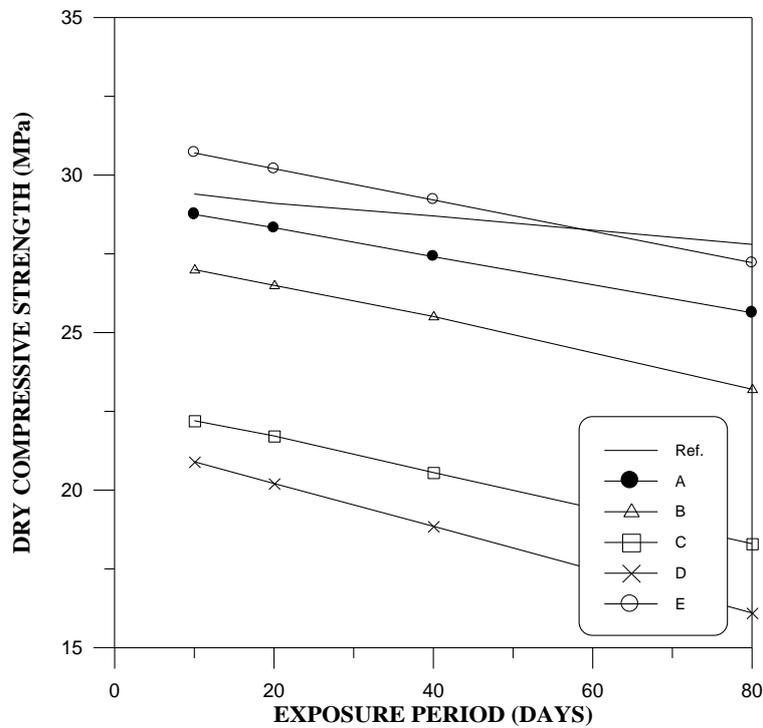


Fig. (4-17): Compressive strength of reference and sulphur mortar specimens after exposure to 4.0% concentration of nitric acid solution

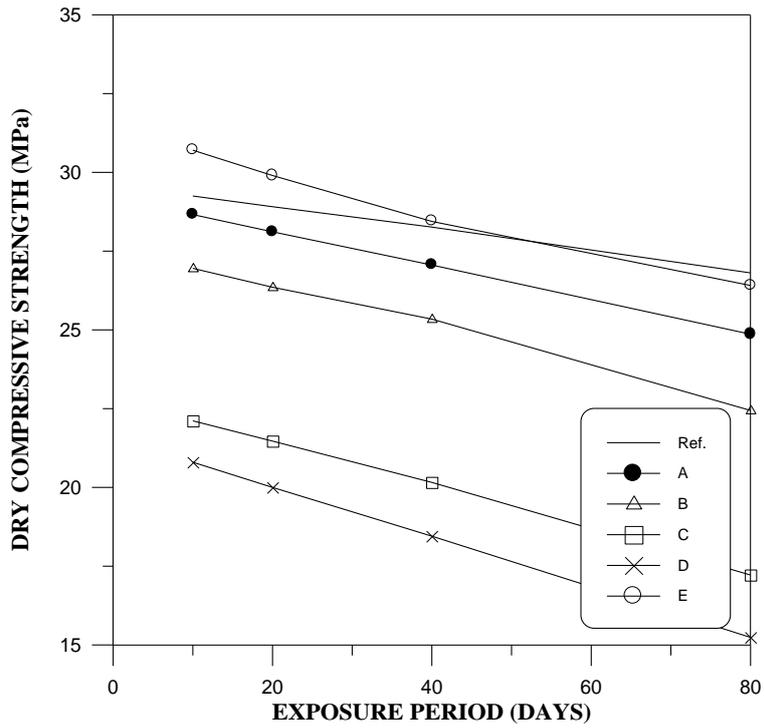


Fig. (4-18): Compressive strength of reference and sulphur mortar specimens after Exposure to 10% concentration of nitric acid solution

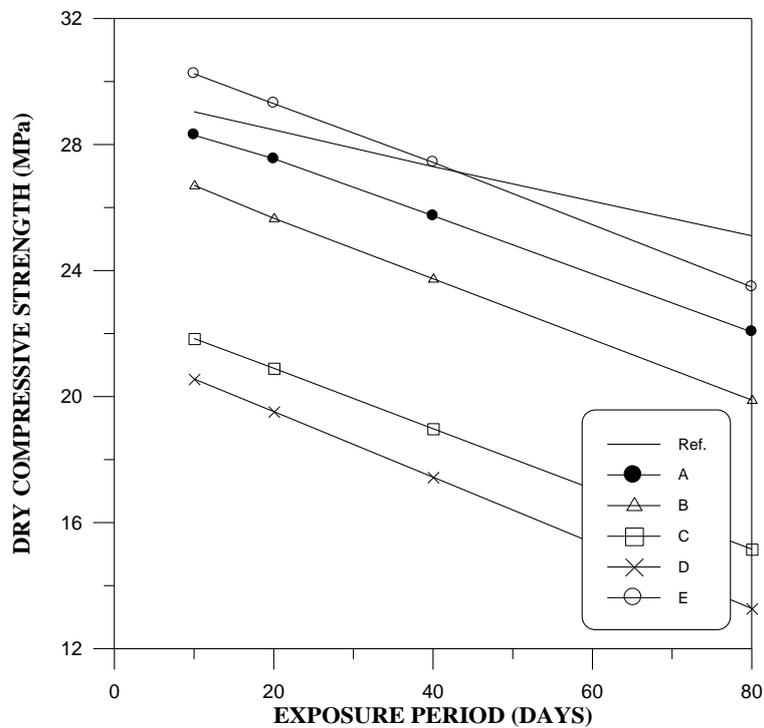


Fig. (4-19): Compressive strength of reference and sulphur mortar specimens after exposure to 8% concentration of nitric acid solution

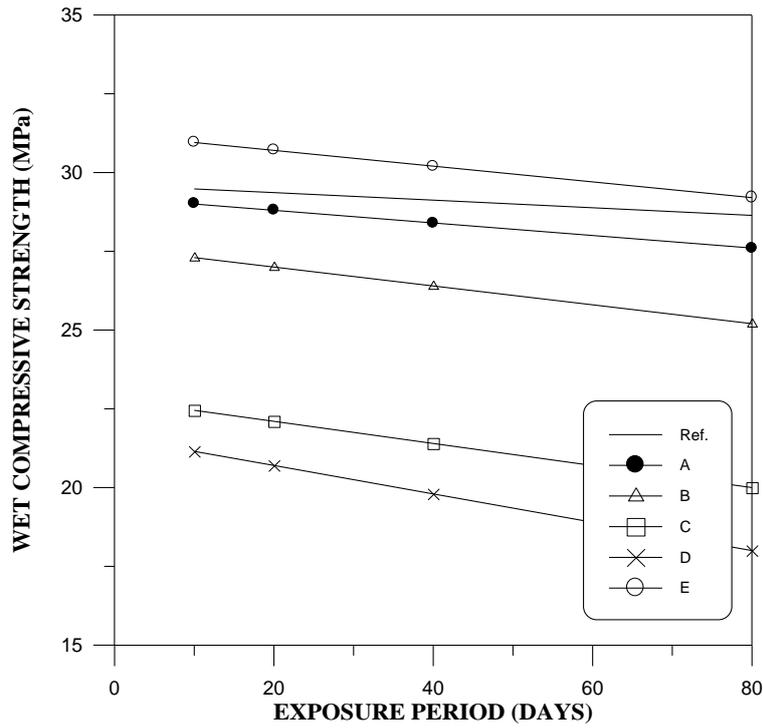


Fig. (4-20): Compressive strength of reference and sulphur mortar specimens after exposure to 2% concentration of sulphuric acid solution

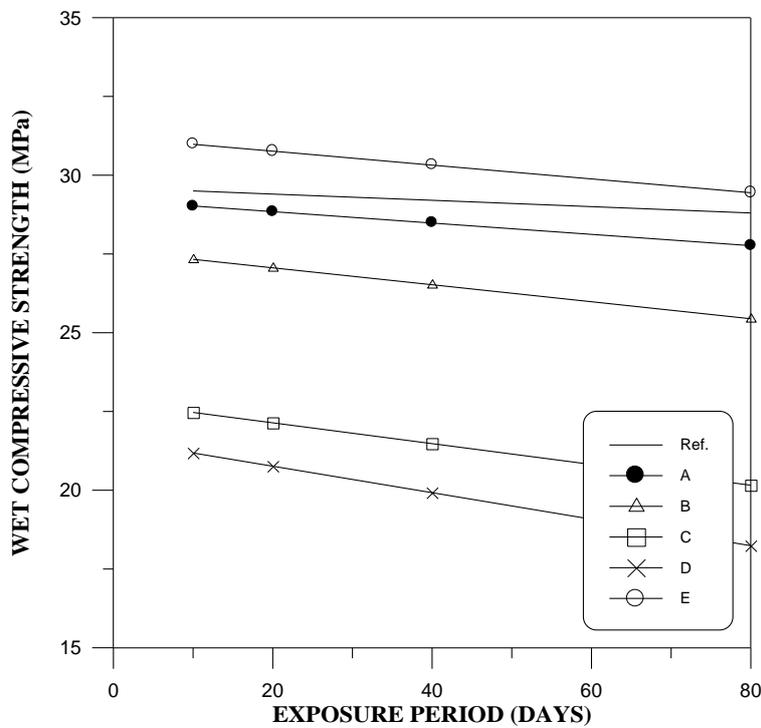


Fig. (4-21): Compressive strength of reference and sulphur mortar specimens after exposure to 4% concentration of sulphuric acid solution

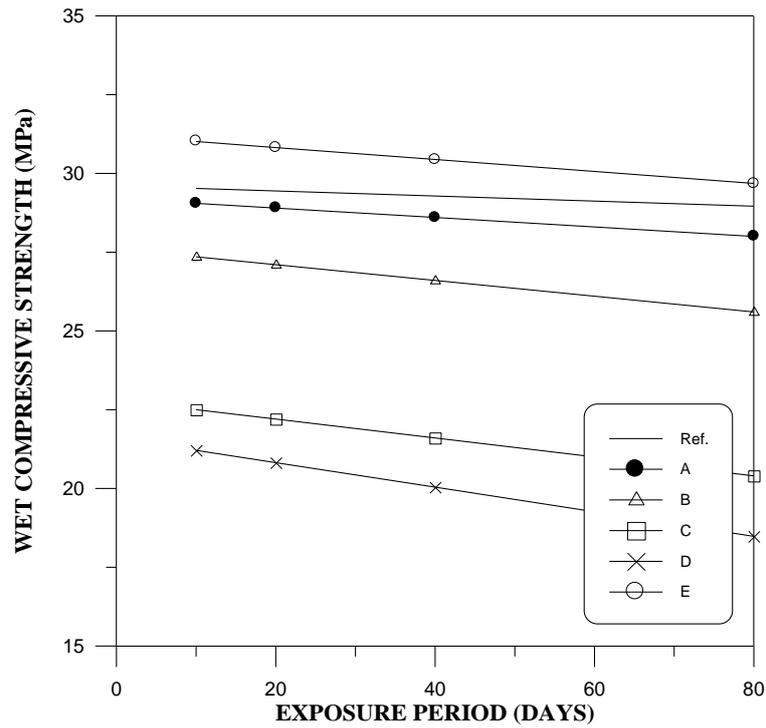


Fig. (4-22): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

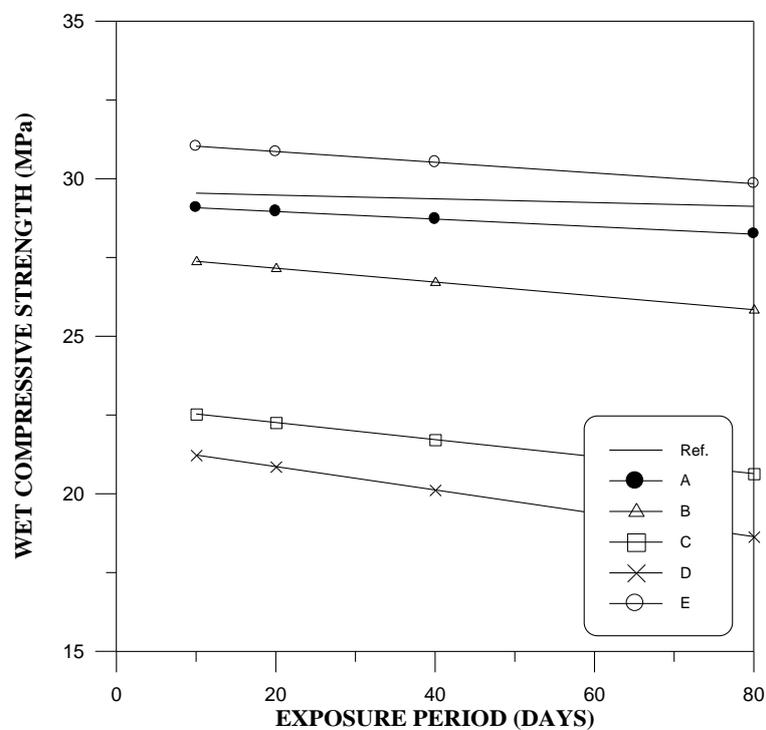


Fig. (4-23): Compressive strength of reference and sulphur mortar specimens after exposure to 15% concentration of sulphuric acid solution

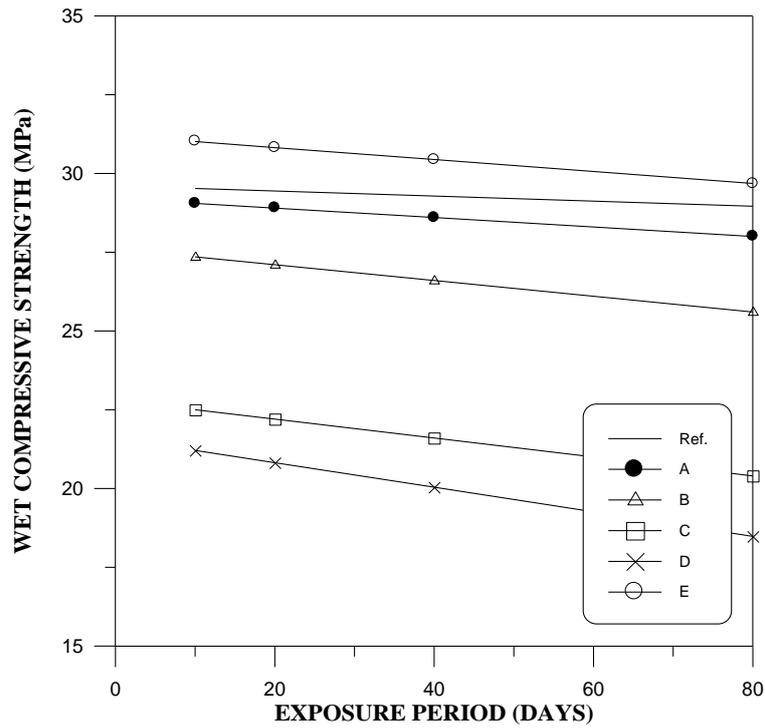


Fig. (4-24): Compressive strength of reference and sulphur mortar specimens after exposure to 9% concentration of sulphuric acid solution

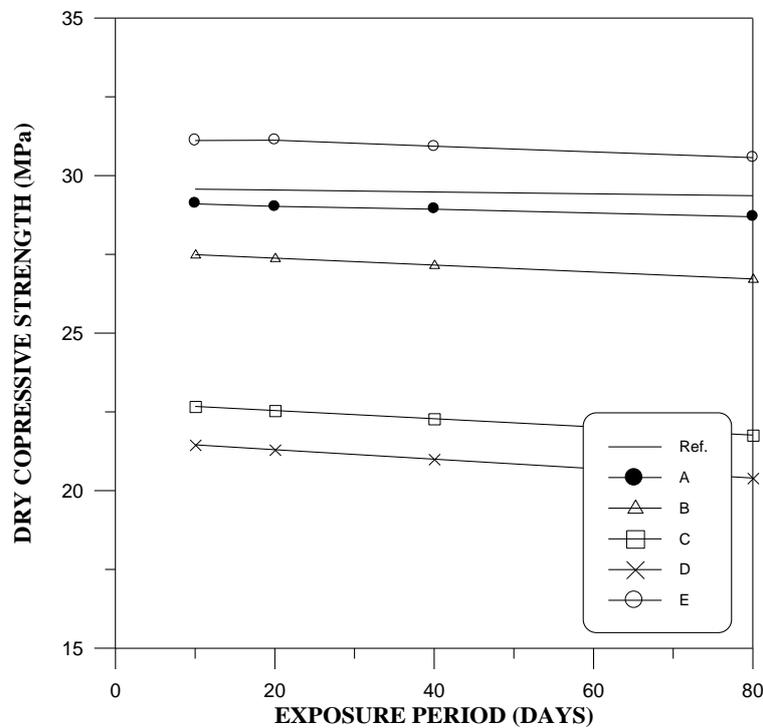


Fig. (4-25): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

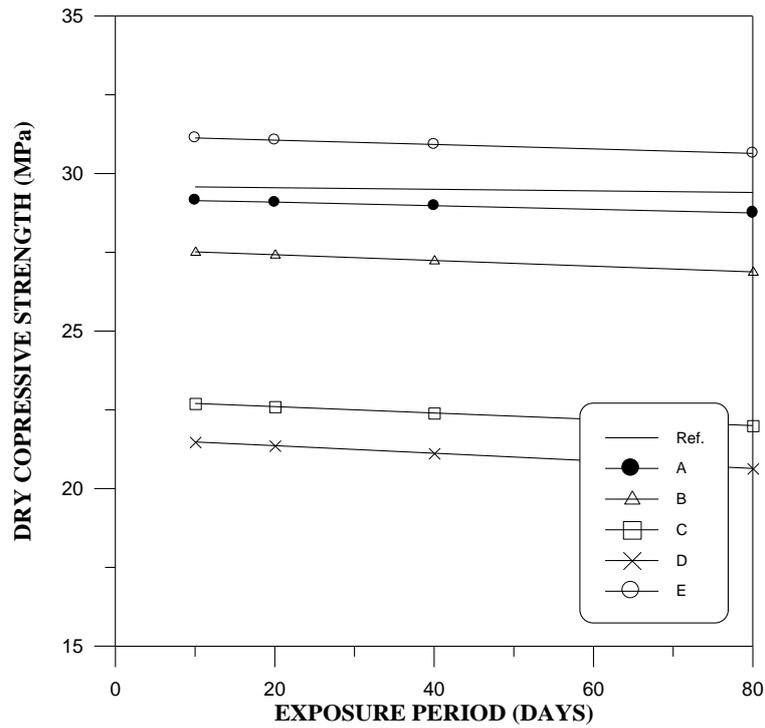


Fig. (4-26): Compressive strength of reference and sulphur mortar specimens after exposure to 5% concentration of sulphuric acid solution

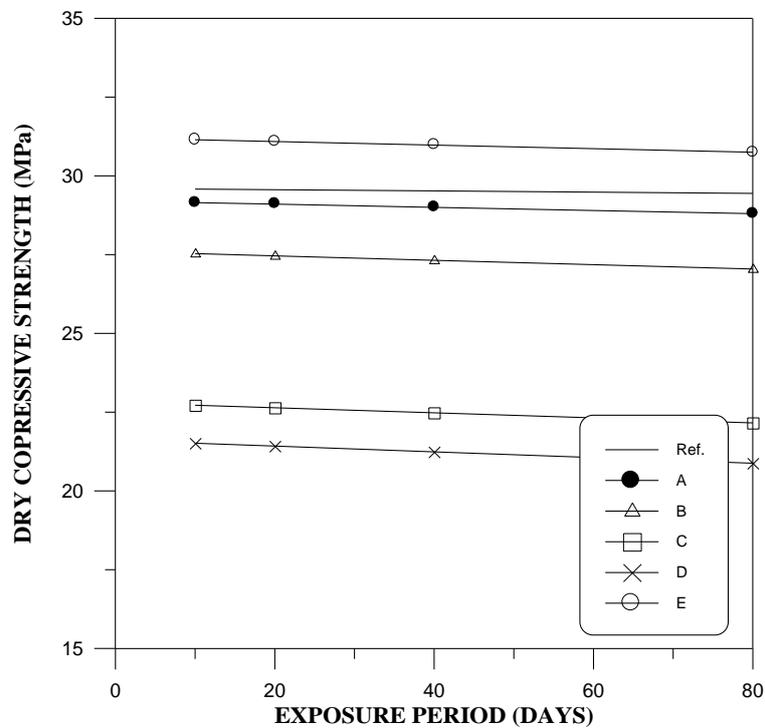


Fig. (4-27): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

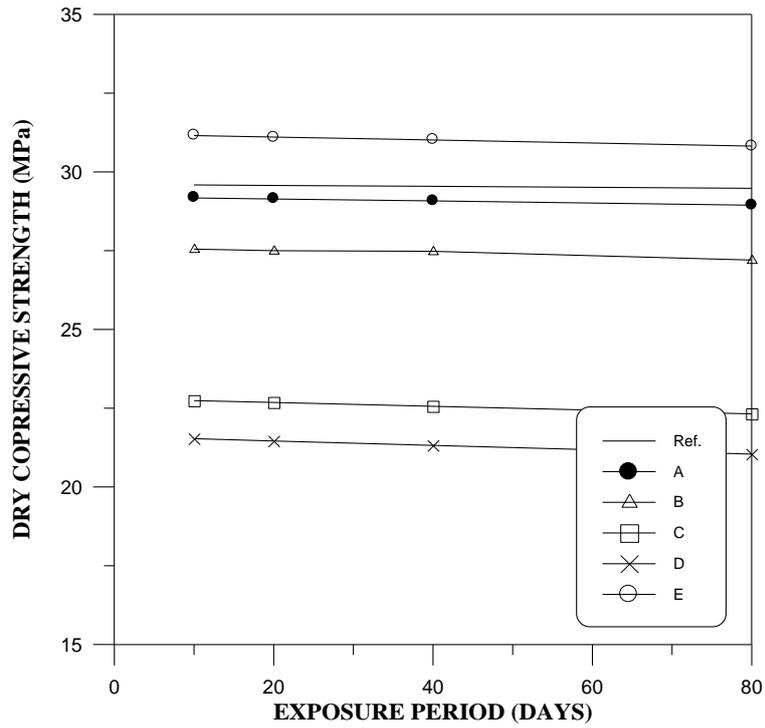


Fig. (4-28): Compressive strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

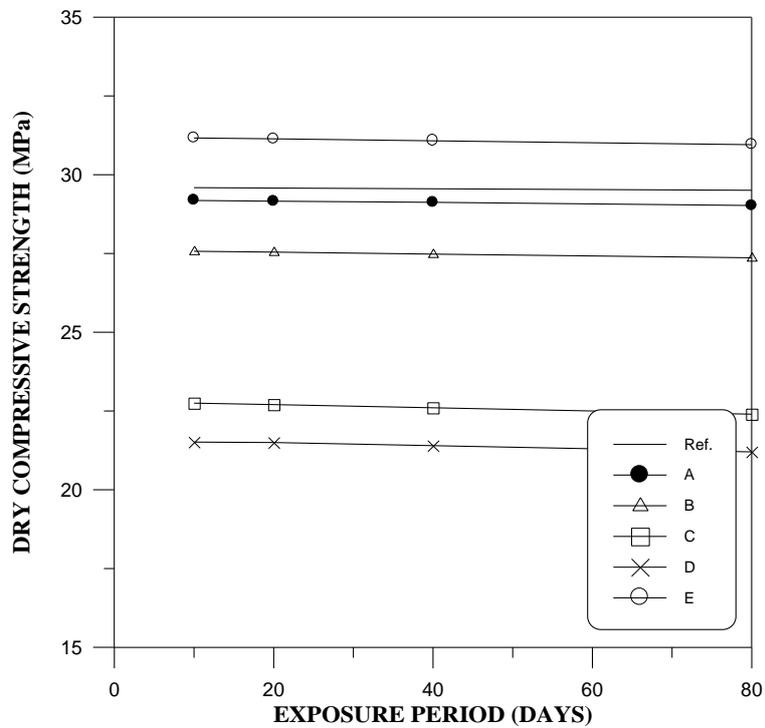


Fig. (4-29): Compressive strength of reference and sulphur mortar specimens after Exposure to 10% concentration of sulphuric acid solution

Table (4-9): Modulus of rupture of reference and sulphur mortar mixtures after exposure to sulphuric acid solutions.

Series	Glass sand % by weight	Sulphur Cement % by weight	Modulus of rupture of dry samples after exposure to acidic solutions (MPa)																			
			Before exposure				10 % concentration				20 % concentration				30 % concentration				40 % concentration			
			1 days	2 days	3 days	8 days	1 days	2 days	3 days	8 days	1 days	2 days	3 days	8 days	1 days	2 days	3 days	8 days	1 days	2 days	3 days	8 days
REF.	100	100	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	
D	70	20	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	
C	71.4	28.6	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	
B	76.0	33.0	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	
E	77.0	37.0	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	
A	70	30	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	

Table (4-1): Modulus of rupture of reference and sulphur mortar mixtures after exposure to hydrochloric acid solutions.

Series	Glass sand % by weight	Sulphur Cement % by weight	Modulus of rupture of dry samples after exposure to acidic solutions (MPa)																							
			Before exposure				22 % concentration				20 % concentration				20 % concentration				10 % concentration				10 % concentration			
			1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days				
REF.	100	100	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34						
D	70	20	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34						
C	71.4	28.6	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34						
B	66.0	34.0	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34						
E	62.0	38.0	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34						
A	60	40	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34						

Table (4-11): Modulus of rupture of reference and sulphur mortar mixtures after exposure to hydrochloric acid solutions.

Series	Glass sand % by weight	Sulphur Cement % by weight	Modulus of rupture of wet samples after exposure to acidic solutions (MPa)																				
			Before exposure				10 % concentration				20 % concentration				30 % concentration				40 % concentration				
			1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	1. days	2. days	3. days	8. days	
REF.	100	100	1.3 4	1.3 36	1.3 32	1.3 23	1.3 20	1.3 19	1.3 37	1.3 34	1.3 27	1.3 27	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	1.3 14	
D	70	20	2.3 4	2.3 58	2.2 54	2.1 40	1.9 11	2.3 9	2.2 57	2.1 52	1.9 32	2.3 12	2.2 12	2.1 12	1.9 56	2.3 10	2.2 10	2.1 10	1.9 10	2.3 10	2.2 10	2.1 10	1.9 10
C	71.4	28.6	2.4 44	2.4 22	2.3 77	2.2 9	2.1 8	2.4 22	2.3 89	2.2 8	2.1 26	2.3 87	2.2 8	2.1 8	2.4 43	2.3 43	2.2 43	2.1 43	2.4 43	2.3 43	2.2 43	2.1 43	2.4 43
B	67	33	2.5 9	2.5 76	2.4 42	2.3 73	2.0 29	2.5 29	2.4 77	2.3 82	2.1 7	2.5 49	2.4 49	2.3 49	2.0 11	2.5 11	2.4 11	2.3 11	2.0 11	2.5 11	2.4 11	2.3 11	2.0 11
E	62.5	37.5	3.1 1	3.1 8	3.1 54	2.9 97	2.8 8	3.1 87	3.1 57	3.1 87	3.1 12	3.1 12	3.1 12	3.1 12	3.1 1	3.1 1	3.1 1	3.1 1	3.1 1	3.1 1	3.1 1	3.1 1	3.1 1
A	60	40	2.9 4	2.9 30	2.9 58	2.8 57	2.7 40	2.9 46	2.8 76	2.7 82	2.6 7	2.9 76	2.8 76	2.7 76	2.9 39	2.8 39	2.7 39	2.6 39	2.9 39	2.8 39	2.7 39	2.6 39	2.9 39

Table (4-12): Modulus of rupture for reference ,and sulphur mortar mixtures after exposure to nitric acid solutions

Series	Sulphur cement% by weight	Glass sand % by weight	Modulus of rupture of dry samples after exposure to acidic solutions (MPa)																
			Before exposure	2. % concentration				4. % concentration				6. % concentration				8. % concentration			
				1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days	1. days	2. days	4. days	8. days
Ref.	0.0	100	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	
D	20	70	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	
C	28.5	71.5	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	
B	33.0	67.0	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	2.74	
E	37.0	63.0	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	
A	40	60	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	

Table (4-13): Modulus of rupture for reference and sulphur mortar mixtures after exposure to nitric acid solutions

Series	Glass sand % by weight	Sulphur cement % by weight	Modulus of rupture of wet samples after exposure to acidic solutions, (MPa)																	
			Before exposure	2.0% concentration				4.0% concentration				6.0% concentration				8.0% concentration				
				1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	
Ref	0.0	10.0	1.34	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	
D	20	70	2.36	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
C	28.5	71.5	2.45	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
B	33.0	67.0	2.57	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
E	37.0	63.0	2.61	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
A	40	60	2.69	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62

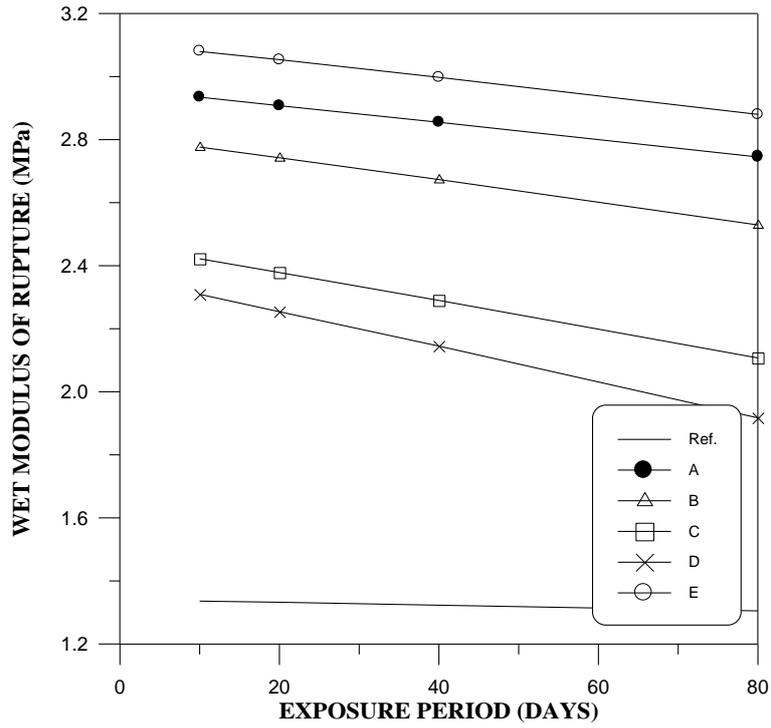


Fig. (4-30): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric acid solution

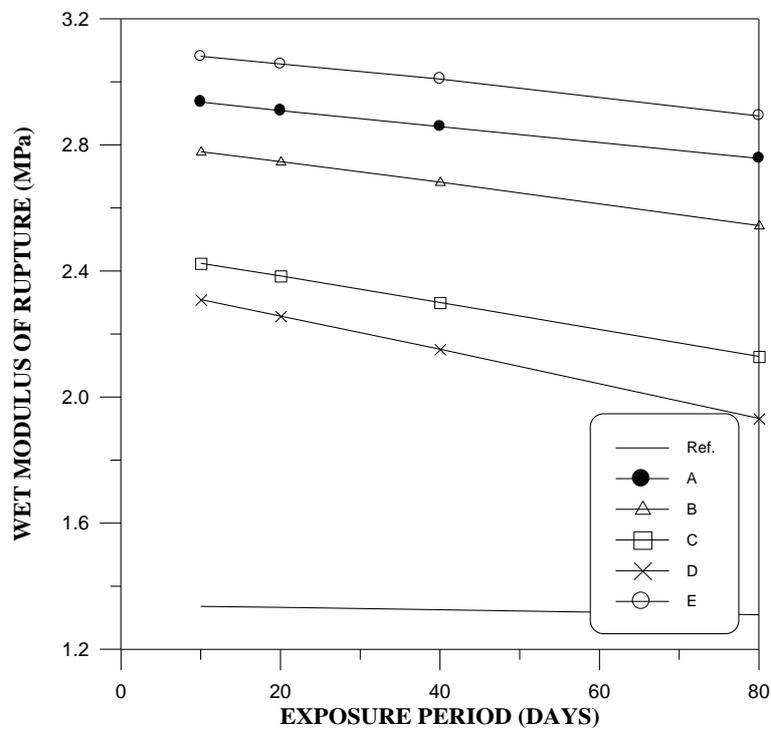


Fig. (4-31): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric Acid solution

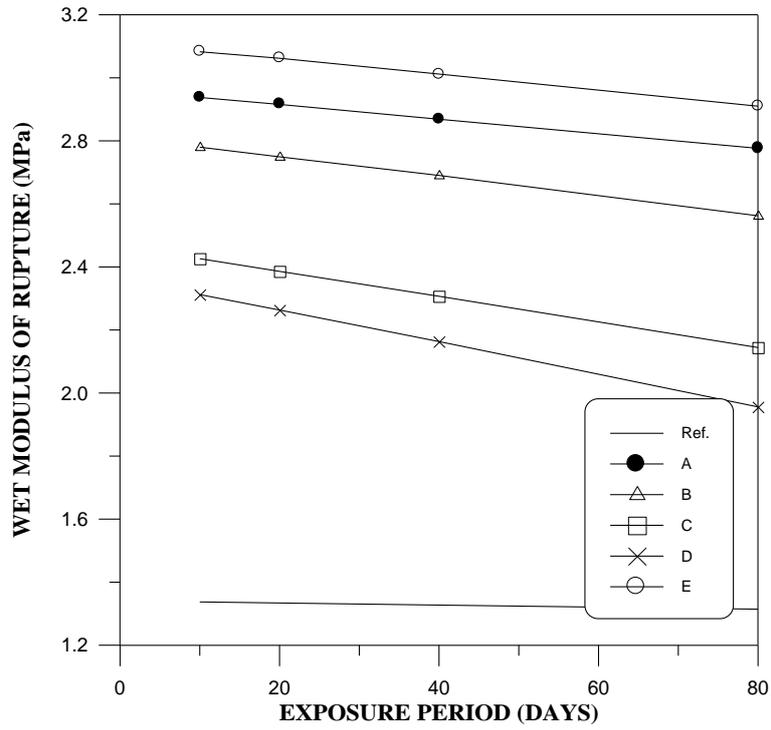


Fig. (4-32): Flexural strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

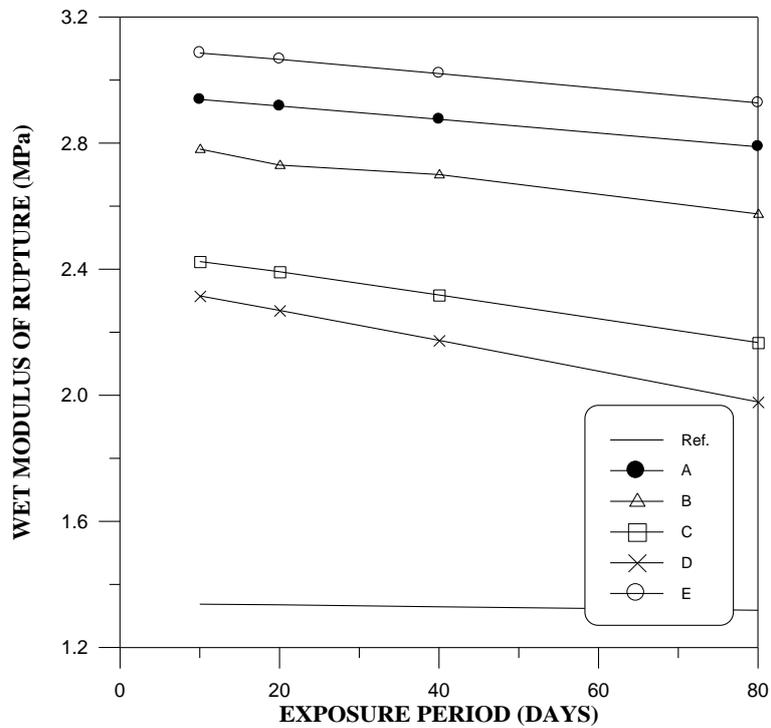


Fig. (4-33): Flexural strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric Acid solution

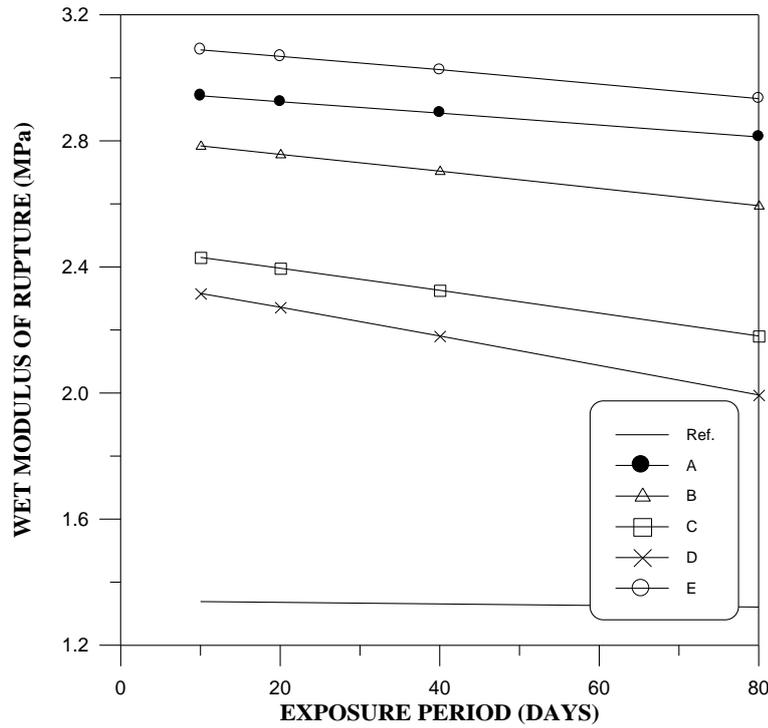


Fig. (4-24): Flexural strength of reference and sulphur mortar specimens after exposure to 32% concentration of hydrochloric acid solution

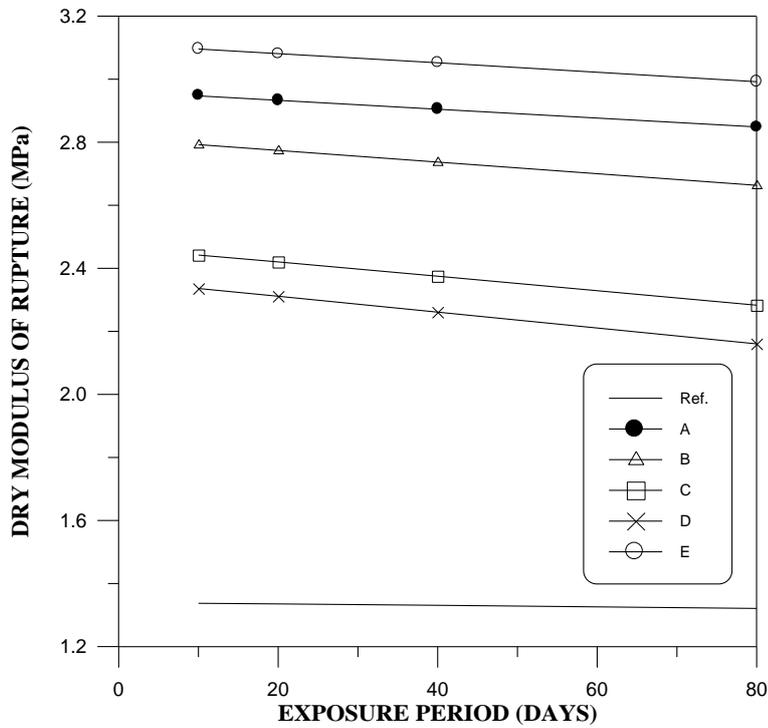


Fig. (4-25): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric acid solution

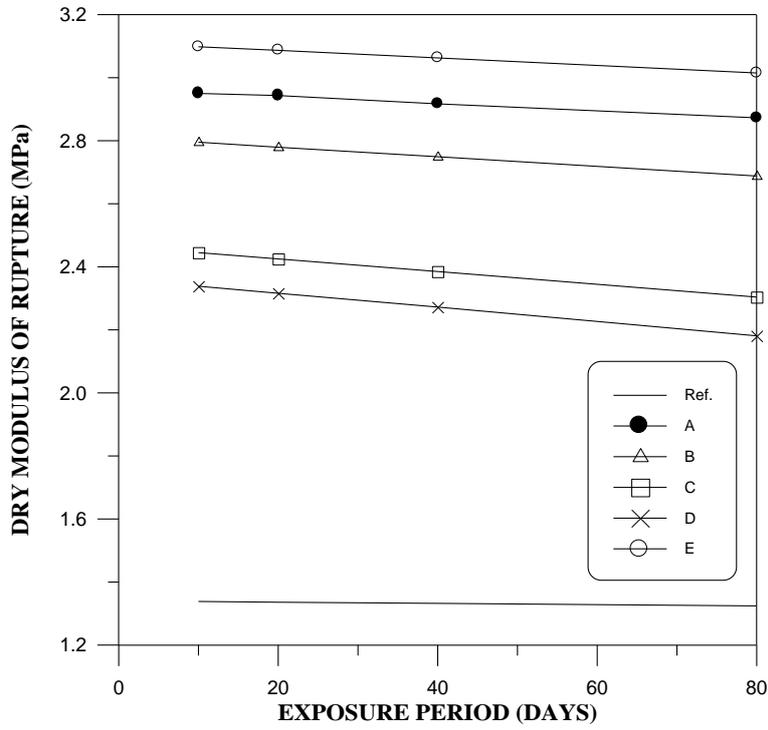


Fig. (4-36): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of hydrochloric acid solution

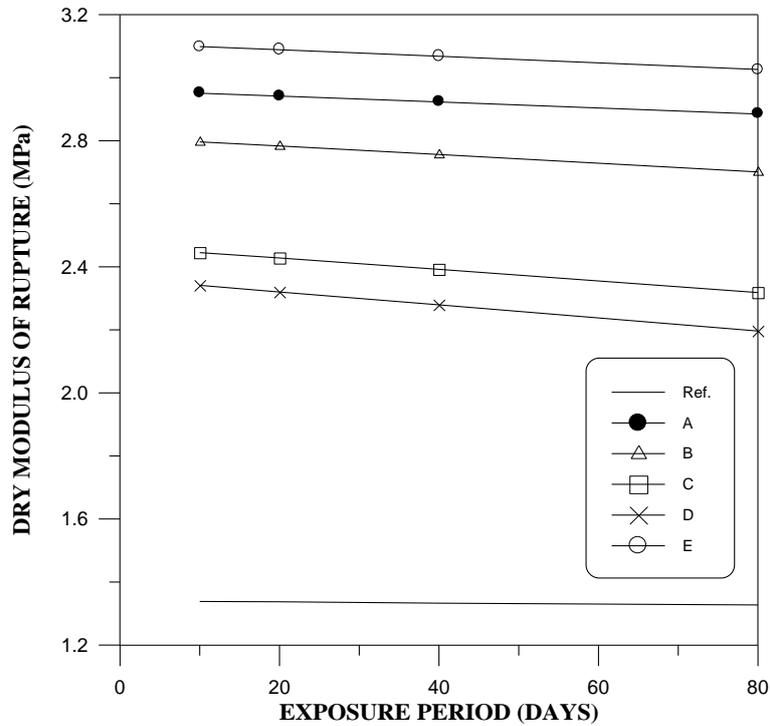


Fig. (4-37): Flexural strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

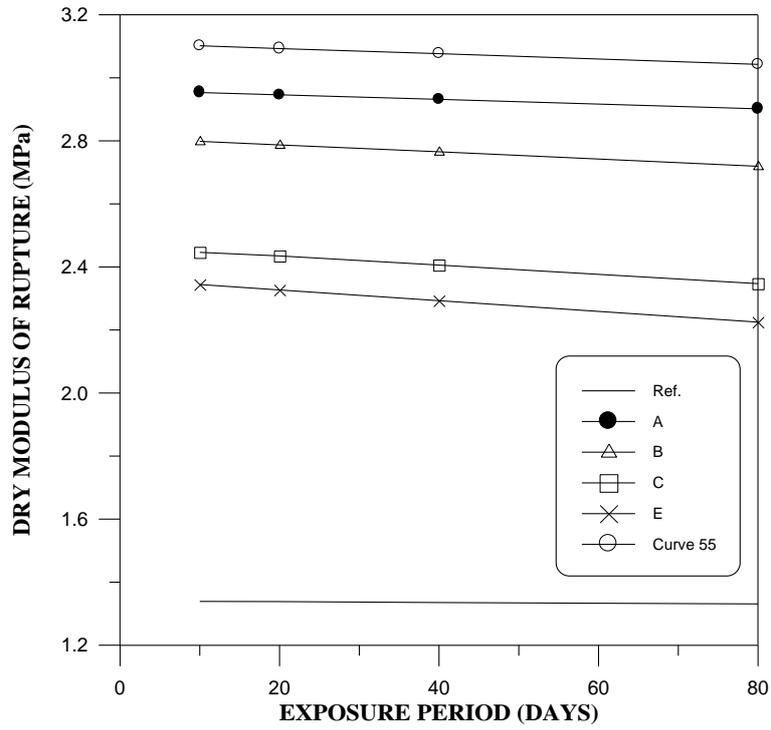


Fig. (4-38): Flexural strength of reference and sulphur mortar specimens after exposure to 20% concentration of hydrochloric acid solution

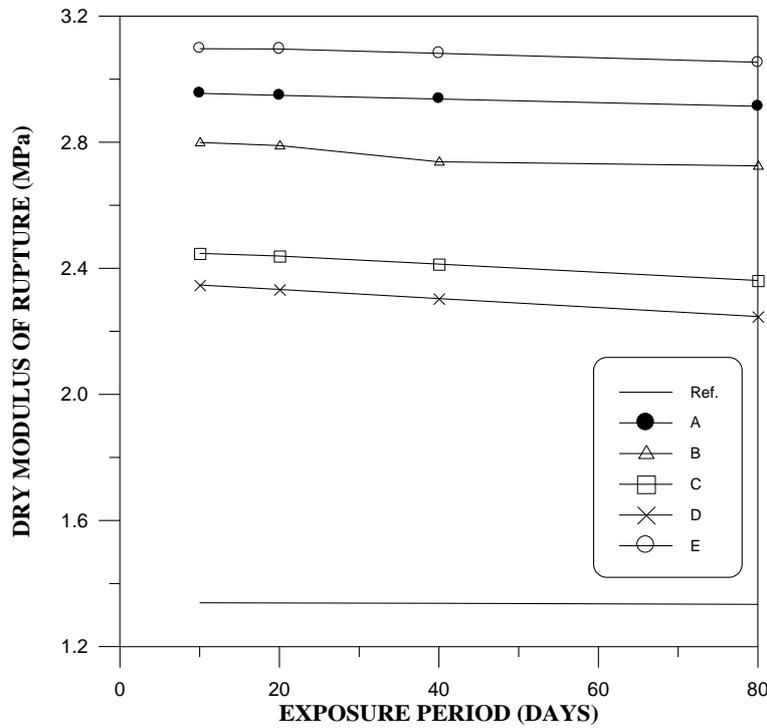


Fig. (4-39): Flexural strength of reference and sulphur mortar specimens after exposure to 30% concentration of hydrochloric acid solution

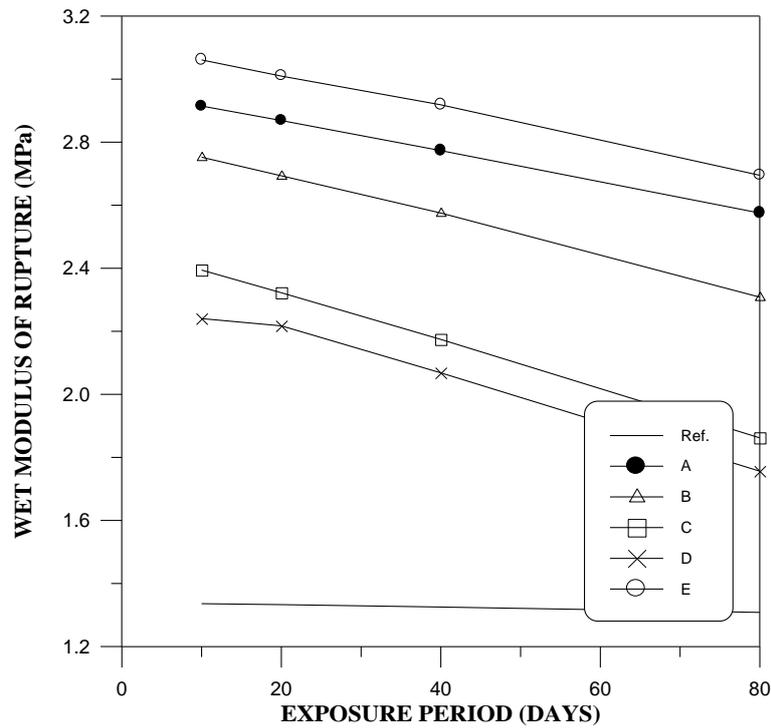


Fig. (4-40): Flexural strength of reference and sulphur mortar specimens after exposure to 20% concentration of nitric acid solution

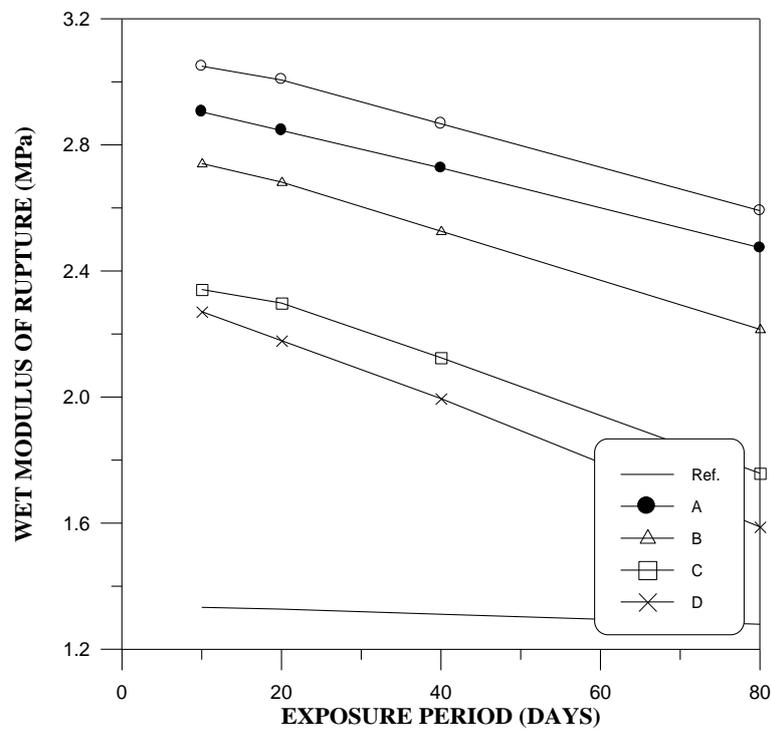


Fig. (4-41): Flexural strength of reference and sulphur mortar specimens after exposure to 40% concentration of nitric acid solution

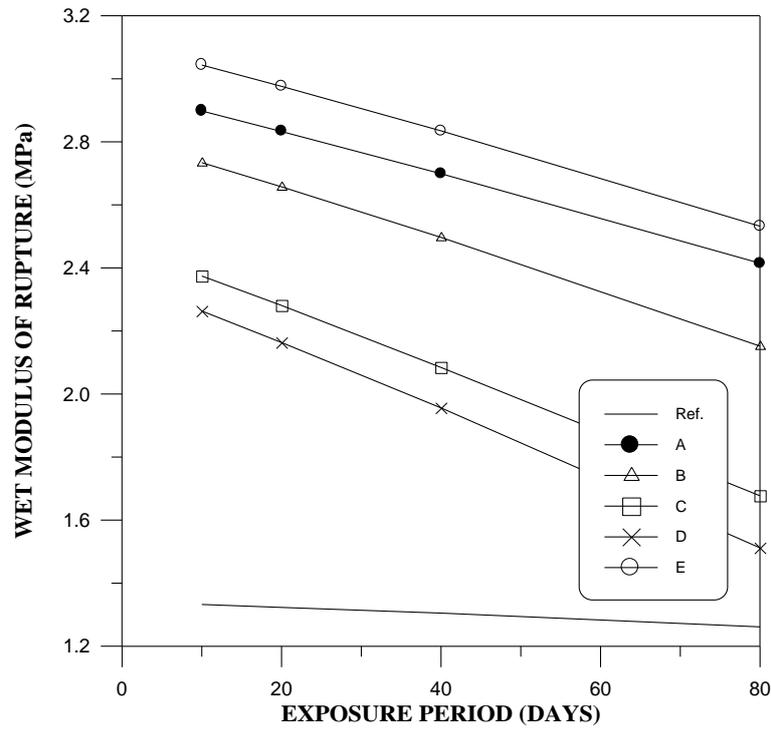


Fig. (4-42): Flexural strength of reference and sulphur mortar Specimens after exposure to 70% concentration of nitric acid solution

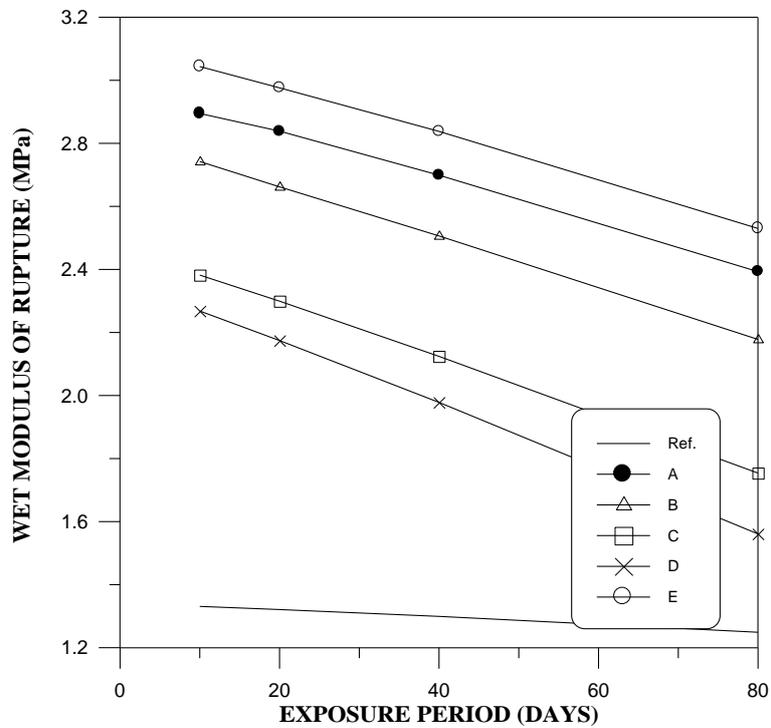


Fig. (4-43): Flexural strength of reference and sulphur mortar specimens after exposure to 80% concentration of nitric acid solution

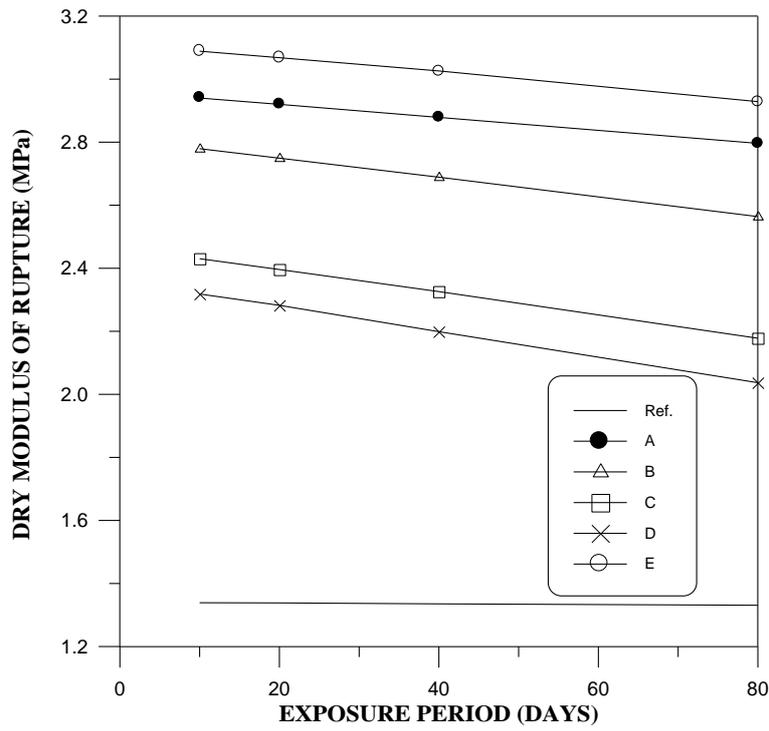


Fig. (4-44): Flexural strength of reference and sulphur mortar Specimens after exposure to 20% concentration of nitric acid solution

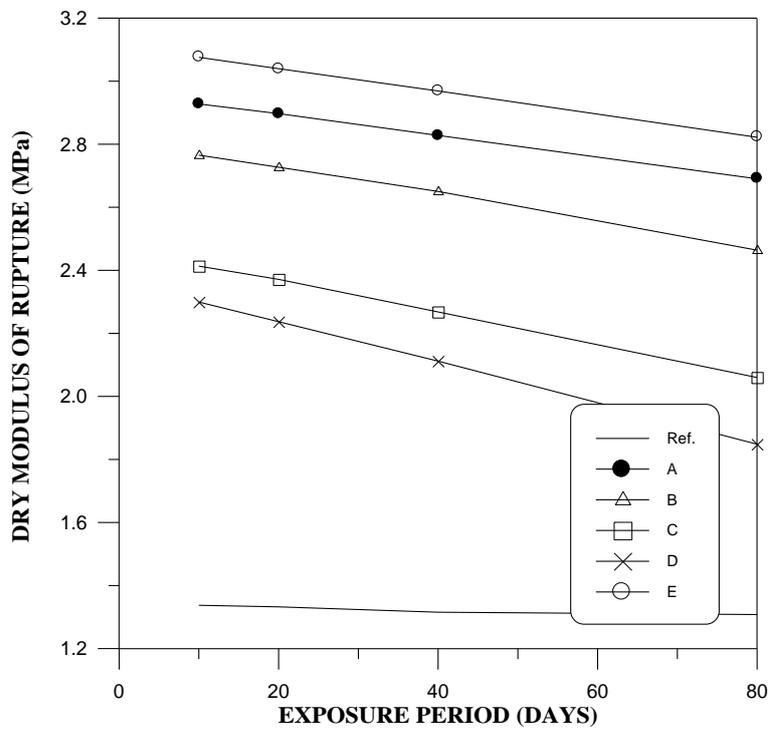


Fig. (4-45): Flexural strength of reference and sulphur mortar Specimens after exposure to 40% concentration of nitric acid solution

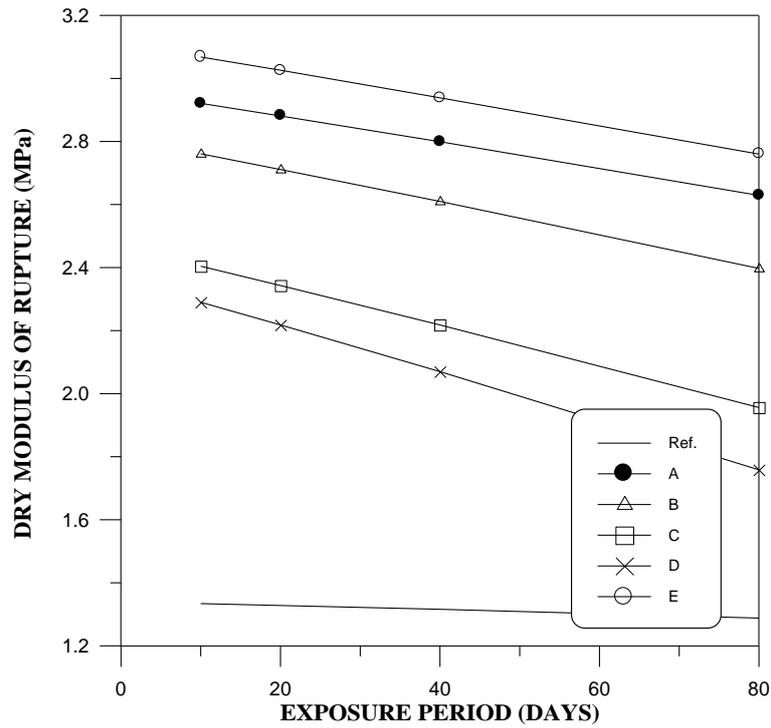


Fig. (4-46): The Flexural Strength of Reference and sulphur mortar Specimens after Exposure to 10% Concentration of Nitric Acid solution

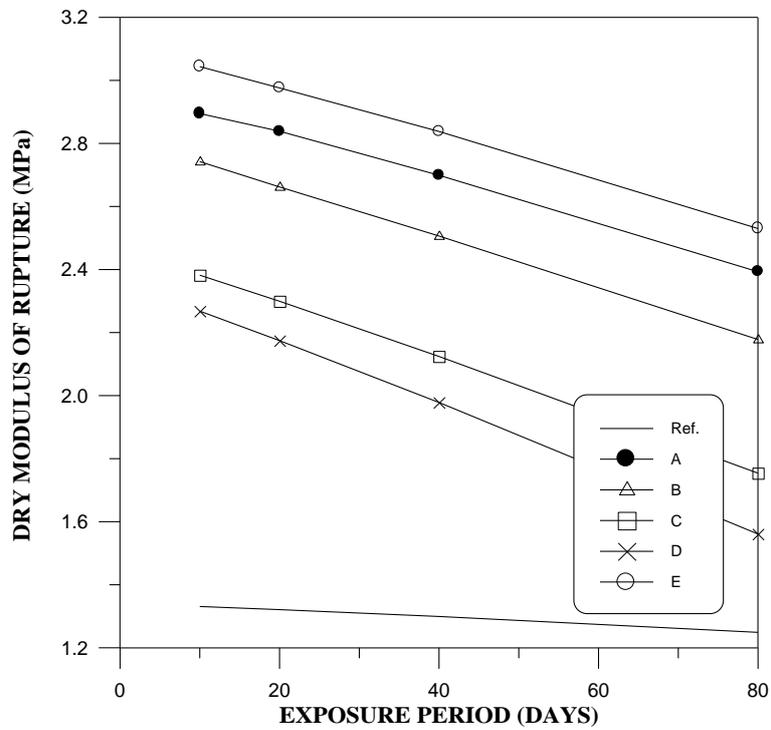


Fig. (4-47): Flexural strength of reference and sulphur mortar specimens after exposure to 8% concentration of nitric acid solution

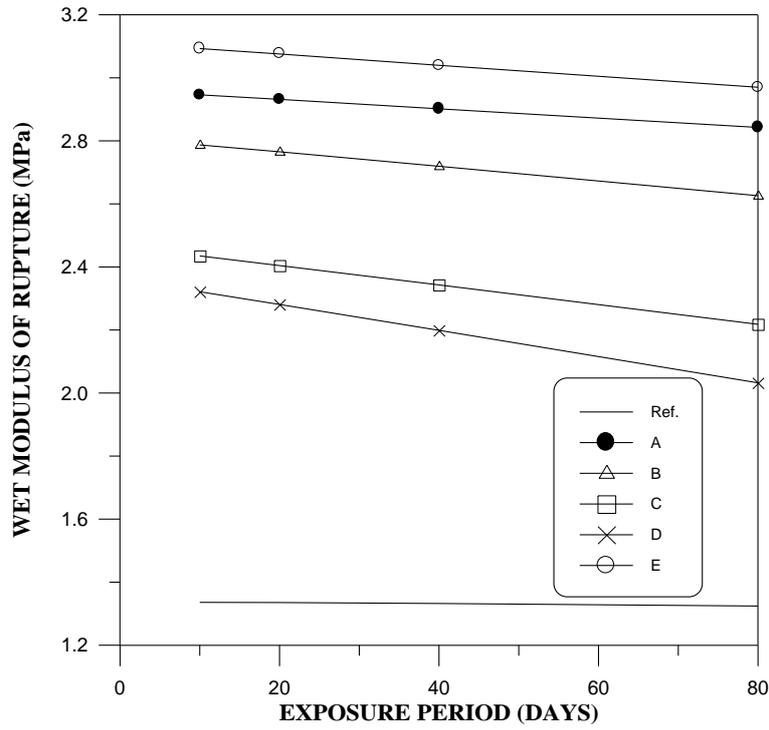


Fig. (4-18): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

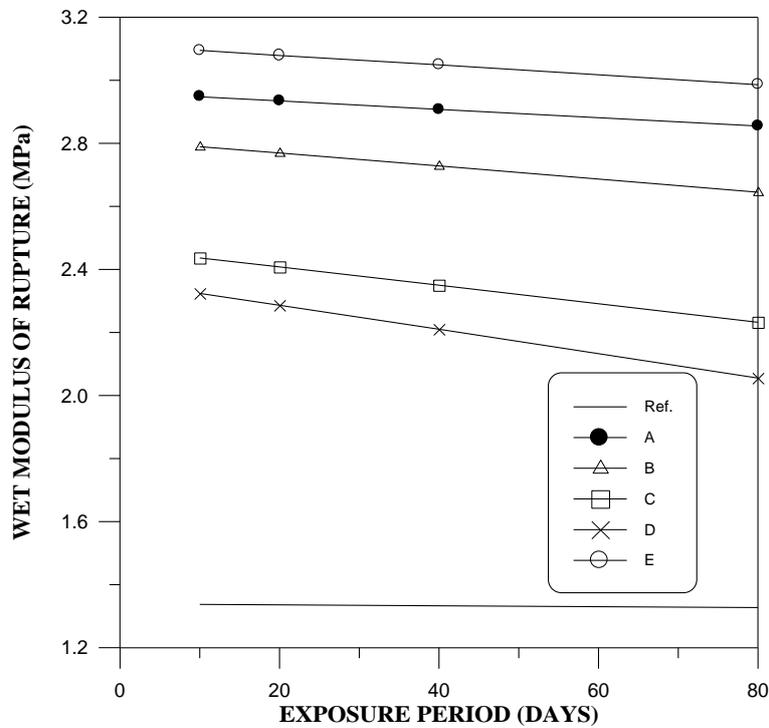


Fig. (4-19): Flexural strength of reference and sulphur mortar specimens after exposure to 5% concentration of sulphuric acid solution

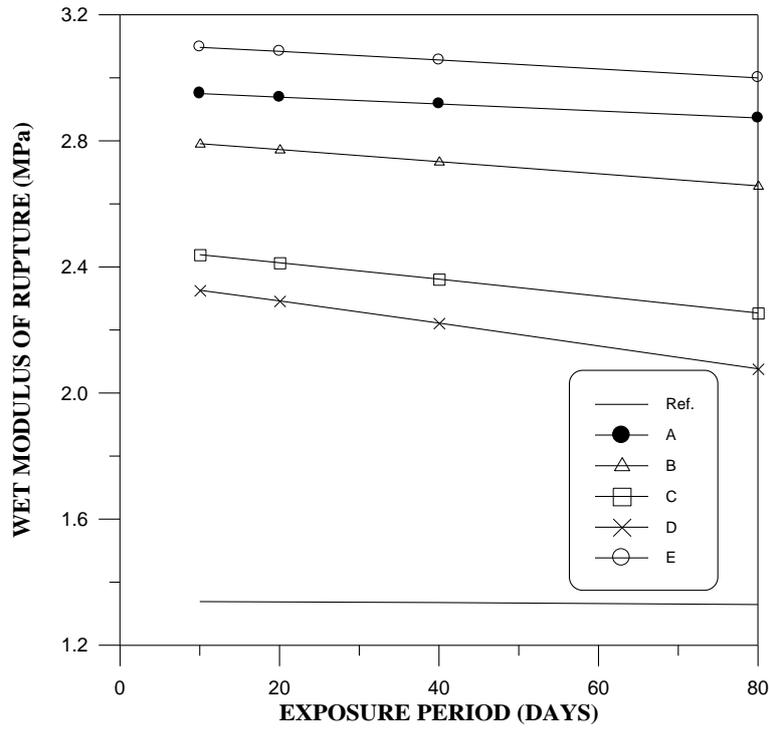


Fig. (4-50): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

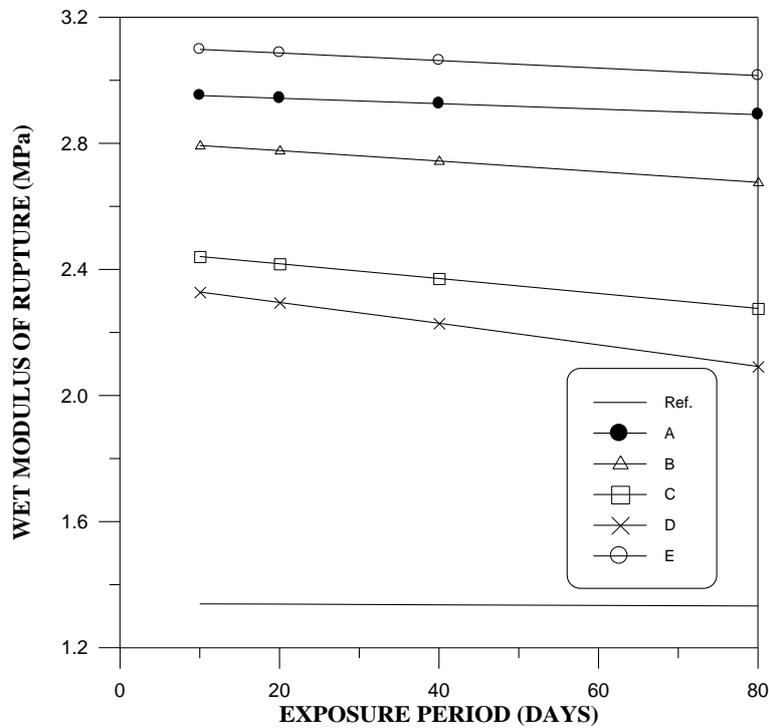


Fig. (4-51): Flexural strength of reference and sulphur mortar specimens after exposure to 8% concentration of sulphuric acid solution

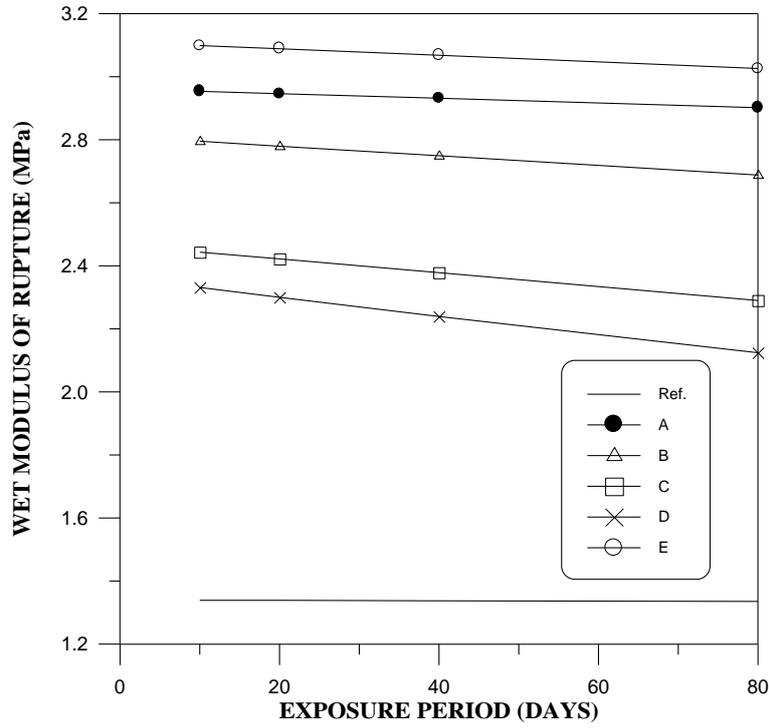


Fig. (4-52): The flexural strength of reference and sulphur mortar specimens after exposure to 9% concentration of sulphuric acid solution

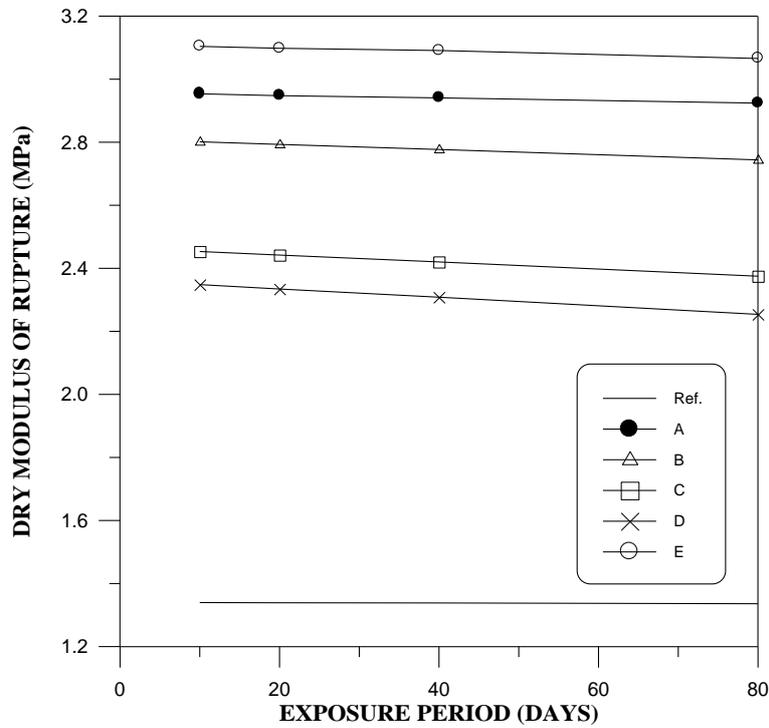


Fig. (4-53): Flexural strength of reference and sulphur mortar specimens after exposure to 10% concentration of sulphuric acid solution

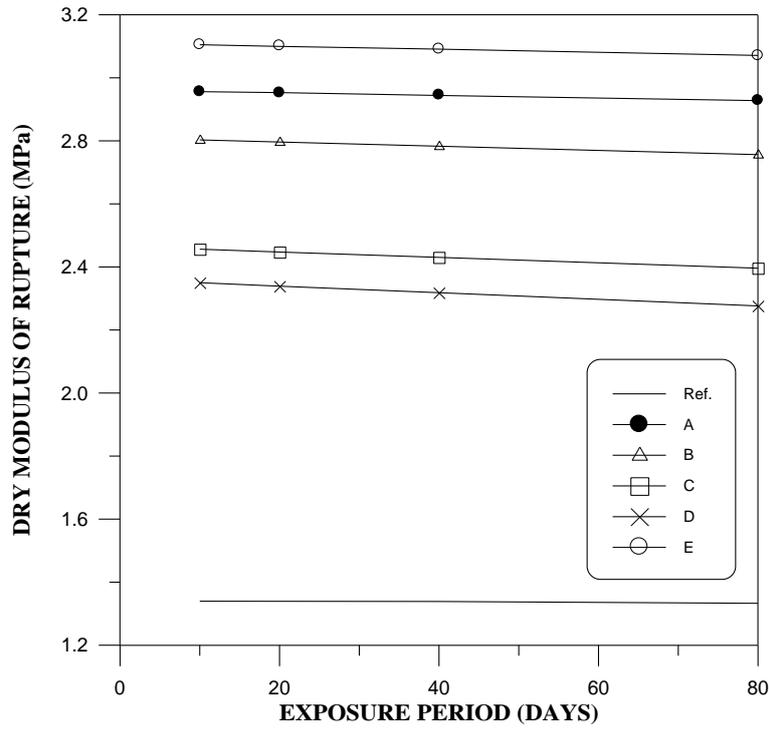


Fig. (4-54): Flexural strength of reference and sulphur mortar specimens after exposure to 5% concentration of sulphuric acid solution

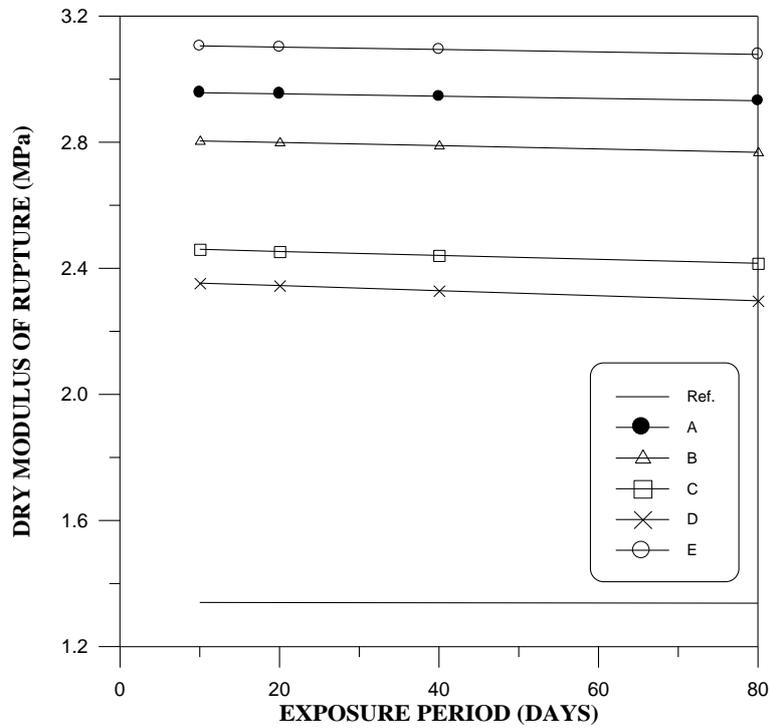


Fig. (4-55): Flexural strength of reference and sulphur mortar specimens after exposure to 7% Concentration of sulphuric acid solution

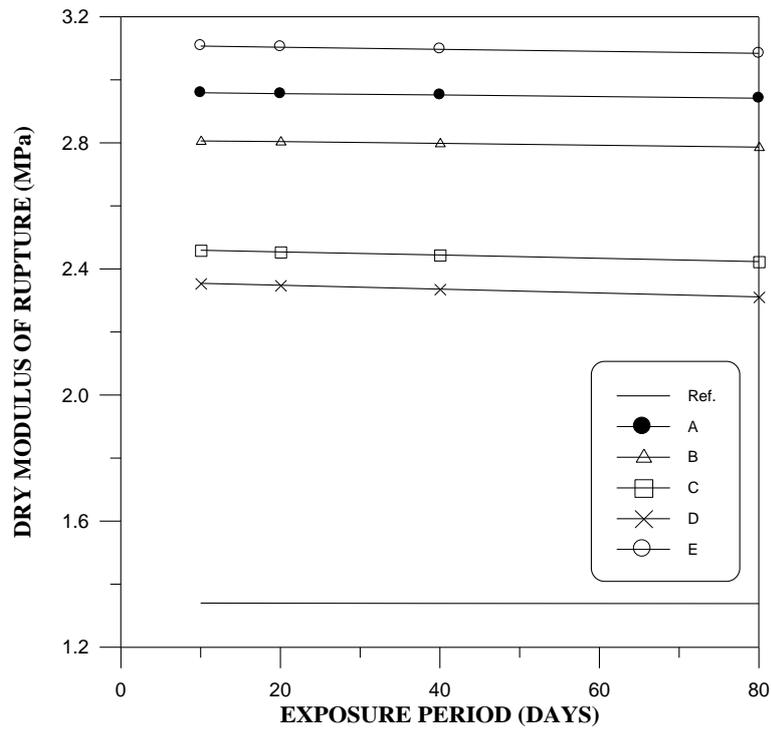


Fig. (4-56): Flexural strength of reference and sulphur mortar specimens after Exposure to 1% concentration of sulphuric acid solution

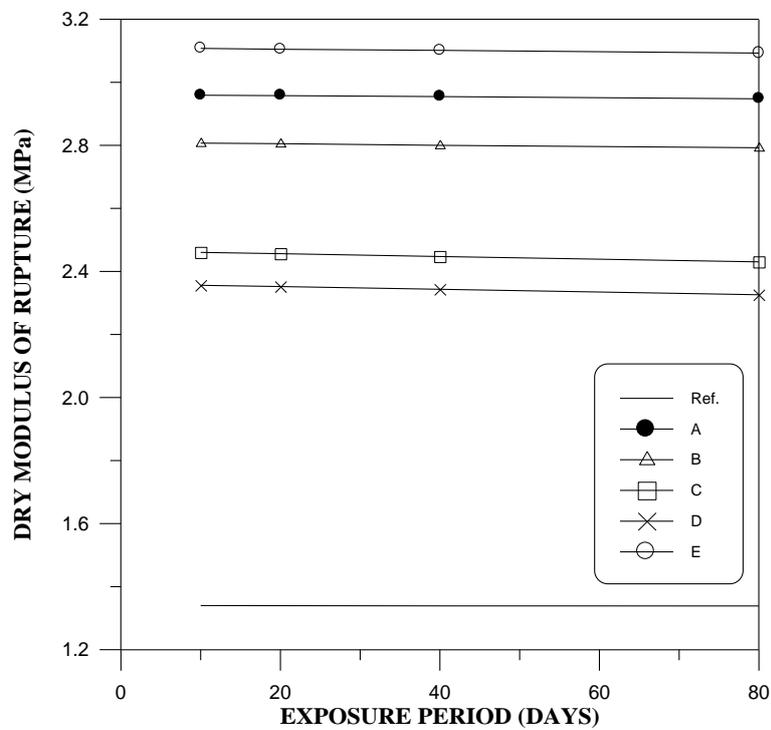


Fig. (4-57): Flexural strength of reference and sulphur mortar specimens after exposure to 9% concentration of sulphuric acid solution

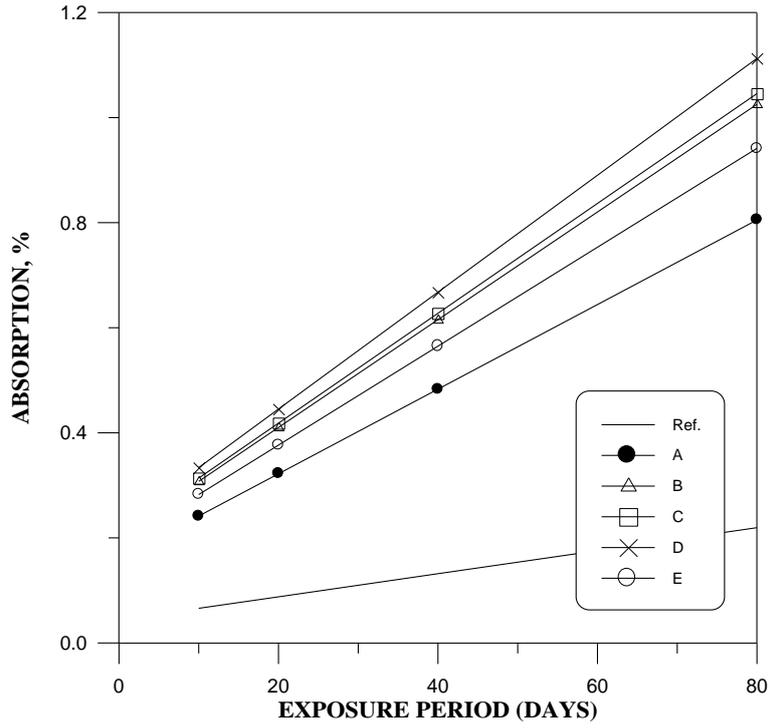


Fig. (4-58): Absorption of sulphur mortar specimens with time after exposure to 10% concentration of hydrochloric acid solution

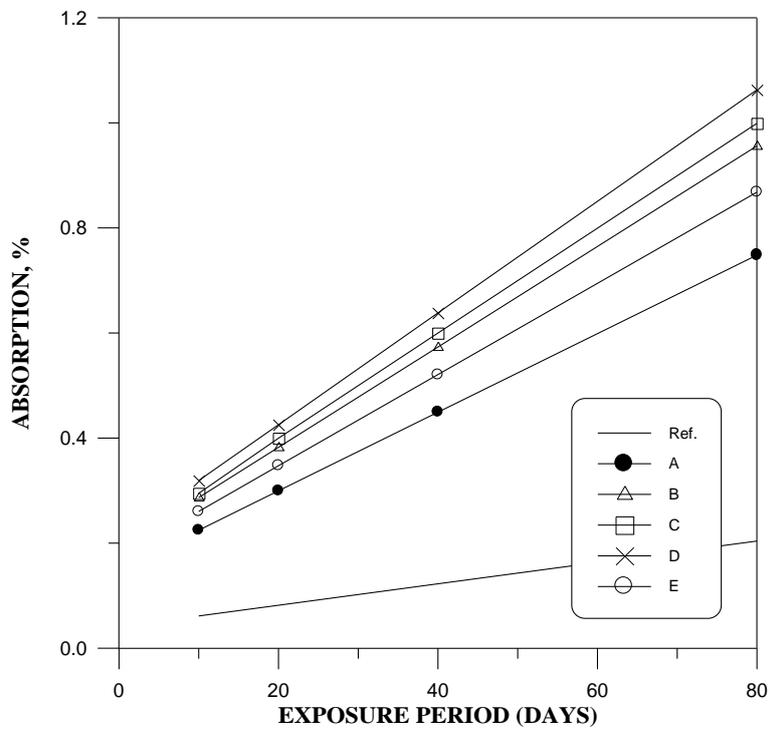


Fig. (4-59): Absorption of sulphur mortar Specimens with time after exposure to 10% concentration of hydrochloric acid solution

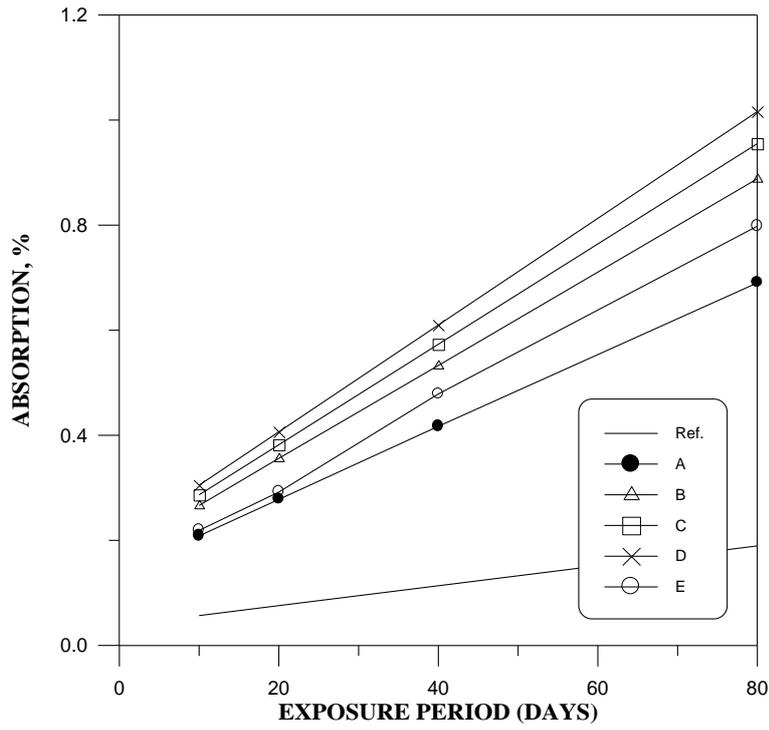


Fig. (4-60): Absorption of sulphur mortar specimens with time after exposure to 20% concentration of hydrochloric acid solution

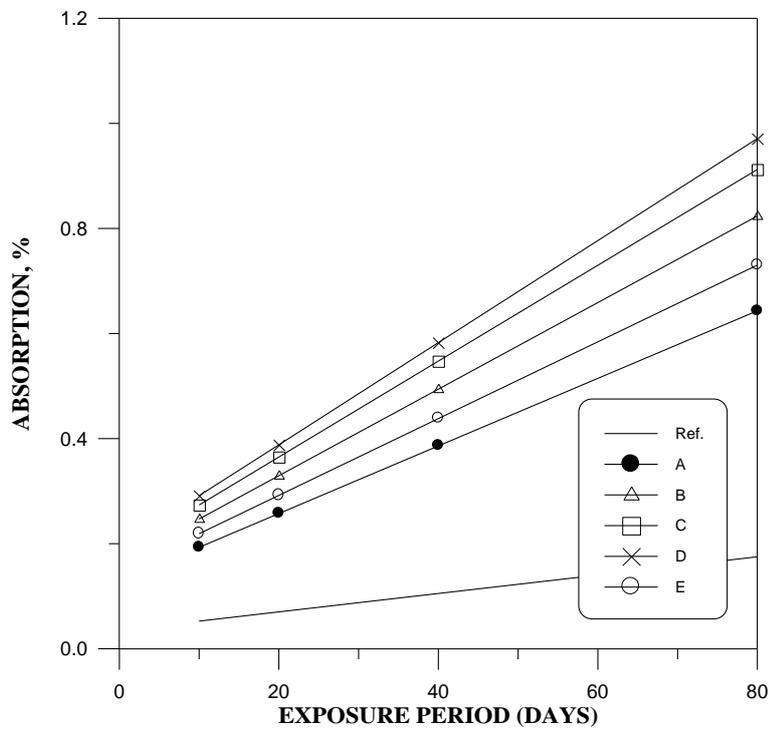


Fig. (4-61): Absorption of sulphur mortar specimens with time after exposure to 20% concentration of hydrochloric acid solution

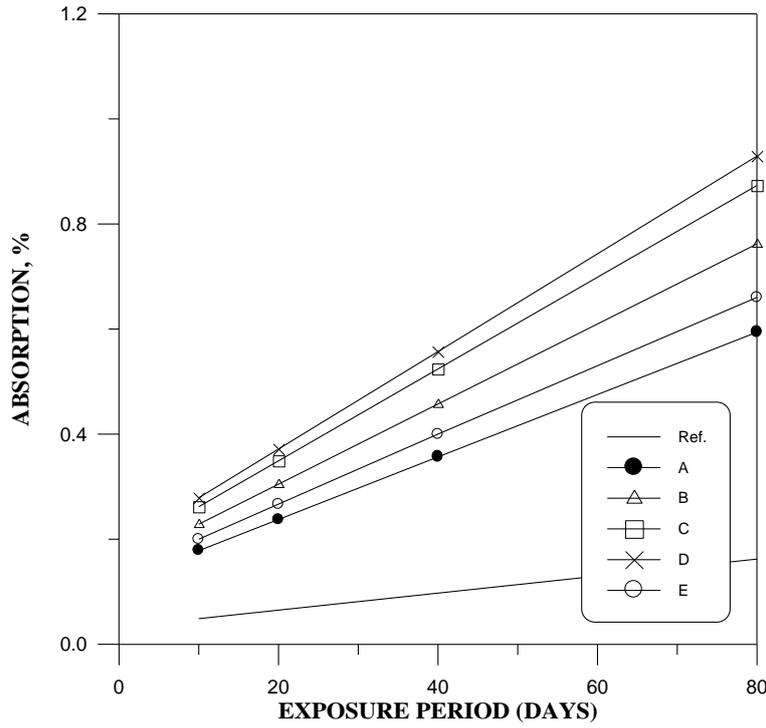


Fig. (4-62): Absorption of sulphur mortar specimens with time after exposure to 32% concentration of hydrochloric acid solution

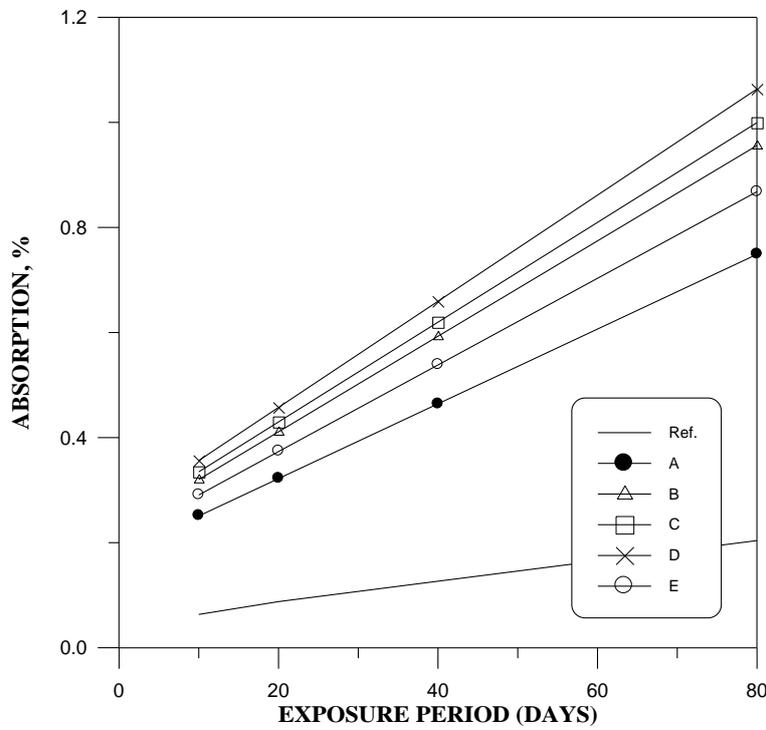


Fig. (4-63): Absorption of sulphur mortar specimens with time after exposure to 2% concentration of nitric acid solution

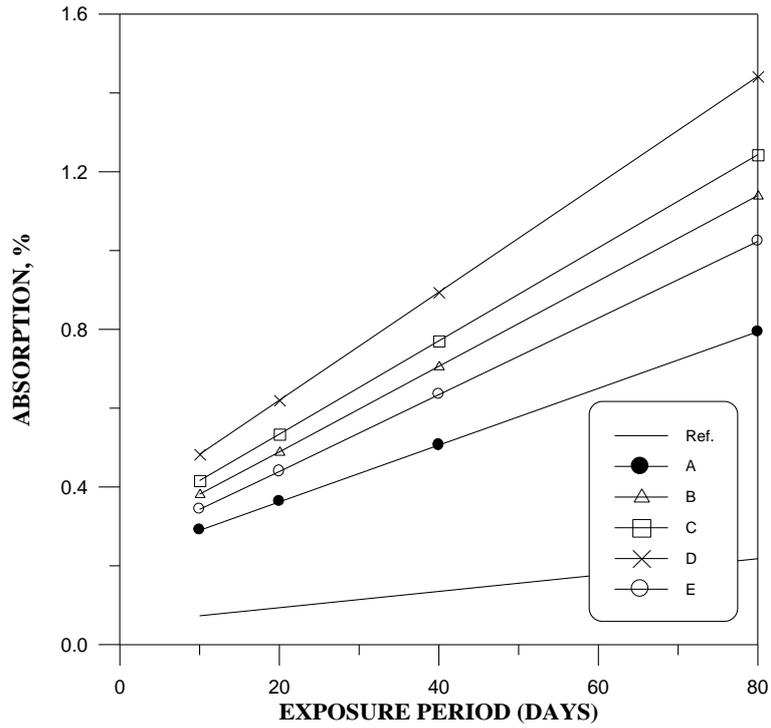


Fig. (4-64): Absorption of sulphur mortar specimens with time after exposure to 4% concentration of nitric acid solution

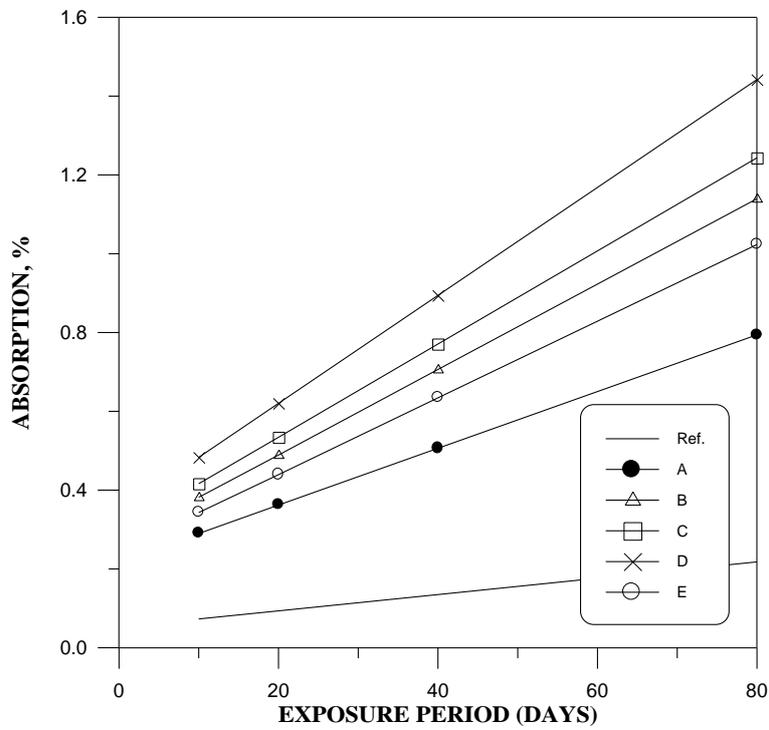


Fig. (4-65): Absorption of sulphur mortar specimens with time after exposure to 6% concentration of nitric acid solution

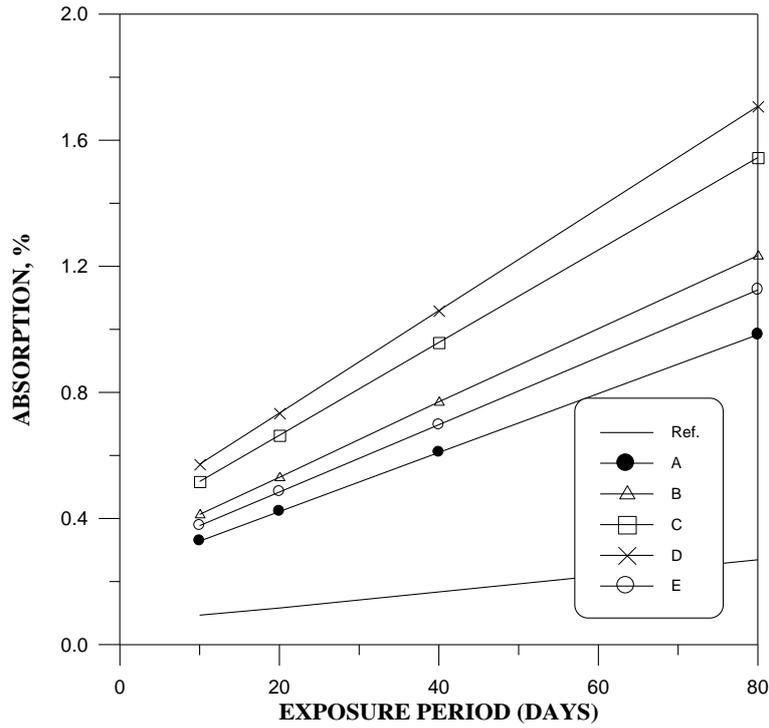


Fig. (4-66): Absorption of sulphur mortar specimens with time after exposure to 1% concentration of nitric acid solution

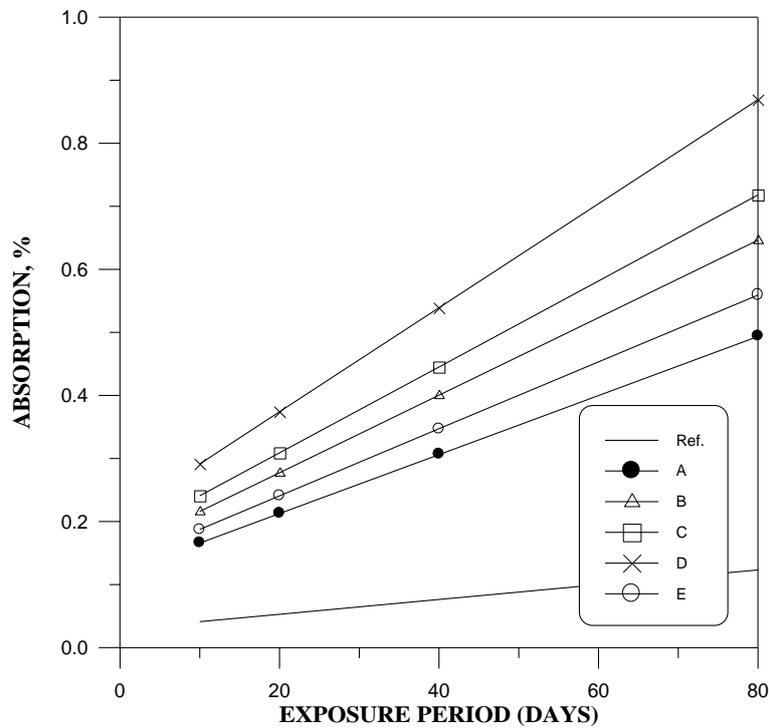


Fig. (4-67): Absorption of sulphur mortar specimens with time after exposure to 2% concentration of sulphuric acid solution

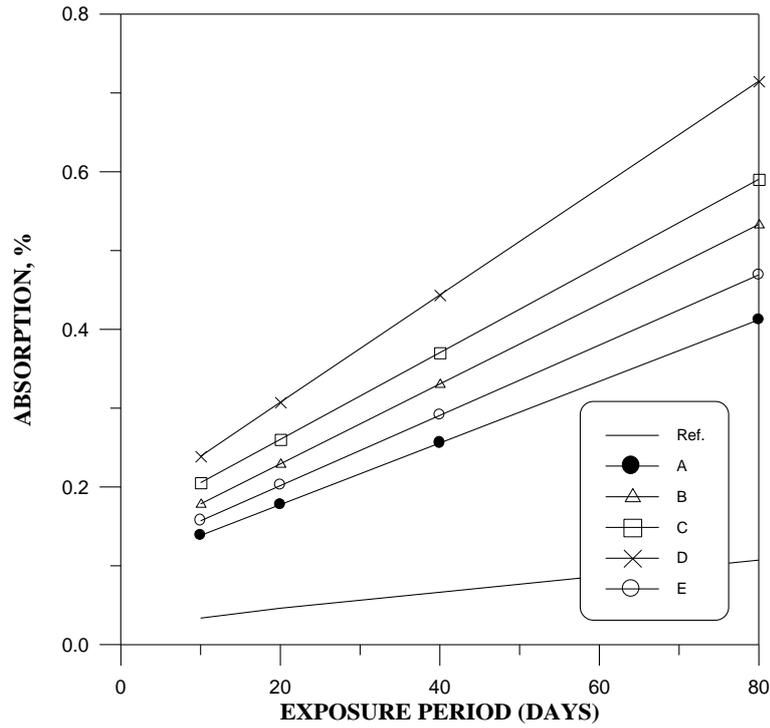


Fig. (4-68): Absorption of sulphur mortar specimens with time after exposure to 5% concentration of sulphuric acid solution

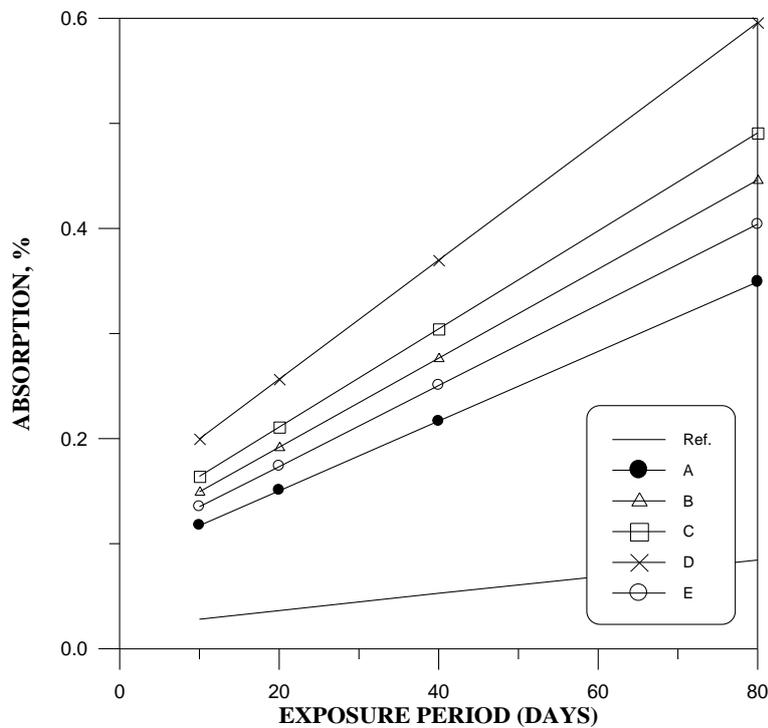


Fig. (4-69): Absorption of sulphur mortar specimens with time after exposure to 6% concentration of sulphuric acid solution

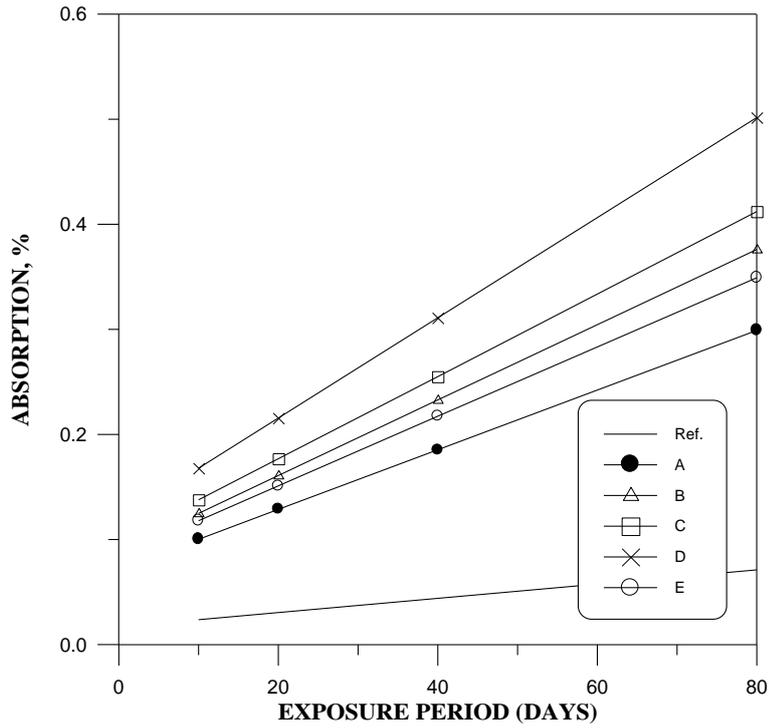


Fig. (4-10): Absorption of sulphur mortar specimens with time after exposure to 10% concentration of sulphuric acid solution

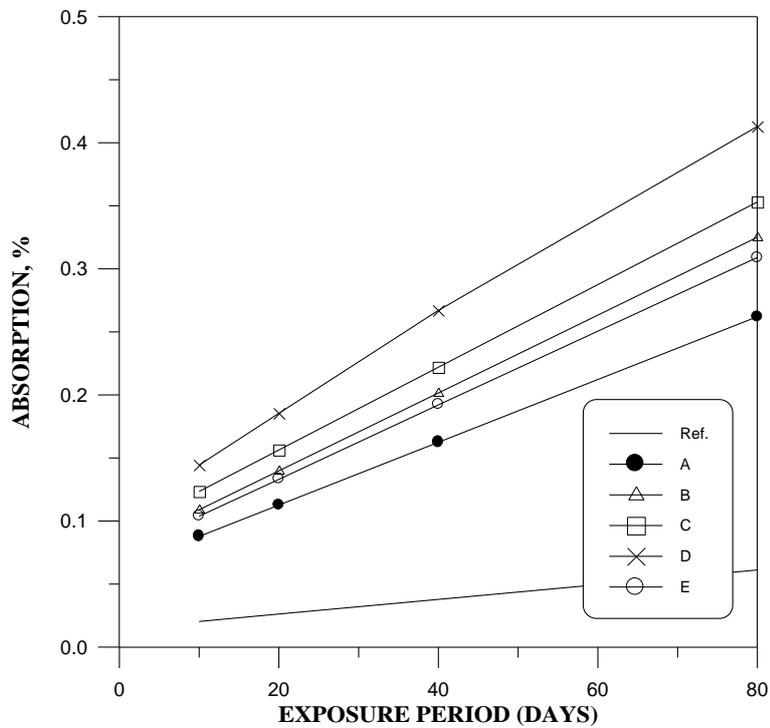


Fig. (4-11): Absorption of sulphur mortar specimens with time after exposure to 18% concentration of sulphuric acid solution

Table (4-14): Absorption of reference and sulphur mortars after exposure to sulfuric acid solutions

Series	Glass sand % by weight	Sulphur cement % by weight	Absorption after exposure to acidic solutions,(
			Before exposure	2.0% concentration				4.0% concentration				6.0% concentration				concentration					
				1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days				
Ref	100	100	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6
D	70	70	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6
C	71.5	71.5	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6
B	72.0	72.0	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6
E	72.0	72.0	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6
A	70	70	-	100	91	82	76	71	66	61	56	51	46	41	36	31	26	21	16	11	6

Series	Glass sand % by weight	Sulphur cement % by weight	Absorption after exposure to acidic solutions, (%)												
			Before exposure	2.0% concentration				4.0% concentration				6.0% concentration			
				1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	8.0 days	1.0 days	2.0 days	4.0 days	
Ref	0.0	10.0	-	0.0 68	0.0 87	0.1 26	0.2 44	0.0 71	0.0 93	0.1 34	0.2 17	0.0 82	0.1 6	0.1 02	
D	70	20	-	0.3 06	0.4 07	0.6 09	1.0 63	0.4 87	0.6 2	0.7 93	1.3 42	0.0 3.0	0.6 81	0.9 82	
C	71.4	28.6	-	0.3 34	0.4 29	0.6 19	0.9 99	0.3 16	0.0 34	0.7 7.0	1.2 43	0.4 7.0	0.6 3.4	0.7 71	
B	66.0	34.0	-	0.3 2.0	0.4 1.0	0.0 92	0.9 00	0.3 81	0.4 89	0.7 66	1.1 39	0.3 98	0.0 11	0.7 38	
E	62.0	38.0	-	0.2 9.0	0.3 73	0.0 37	0.7 68	0.3 43	0.4 39	0.6 34	1.0 23	0.3 6.0	0.4 63	0.6 68	
A	6.0	4.0	-	0.2 0.0	0.3 21	0.4 64	0.7 43	0.2 89	0.3 62	0.0 6	0.7 94	0.3 1.0	0.3 93	0.0 61	

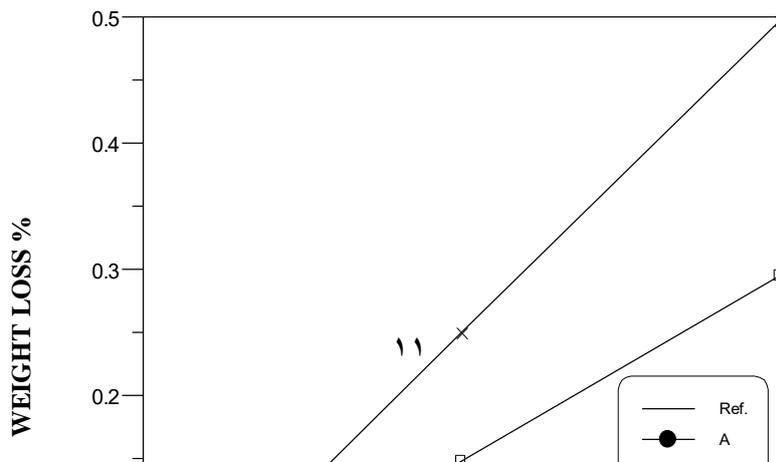


Fig. (4-72): Weight loss of sulphur mortar specimens with time after exposure to 10% concentration of hydrochloric acid

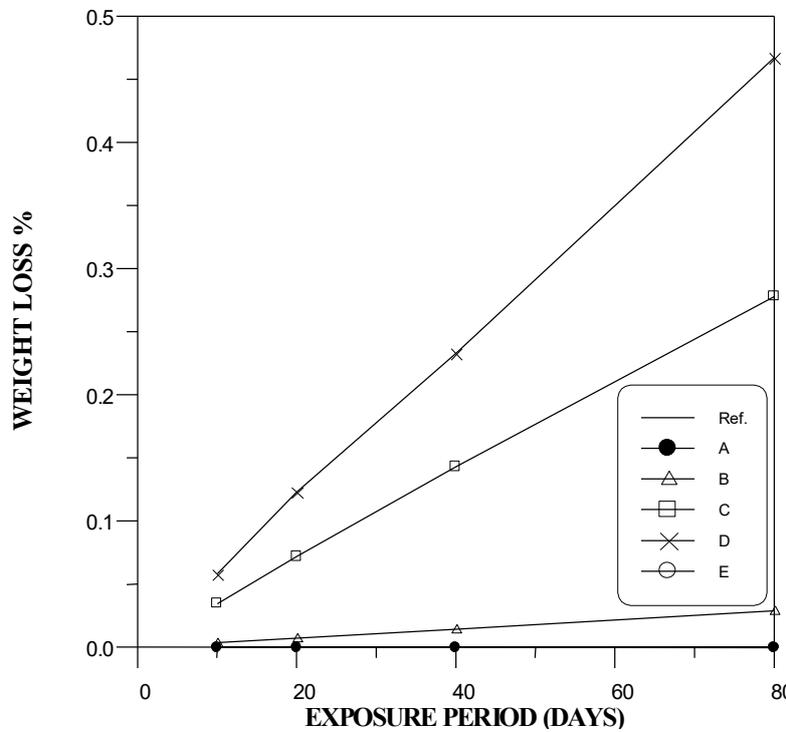


Fig. (4-73): Weight loss of sulphur mortar specimens with time after exposure to 10% concentration of hydrochloric acid

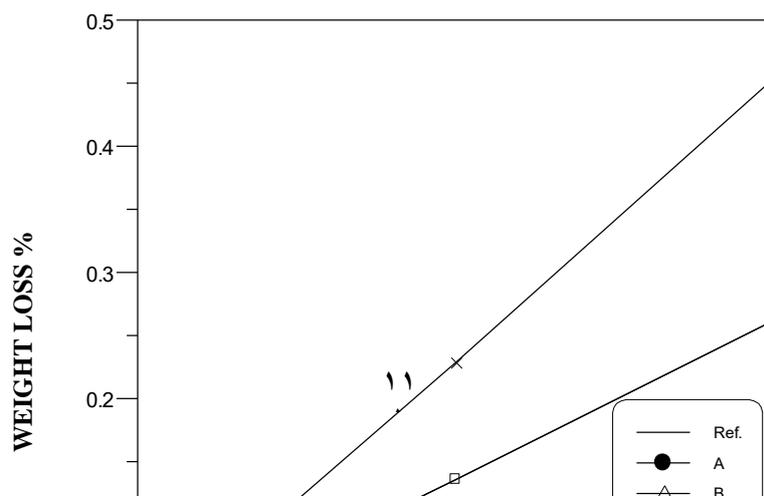


Fig. (4-44): Weight loss of sulphur mortar specimens with time after exposure to 20% concentration of hydrochloric acid

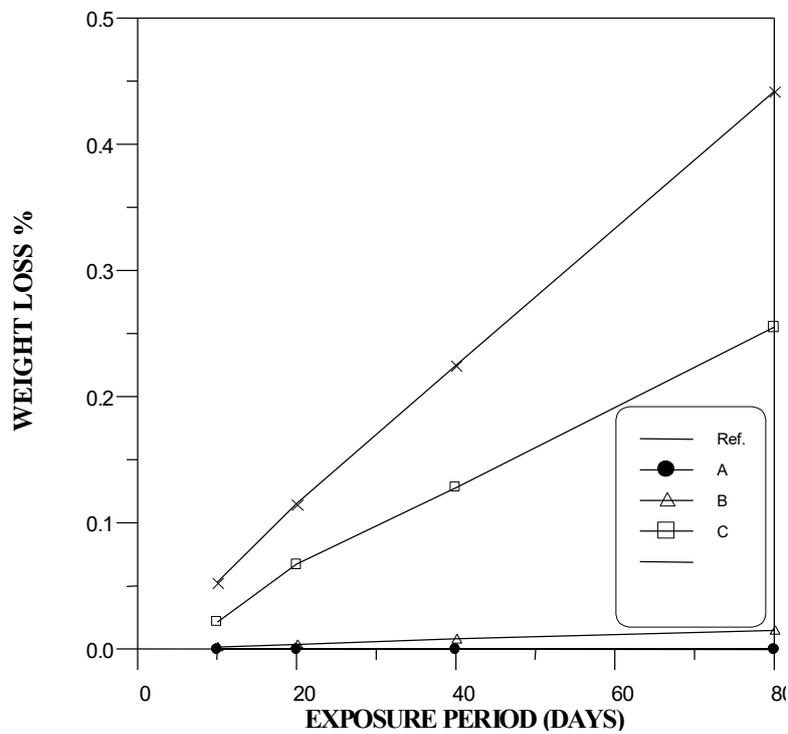


Fig. (4-45): Weight loss of sulphur mortar specimens with time after exposure to 20% concentration of hydrochloric acid

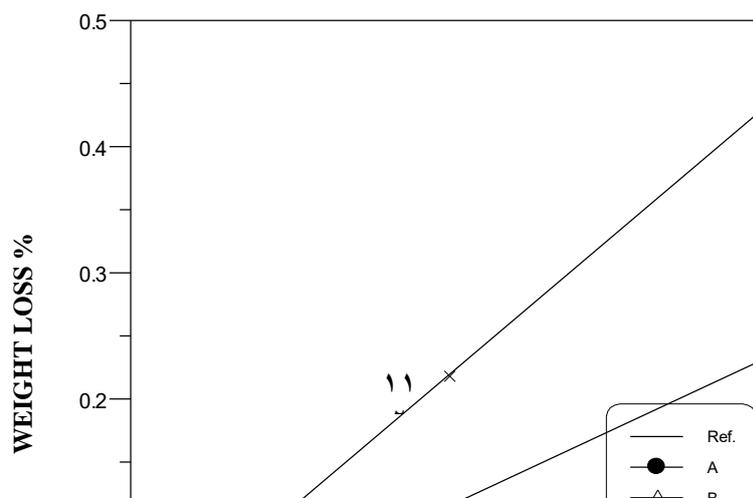


Fig. (4-76): Weight loss of sulphur mortar specimens with time after exposure to 32% concentration of hydrochloric acid

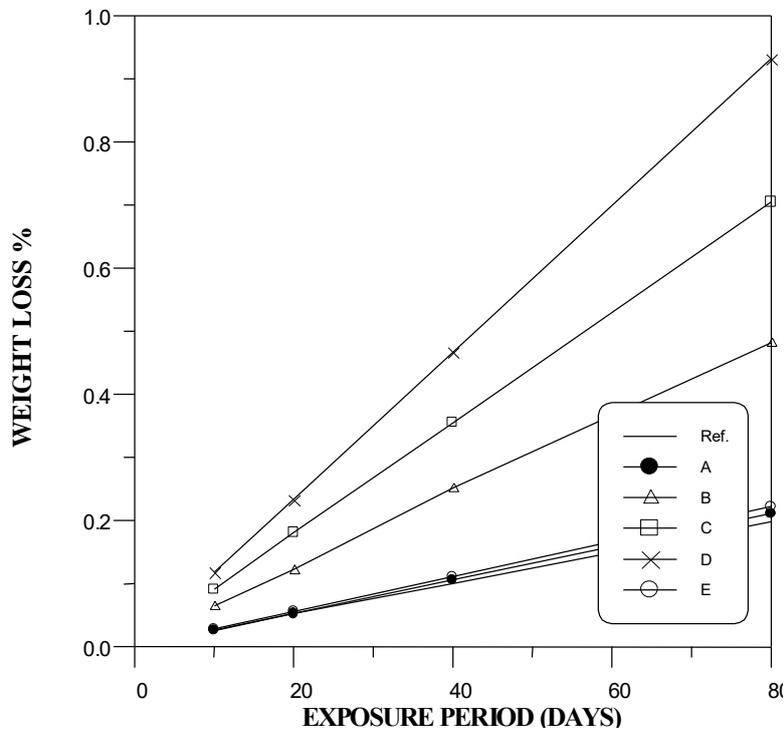


Fig. (4-77): Weight loss of sulphur mortar specimens with time after exposure to 20% concentration of nitric acid

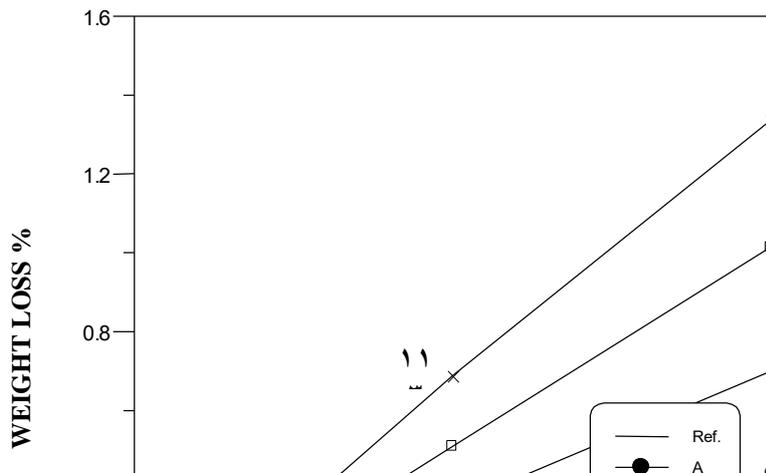


Fig. (٤-٧٨): Weight loss of sulphur mortar specimens with time after exposure to ٤.٠% concentration of nitric acid

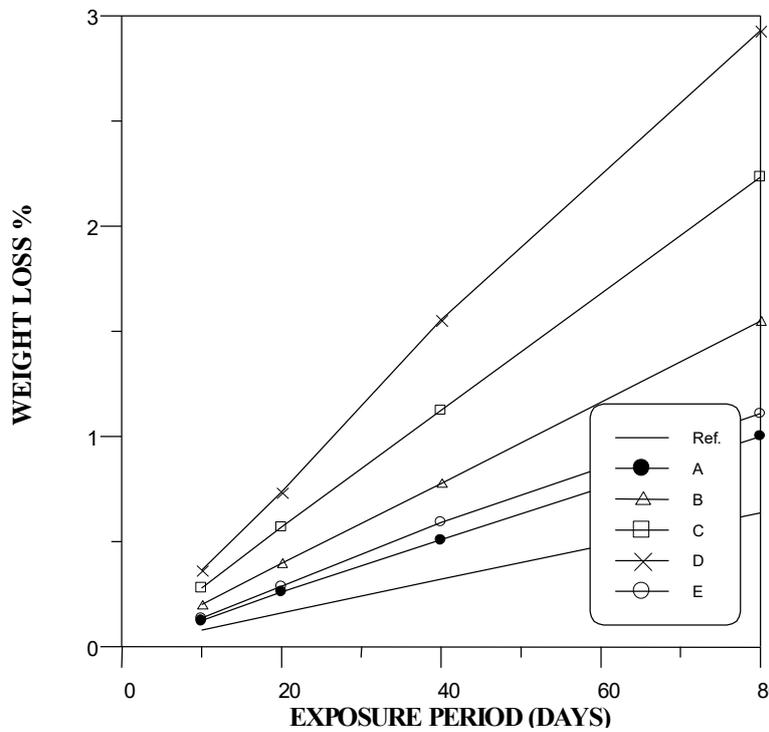


Fig. (٤-٧٩): Weight loss of sulphur mortar specimens with time after exposure to ٦.٠% concentration of nitric acid

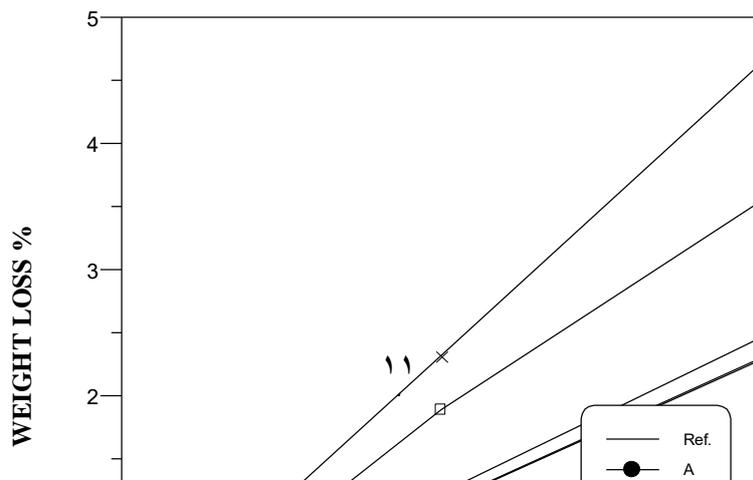


Fig. (4-8): Weight loss of sulphur mortar specimens with time after exposure to 10% concentration of nitric acid

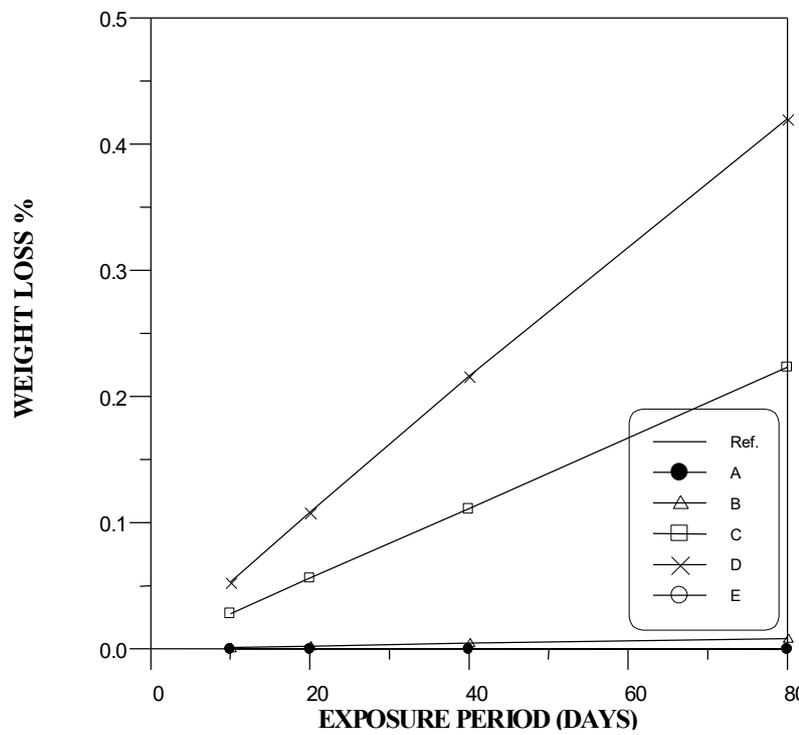


Fig. (4-9): Weight loss of sulphur mortar specimens with time after exposure to 20% concentration of sulphuric acid

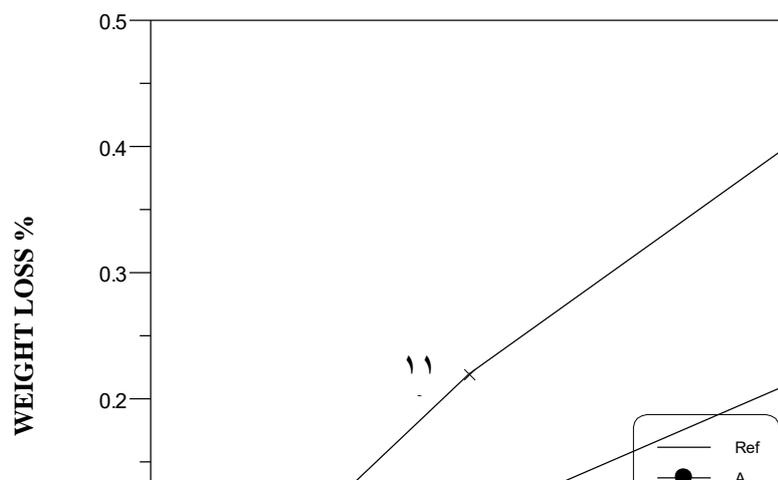


Fig. (٤-٨٢): Weight loss of sulphur mortar specimens with time after exposure to ٤٠% concentration of sulphuric acid

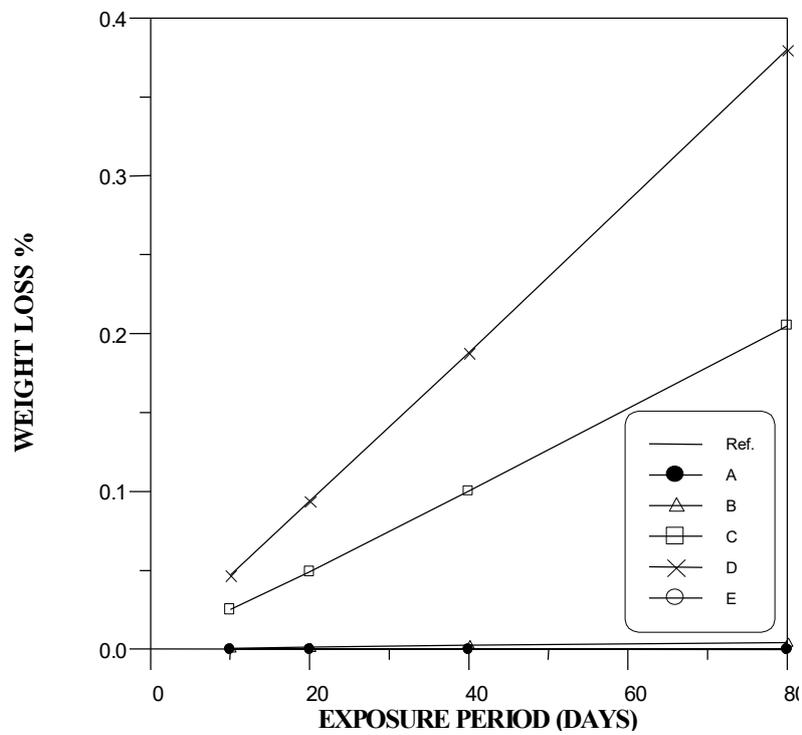


Fig. (٤-٨٣): Weight loss of sulphur mortar specimens with time after exposure to ٦٠% concentration of sulphuric acid

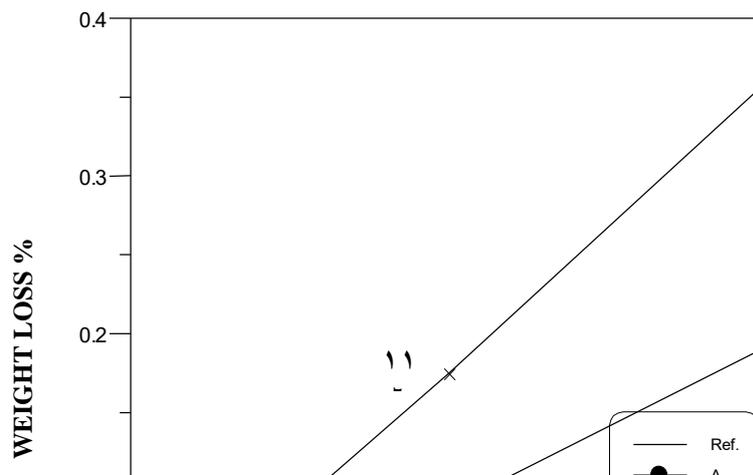


Fig. (4-14): Weight loss of sulphur mortar specimens after exposure to 10% concentration of sulphuric acid

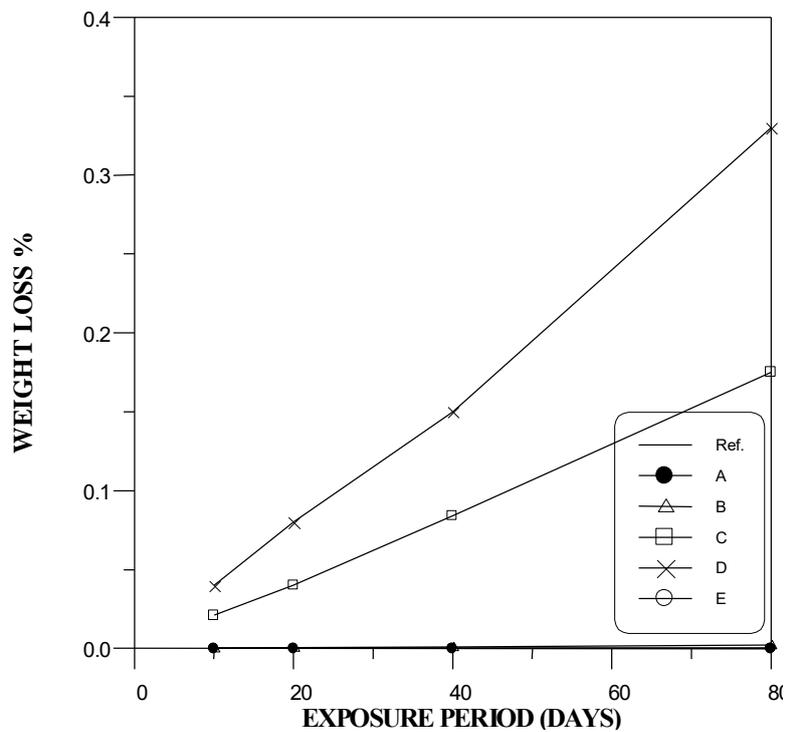


Fig. (4-15): Weight loss of sulphur mortar specimens with time after exposure to 10% concentration of sulphuric acid



CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions:

On the basis of the results of this work, the following conclusions can be drawn:

1. An acid resisting mortar can be produced by mixing of sulphur cement and glass sand.
2. The optimum content of sulphur cement is 37.0% by total weight and glass sand is 62.0% by total weight.
3. At optimum content of sulphur cement, high strength mortar can be obtained with an average compressive strength of 31.2 N / mm² and modulus of rupture of 3.11 N / mm² at 7 days compared to the 29.6 N/mm² and 1.34 N / mm² for reference (sulphur cement only) mixtures.
4. The strength increases with increasing sulphur cement content to 37.0% by total weight and show a small decrease in strength when sulphur cement content increases to 40% by total weight.
5. Reference and sulphur mortar mixtures show very slightly decrease in dry compressive strength and dry flexural strength with time when exposed to sulphuric and hydrochloric acid solutions with various

concentrations and show a slightly high decrease in dry compressive strength and dry flexure strength with time of exposure to nitric acid solutions for various concentrations.

٦. Reference and sulphur mortar mixtures show a slow reaction with ٩٨% concentration of sulphuric acid and show exothermic reaction with ٩٨% concentration of nitric acid solution due to evolution of N_2O_4 and SO_2 gases.
٧. Regardless of the type of mixture and for a given concentration of acid, the decrease in dry and wet compressive and flexural strength decreases with an increase in the concentration of sulphuric and hydrochloric acid and increases with an increase in the concentration of the nitric acid.
٨. The decrease in dry and wet compressive and flexural strength is dependent on the percentage of sulphur cement.
٩. For a given type of mixture, the absorption of specimens increases with decreasing concentration of sulphuric and hydrochloric acid and increases with increasing concentration of nitric acid.
١٠. For a given concentration of acid, compressive and flexural strengths are closely related to each other. The ratio of flexural strength / compressive strength depends on sulphur cement content and type of mixtures and the lower ratio is related to mixtures of higher sulphur cement content i.e. ٣٧.٥ % and the high ratio is associated with mortar of lower sulphur cement content which is the ٢٥ %.
١١. The weight loss is inversely proportional with sulphur cement content. Hence, the weight loss is not pronounced in reference mixtures and insignificant in (E) and (A) mortar mixtures.

۱۲. The thermal expansion results show insignificant results for sulphur mortar mixtures and very slight result for sulphur cement specimens. This is due to the considerable sand content.
۱۳. The shrinkage results show a high result for sulphur cement specimens and relatively slight results for sulphur mortar mixture. This is due to the considerable sand content.

۵.۲ Recommendations for Future Work:

۱. A research work is needed to use sulphur mortars with various fillers and exposed to acidic environments.
۲. An investigation is required to study the effect of various types of sand on mechanical properties and chemical resistance of sulphur mortar exposed to different concentrations of acidic solutions.
۳. Further studies are required to examine the durability of sulphur concrete exposed to acidic environments.
۴. Further studies are required to investigate the effect of surface coatings with sulphur mixtures on chemical resistance and mechanical properties of concrete.
۵. Further studies are required to investigate the effect of sulphur infiltrated concrete on mechanical properties and chemical resistance of concrete.

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