Republic of Iraq
Ministry of Higher Education and Scientific Research
University of Babylon
College of Engineering
Department of Civil Engineering

EFFECT OF SULPHATES IN FINE AGGREGATE ON DRYING SHRINKAGE CRACKING IN END RESTRAINED CONCRETE MEMBERS

A Thesis

Submitted to the College of Engineering of the University of Babylon in Fulfillment of Partial Requirements for the Degree of Master of Science in Civil Engineering

By

JINAN JAWAD HASSAN ALWASH

Supervised by

ASST. PROF. DR. MAHDI S. ESSA
ASST. PROF. MR. SAMIR A. AL-MASHHEDI

December 2005 Thou-Al-Qa'ada 1426

إلى

ذكرى أمي وأبي العطرة

رحمهما الله تعالى

جنـــان

j

نَرْفَعُ دَرَجَاتٍ مَنْ نَشَاءُ وَفَوْقَ

كُلِّ ذِي عِلْمٍ عَلِيمٌ

صدق الله العظيم

سورة يوسف ، الاية 76

الخلاصـــة

يتناول هذا البحث دراسة تأثير الكبريتات الموجودة في الرمل على تشققات انكماش الجفاف في الخرسانة. في هذه الدراسة استخدم نموذج يعتقد انه يشابه إلى حد ما الظروف الطبيعية والموقعية. تم صب عدد من العتبات الخرسانية المقيدة النهاية ونماذج غير مقيدة لحساب الانكماش الحر ومن ثم تعريضها لظروف المختبر. وتم أيضا صب نماذج لغرض تعين مقاومة الانضغاط، مقاومة الشد (الانشطار) ومعامل المرونة. جرى تصميم خلطة خرسانية بمقاومة انضغاط (35 ميغا باسكال) وتثبيتها على جميع العمل. محتوى الكبريتات في الرمل كان 0.29%، 0.5%، 1%، 1.5% التي قابلت نسبة كبريتات كلية في الخلطة من وزن السمنت تساوي [3.07%، 3.355%، 4.03%، 4,7%] في الخلطات التي استخدمت سمنت بورتلاندي اعتيادي ورمل من منطقة 2و[3,033%،3,28 %،3,84%،4,42%] في الخلطات التي استخدمت سمنت بورتلاندي اعتيادي ورمل من منطقة 4و [2.77 %، 3.055% ، 3.73، 4.41%] في الخلطات التي استخدمت سمنت مقاوم للأملاح ورمل من منطقة 2 و [2.733%، 2.973%، 3.55%، 4.12%] في الخلطات التي استخدمت سمنت مقاوم للأملاح ورمل من منطقة 4.

بينت النتائج العملية بأن زيادة نسبة الكبريتات الموجودة في الرمل تؤدي إلى انخفاض مقدار انكماش الجفاف الطليق في الأعمار المبكرة في حين إن النسب العالية من الكبريتات والتي كانت (1.5% من وزن الرمل) والتي قابلت نسبة كبريتات كلية في الخلطة من وزن السمنت تساوي [4.7% عند إستخدام سمنت بورتلاندي اعتيادي ورمل من منطقة 2 ، 4.42% عند استخدام سمنت بورتلاندي اعتيادي ورمل من منطقة 4، 4.41% عند استخدام سمنت مقاوم للأملاح ورمل من منطقة 2 و 4.12% عند استخدام سمنت مقاوم للأملاح ورمل من منطقة 4] تسبب زيادة مقدار انكماش الجفاف في الأعمار المتأخرة.

اعتمادا على نتائج هذا البحث يمكن الاستنتاج بأن زيادة محتوى الكبريتات تسبب زيادة في انفعال الشد الأقصى (tensile strain capacity) والزحف (creep) للخرسانة, إن الزيادة في انفعال الشد الأقصى كانت حوالي 24.38%والزيادة في الزحف حوالي 24.9% عند استخدام رمل من المنطقة 4 في الخلطة التي تحتوي على سمنت بورتلاندي اعتيادي ونسبة كبريتات 1.5%وتم إنضاجها لمدة 3 أيام. إن إضافة الكبريتات تؤخر من حدوث تشققات الانكماش وان تطور عرض الشق يصبح أبطأ مع زيادة الكبريتات إلى حد معين يمثل النسبة المثلى للكبريتات وفي الخرسانة ذات النسبة العالية من الكبريتات (1.5% من وزن الرمل) فان عرض الشق يتطور أكثر من الخرسانة ذات نسبة الكبريتات القليلة.

إن زيادة فترة الإنضاج من 3 إلى 28 يوم سبب ابتعاد وقت حدوث الشق وزيادة انفعال الشد الأقصى ،انفعال الشد الأقصى المرن وانفعال الزحف في الخرسانة. علاوة على ذلك إن مقاومة انضغاط الخرسانة تزداد بزيادة الكبريتات إلى حد معين يمثل النسبة المثلى للكبريتات والذي كان (1% من وزن الرمل) ثم تبدأ بعد ذلك بالانخفاض عند تجاوز هذه النسبة وان مقاومة الشد (الانشطار) ومعامل المرونة يبديان اتجاها مشابها للذي لوحظ في مقاومة الانضغاط.

وأخيرا تم اقتراح وتطوير نموذج رياضي يعتمد على معادلات غير خطية متعددة المتغيرات للحصول على قيم تخمينية لانفعال الانكماش وكانت قيمة معامل الارتباط (0.987) فيما كان الاختلاف بين القيم الحقيقية للانكماش والقيم المخمنة بحدود (±60.13×10^{-6}).

CERTIFICATE

We certify that the thesis titled “**Effect of Sulphates in Fine Aggregate on Drying Shrinkage Cracking in End Restrained Concrete Members**", was prepared by **"Jinan Jawad Hassan Alwash**", under our Supervision at Babylon University in Fulfillment of Partial Requirements for the Degree of Master of Science in Civil Engineering .

Signature	**Signature**
Name:	**Name:**
Assist. Prof. Dr. Mahdi S. Essa	Assist. Prof. Mr. Samir A. Al-Mashhedi
Date: / / 2005	**Date:** / / 2005

ACKNOWLEDGMENT

I wish to express deep appreciation to my supervisors Asst . prof . Dr. Mahdi S. Essa and Asst. prof. Mr. Samir A.AL-Mashedi .
I'm very grateful to prof. Dr. Riyadh S. AL-Rawi for his assistance and advice.

I also have a great appreciation for Asst, prof. Dr. Mohammed M. Salman for his assistance and advice.

I would also record my thanks to the staff of construction material laboratory of civil engineering department of Baghdad University, especially Suhaila Gh. Matter.

Special thanks are presented to the staff of AL- Kufa cement plant.

I'm really grateful to my family for their encouragement and support during the course of this work.

Finally, thanks to all who participate in providing help and assistance to complete this work especially Hussein Mared, Abbass Salim Abbass and Mohammed Mansour.

Jinan 2005

ABSTRACT

This investigation is conducted to study the effect of sulphates in sand on the drying shrinkage cracking in restrained concrete members.

In this study a restrained shrinkage model [which is believed to resemble field conditions] was used. End restrained concrete beams of concrete mixes with design compressive strength (35 MPa), were cast and exposed to laboratory conditions. Specimens were cast also for compressive strength, splitting tensile strength and modulus of elasticity measurements.

Four levels of SO_3 content in sand were investigated these levels were about 0.29%, 0.5%, 1.0%, and 1.5%. Which yield [3.07%, 3.355%, 4.03% and 4.7%] total SO_3 content by weight of cement respectively for concrete with OPC and sand of zone 2 and [3.033%, 3.28%, 3.843% and 4.42%] for concrete with OPC and sand of zone 4 and [2.77%, 3.055%, 3.73% and 4.41%] when SRPC and sand of zone 2 is used, while yield [2.733%, 2.93%, 3.53%, and 4.12%] for SRPC and sand of zone 4.

Experimental results showed that the increase in the sulphates content of sand causes a reduction in free drying shrinkage strain at early ages, whereas the existence of sulphate in high percentage 1.5% by weight of sand, thus yielding [total SO_3 contents by weight of cement 4.71%for the concrete specimen with OPC and sand of zone 2 and 4.42% for the specimen with OPC and sand of zone 4 and 4.41% when SRPC and sand of zone 2 is used ,while it is equal to 4.12% when SRPC and sand of zone 4 is used] would increase the shrinkage at later ages.

Based on the results of this work, it can be concluded that the increase in sulphates content causes increasing in tensile strain capacity and creep (at cracking).The tensile strain capacity increases about 24.38% and the creep increases about 24.9% when using sand from zone 4 and containing sulphates of 1.5% by weigh of OPC and 3 days moist curing.

Also, it was found that sulphates addition retards the occurrence of shrinkage cracks. Furthermore, the crack width development became slower with sulphates increase up to the optimum value. But the crack width in concrete samples of high sulphate content (1.5% by weight of sand] develops more than that in concrete with low sulphate content.

It was concluded that 28 days moist curing instead of 3 days moist curing causes increasing in cracking time, tensile strain capacity, elastic tensile strain capacity and creep strain.

It was observed that the compressive strength increased with increasing the sulphate content up to the optimum value which was found to be about 1.0% (by weight of sand) and then it decreased. The splitting tensile strength and modulus of elasticity show trend somewhat similar to that observed in compressive strength.

Finally a mathematical model for the prediction of shrinkage strain was proposed and developed in this study. This model uses multivariable non-linear regression equation to evaluate good correlation coefficient (R=0.987) with less difference between the observed and predicted shrinkage strain (df=$\pm 60.13 x 10^{-6}$).

LIST OF CONTENTS

Title	Page

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: LITERATURE REVIEW

Title	Page

CHAPTER THREE : Experimental Work

Title	Page

CHAPTER FOUR : Analysis Of Results And Discussion

CHAPTER FIVE : CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

Title	Page

LIST OF TABLES

LIST OF PLATES

NOTATIONS

Most commonly used symbols are listed below, these and others are defined where they appear in the research

Symbol	Description
C	Creep (at cracking time) .
$\overline{C}$	Constant of total net shrinkage.
C_a	Creep strain after cracking.
C_b	Creep strain before cracking.
C/S	Cement to sand ratio.
CT	Curing time .
d	Bar diameter .
DEF	Delayed ettringite formation.
df	Range of the difference between the actual and predicted shrinkage.
E_c	Modulus of elasticity for concrete.
E_g	Modulus of elasticity for aggregate.
E.T.S.C	Elastic tensile strain capacity.
e_{shr}	Final shrinkage strain.
e_{sh}	Free shrinkage .
e_{ult}	Elastic tensile strain capacity.
FM	Fineness modulus .
F.S	Free shrinkage .
G	Gravel content .
g	Relative volume concentration of aggregate .
H	Wall height.
I.R	Insoluble residue .
K	Constant .
K_1	Constant .
L	Slab length .
L.O.I	Loss on Ignition .
L.S.F	Lime saturation factor.
n	Factor.
OPC	Ordinary Portland cement.
R	Correlation coefficient .
R_a	Degree of restraint after cracking .
R_b	Degree of restraint before cracking .
S	Sand content.
S_1	Stress corresponding to a longitudinal strain (0.00005).
S_2	Stress corresponding to 40% of ultimate load.
S_{hc}	Shrinkage of concrete .
S_{hp}	Shrinkage of cement paste .

Symbol	Description
S_{max}	Maximum crack spacing.
S_{min}	Minimum crack spacing.
SRPC	Sulphate resisting Portland cement.
SS	Specific surface area of cement .
SRA	Shrinkage reducing admixtures.
T.S.C	Tensile strain capacity.
μ	Poisson's ratio of concrete .
μ_g	Poisson's ratio of aggregate.
W/C	Water to cement ratio .
W_i	Width of crack at the onset of cracking .
W/S	Water to sand ratio .
W_{max}	Maximum crack width .
ρ	Steel reinforcement ratio .
ρR	Effect of end restraint as a ratio .
$\in_2$	Longitudinal strain produced by stress S_2.

INTRODUCTION

CHAPTER 1

1.1 General

The principal volume changes that may occur in concrete are caused by settlement of fresh mass of concrete, reaction of high alkali cement with certain reactive aggregates, sulphate attack and changes in moisture content in the concrete (especially drying shrinkage) [1]. The last two are the major problems facing the engineers in this country and in Middle East too, due to weather condition.

Unrestrained shrinkage takes place on loss of moisture from the concrete and in the absence of applied stress.

Restrained concrete movement usually leads to cracking. Hot weather usually aggravates such cracking. The restrained shrinkage (which is commonly present in practice) will induce tensile stresses in concrete and when these stresses exceed the tensile strength of concrete cracking will take place.

Cracks may ease the ingress of moisture, oxygen, and chloride ions to the depth of the reinforcing steel. This, in turn, may lead to an increase in the rate of corrosion of steel and areduction in service life. Also cracks are aesthetically unpleasant and may impair strength, water tightness and durability of structures [2].

Durable concrete should withstand the condition for which it has been designed, without deterioration over a period of years [3].

Cracking also may take place due to delayed ettringite formation. The ettringite (calcium sulphoaluminate) occurs when the sulphates in concrete ingredients would react with calcium aluminates, mainly (C_3A) and to the lesser degree (C_4AF) and water [1]. This reaction is accompanied by a significant increase in solid volumes. The volume of the produced sulphoaluminate is several times larger than that of reacted materials [1, 4].

Sulphate in sand is a major problem encountered in the Middle and Southern part of Iraq. Most of the sulphate salts in sand are composed of calcium, magnesium, potassium and sodium sulphates. calcium sulphate is the most predominant salt present in Iraqi sand. It is usually found in sand as gypsum. About 95% of sulphates in sand are in the form of calcium sulphates [5, 6] because of the low solubility of this type of sulphate.

1.2 Objective of This Work

In the present work, is an attempt to study the effect of sulphates on restrained shrinkage cracking (subjected to natural weather conditions).

Volumetric expansion due to presence of sulphates may decrease the shrinkage strain thus it may decrease shrinkage stress and reduce the damage of cracking. On the other hand; sulphates may cause interior cracking which may accelerate the shrinkage of concrete then shrinkage and shrinkage cracking will be increased. So the effect of sulphates on the shrinkage cracking will increase. This has prompt us to indulge in such investigation. .

The splitting tensile strength, modulus of elasticity and compressive strength test were adopted where the compressive strength test is one of the most important properties of concrete and most other properties are related to it.

Sand with four different percentages of sulphate (0.29, 0.5, 1, 1.5) were used in this work. The effects of these sulphates on shrinkage cracking of end-restrained concrete members and on the free shrinkage were studied. Also a comparison between their effects on free shrinkage and end restrained shrinkage cracking parameter was made.

1.3 Research Layout

In this investigation, the research work is presented through five chapters.

Chapter Two presents a literature review of the extensive studies performed on the shrinkage, creep, tensile strain capacity, the effect of sulphates on concrete, and other important properties of concrete were discussed in this chapter.

Chapter Three gives details of the experimental work which includes a description of the molds used to achieve shrinkage cracking . Mixing, casting, curing and testing the specimens for shrinkage, tensile strength , modulus of elasticity and compressive strength are discussed.

In Chapter Four: the experimental results of the effect of free shrinkage, crack width development with age, tensile strain capacity, elastic tensile strain capacity, creep, cracking age ,compressive strength, splitting tensile strength, modulus of elasticity and the proposed mathematical regression model were presented and discussed.

Chapter Five is devoted to the main conclusions and commendations for future work .

1.4 Main Variables Used in This Study

The main variables used in this study are:

1- Percentage of sulphate in sand; (0.29%, 0.5%, 1.0%, 1.5% by weight of sand).

2- Type of cement; (OPC and SRPC).

3- Fineness of gypsum (which is the same for sand); zone 2 and zone 4 gradation.

4- Curing time; (3 and 28 days moist curing).

CHAPTER 2

LITERATURE REVIEW

2.1 Shrinkage of Concrete

Shrinkage is a time-dependent volumetric contraction of concrete mass which is associated with the drying out of water cement gel. Shrinkage can cause harmful stresses and often deleterious cracks in concrete when it is not controlled.

2.2 Types of Concrete Shrinkage

There are different types of concrete shrinkage, which can be summarized as below.

2.2.1 Plastic Shrinkage

It is the volume change that takes place in concrete whilst it is still fresh in the plastic form, within the first few hours after it has been placed. Plastic shrinkage occurs primarily due to the heat librated during hydration, absorption of mixing water and bleeding [7].

According to ACI Committee 305 [8], if evaporation is more than 1 kg/m^2/hr plastic shrinkage cracks may occur. ACI Committee 209 [9] reported that the volumetric contraction while cement paste is plastic may reach 1% of absolute volume of dry cement.

2.2.2 Drying Shrinkage

Drying shrinkage is the most important type of concrete shrinkage. This shrinkage is due to water loss of concrete stored in unsaturated air. There are three types of water in concrete: Capillary water, Gel water and non evaporable water [10]. Capillary water is easy to evaporate. Gel water is difficult to evaporate, its evaporation may take 20 years and this is the principal cause of drying shrinkage. While the non-evaporable water is very difficult to evaporate under the normal conditions. Drying shrinkage occurs as the concrete hardens and is allowed to dry. This reduction in dimension is attributed to the shrinkage of the cement gel which is partly irreversible [3].

The change in the volume of drying concrete is not equal to the volume of water removed. The loss of free water, which takes place first, causes little or no shrinkage. As drying continues, adsorbed water is removed and the change in the volume of unrestrained hydrated cement past at that stage is equal approximately to the loss of a water layer one molecule thick from the surface of all gel particles since the "thickness" of water molecule is about 1% of the gel particle size, a linear change in dimension of cement past on complete drying to be of the order of $10000x10^{-6}$. Experimentally Lea [4] has observed values up to $4000x10^{-6}$. It has been reported [3] that the removal of the zeolitic water (water which is packed between the layers of the crystals) may affect the shrinkage or part of it. Calcium silicate-one of the main products of hydration of Portland cement-changes its lattice spacing from 14 to 9 Angstrom on drying. Figure (2-1) shows the relation between shrinkage and water loss.

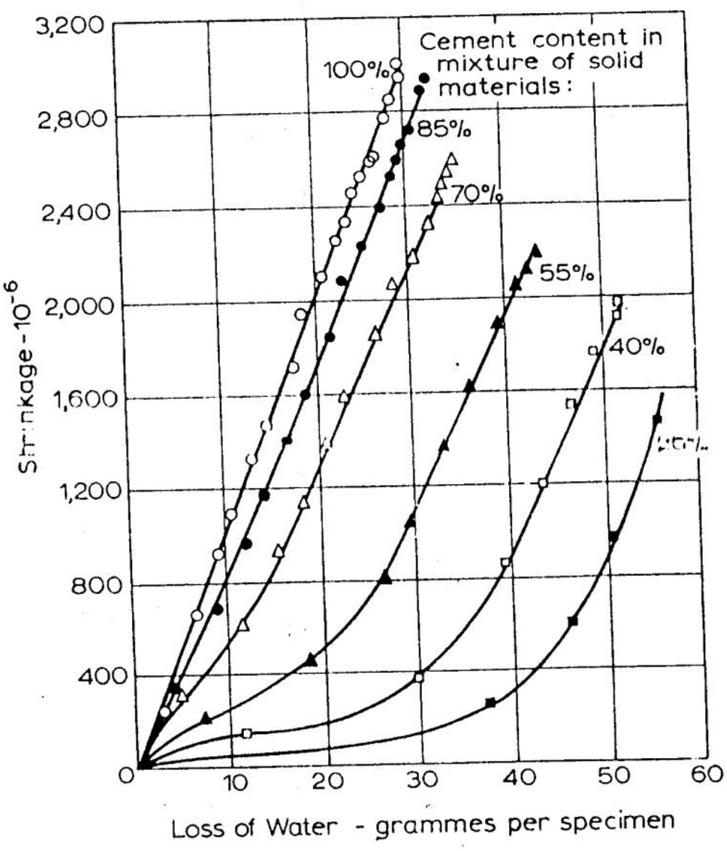


Fig. (2-1): Relation between shrinkage and loss of water specimens of cement – pulverized silica pastes cured for 7 days at 21C° [3].

2.2.3 Carbonation Shrinkage

The presence of carbon dioxide (CO_2) and moisture in air can produce carbonic acid which reacts with hydrated lime in cement and produce ($CaCO_3$).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

This type of shrinkage is usually limited to the surface of concrete[3,11]. The actual rate of carbonation depends on the moisture and the CO_2 content and the relative humidity of the ambient medium.

2.2.4 Autogenous Shrinkage

Autogenous shrinkage in concrete is defined as a self produced change in volume. It occurs in the interior of a large concrete mass. The magnitude of the movement is about ($40x10^{-6}$) at the age of one month and reaches to ($100x10^{-6}$) after five years [3].

Davis [12] assumed that autogenous volume change would be of great importance for dam concrete. He concluded that the autogenous shrinkage value is small in case of large W/C ratio of concrete.

Autogenous shrinkage tends to increase at higher temperatures, with a higher cement content, and possibly with finer cements, and with cements which have a higher C_3A and C_4AF content [13].

2.3 Factors Affecting Shrinkage of Concrete

There are many factors influencing shrinkage of the concrete but the main factors are summarized as follows:

2.3.1 Influence of Aggregate

The aggregate appears to have a great influence on shrinkage of concrete. It occupies about (65-75) % of total concrete volume and restrain the shrinkage of cement paste. Smaller aggregate experience more uniform shrinkage. The type of aggregate, rather than the aggregate size, has an enhanced effect on the concrete shrinkage. Aggregate that shrinks considerably has a low rigidity compared to the tensile stresses developed by the shrinkage of the cement paste. These types of aggregate may also have a large water absorption value which will result in a concrete with higher shrinkage [1].

Han [14] examined the effect of aggregate in high strength concrete on creep and shrinkage. the shrinkage testing was conducted on (100x100x400) mm specimens cured at 20 ± 3°C and 65 relative humidity. The different concrete mixtures included three types of aggregate; crushed gravel, granite, and limestone. The high strength concrete with the limestone aggregate had less shrinkage than the mixtures containing crushed gravel or granite.

The rate of shrinkage of the limestone mixture was less than that of the mixtures containing the other aggregate types. It was determined that the limestone mixture had the highest early elastic modulus which explains the reduced shrinkage behavior.

The influence of aggregate on the shrinkage of concrete has two primary effects. The water demand of the aggregate, and the stiffness of the aggregate relative to the cement paste. The cement paste is the primary source of shrinkage. Aggregate with lower water demand will therefore produce concretes with lower shrinkage characteristics. It has also been determined that higher elastic modulus concrete produces lower creep and shrinkage values. Thus, aggregate affects concrete deformation through water demand, aggregate stiffness and volumetric concentration, and paste/aggregate interaction.

Various equations have been proposed to relate the shrinkage of concrete to the shrinkage of its cement paste and the aggregate content.

Pickett [15] derived on equation of the form:

$$S_{hc} = S_{hp}(1-g)^{n} \tag{2-1}$$

$$n = \frac{3(1-\mu)}{1+\mu+2(1-\mu g)E/E_g} \tag{2-2}$$

Where:

(S_{hc}): The shrinkage of concrete.

(S_{hp}): The shrinkage of cement paste.

(g) : The relative volume concentration of aggregate.

(n) : Factor.

(E, E_g): Modulus of elasticity for concrete and aggregate respectively.

(μ, μ_g) : Poisson's ratio for the concrete and aggregate respectively.

The shrinkage decreases with increased aggregate proportion. For example, increasing the aggregate content from 71% to 74% will reduce shrinkage by about 20% [16]. Figure (2-2) shows the relation between the aggregate content and the ratio of the shrinkage of concrete to the shrinkage of neat cement paste.

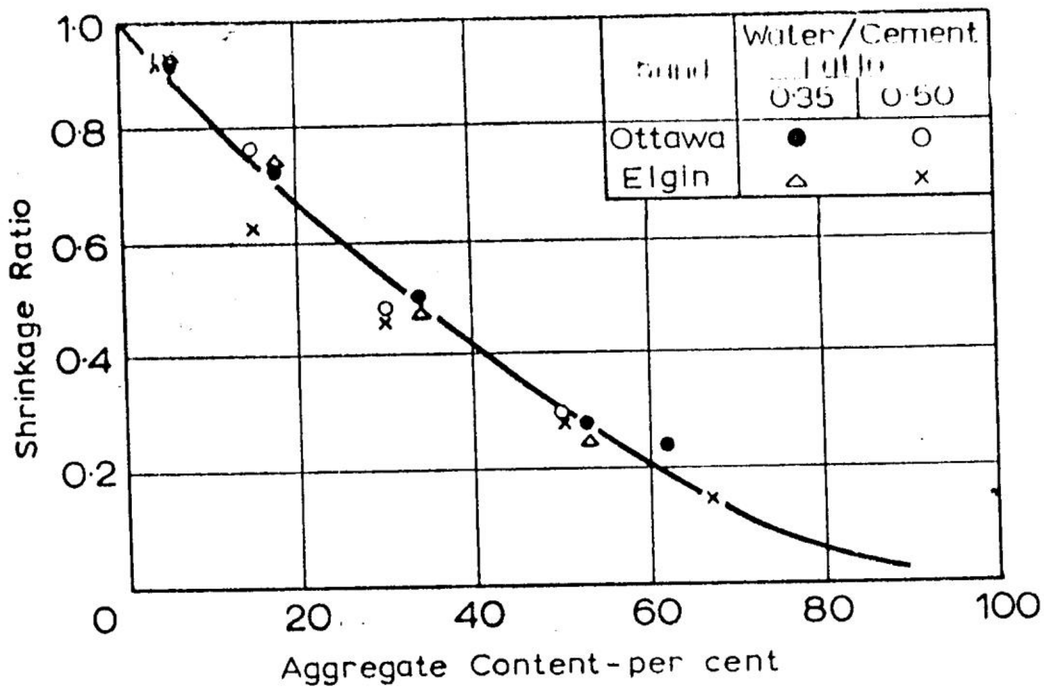


Fig.(2-2): Influence of the aggregate content in concrete (by volume) on the ratio of the shrinkage of concrete to the shrinkage of neat cement paste [16].

Almudaiheem and Hansen [17] studied the effect of specimen size compared to drying shrinkage within their results they found that shrinkage decreases with increasing aggregate content. All of the mixtures had W/C ratios of (0.4) the maximum aggregate size was (9.5) mm. The mixtures consisted of either 50% or 60% aggregate content. The aggregate content had a more profound influence on shrinkage than did the specimen size.

2.3.2 Cement Type and Fineness

Concrete with higher cement results in a higher cracking tendency. Higher fineness of cement gives higher shrinkage since large particles of cement cause more restraint [3].

Troxell et al. [1] concluded that shrinkage of low heat cement (type IV) is greater than that of (type1). This is believed to be due to high (C_2S) content in (type IV) cement, which exhibits high shrinkage. ACI Committee 224 [18] suggested that lower shrinkage of cement paste is associated with lower (C_3A/SO_3) ratio, lower (Na_2O) and (K_2O) content and higher (C_4AF) content.

Carlson [19] pointed out that fineness of cement has probably two opposing influences on shrinkage of concrete. Finer cement hydrates more extensively and thus produces a denser gel, which has a lesser shrinkage. While the gel of the finer cement is stronger and therefore it has a higher effect against restraint of aggregate and this increases shrinkage.

2.3.3 Water Content

The water content has a large influence on the drying shrinkage of concrete because its increase tends to increase shrinkage and at the same time to reduce the concrete strength.

In general, the water content of any mix would indicate the expected shrinkage, following the general pattern of direct proportionality Figure (2-3) [3].

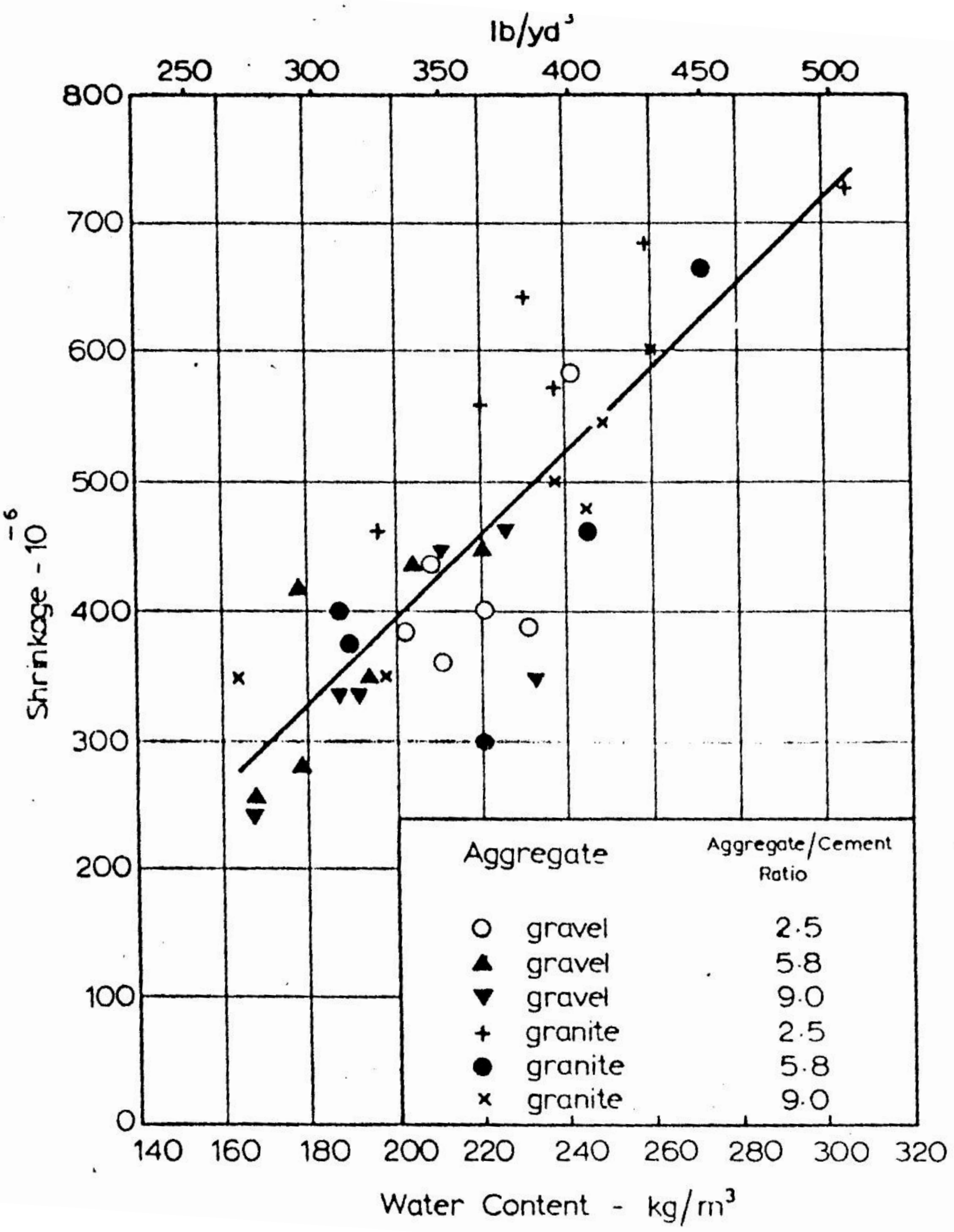


Fig.(2-3): The relation between the water content of fresh concrete and drying shrinkage [3]

Carlson [20] reported that the shrinkage decreases, about (30%) where water content is reduced to 15% a similar trend was given by the

ACI Committee 224 [18] for 10% reduction of water content, the one year drying shrinkage was lowered by about 15%.

2.3.4 Influence of Curing

There are some contradictions about the effect of curing on shrinkage. Alsayed and Amjad [21] tested twelve 1000 mm x 1000 mm x 200 mm concrete slabs and twelve 150 mm x 300 mm cylinders. The specimens were placed to examine the effects of curing conditions on shrinkage. Shrinkage measurements began on the eighth day after specimen fabrication. Watering twice a day, burlap, polyethylene, and air curing were all found to result in high shrinkage rates. Other methods were recommended to reduce the shrinkage rate. Sealing the concrete with resin modified wax or watering the concrete four to five times a day may decrease the shrinkage rate of the concrete.

Tremper and Spellman [22] show that, when concrete was moist cured for 7, 14 and 28 days before drying was started, it achieved about the same shrinkage regardless of its curing durations.

Neville [3] reported that the effect of curing on magnitude of shrinkage is small and that well-cured concrete shrinkage more rapidly.

2.3.5 Influence of Specimen Size

The size and shape of concrete specimen definitely influence the rate of loss or gain of moisture under a given storage condition, and this can affect the rate of volume change as well as the total expansion or contraction.

Almudaiheem and Hansen [17] observed the shrinkage of various specimen size over a one year period. The shrinkage decreased with increasing specimen size. The ultimate shrinkage of paste, mortar, and concrete were found to be independent of specimen size and shape according to the dynamic shrinkage/ weight loss curves. They concluded that the ultimate drying may be estimated from shrinkage versus drying time curves for small laboratory specimens of (25x25x279) mm with the same mixture proportions as the larger structural members.

2.3.6 Relative Humidity

The reduction in the shrinkage is proportional to the increase of relative humidity because of the reduction of water evaporation from the surface of concrete Figure (2-4) [3].

According to Troxell [1] the drying shrinkage of concrete in atmosphere of 70% R.H is about one-third lower than in 50% R.H.

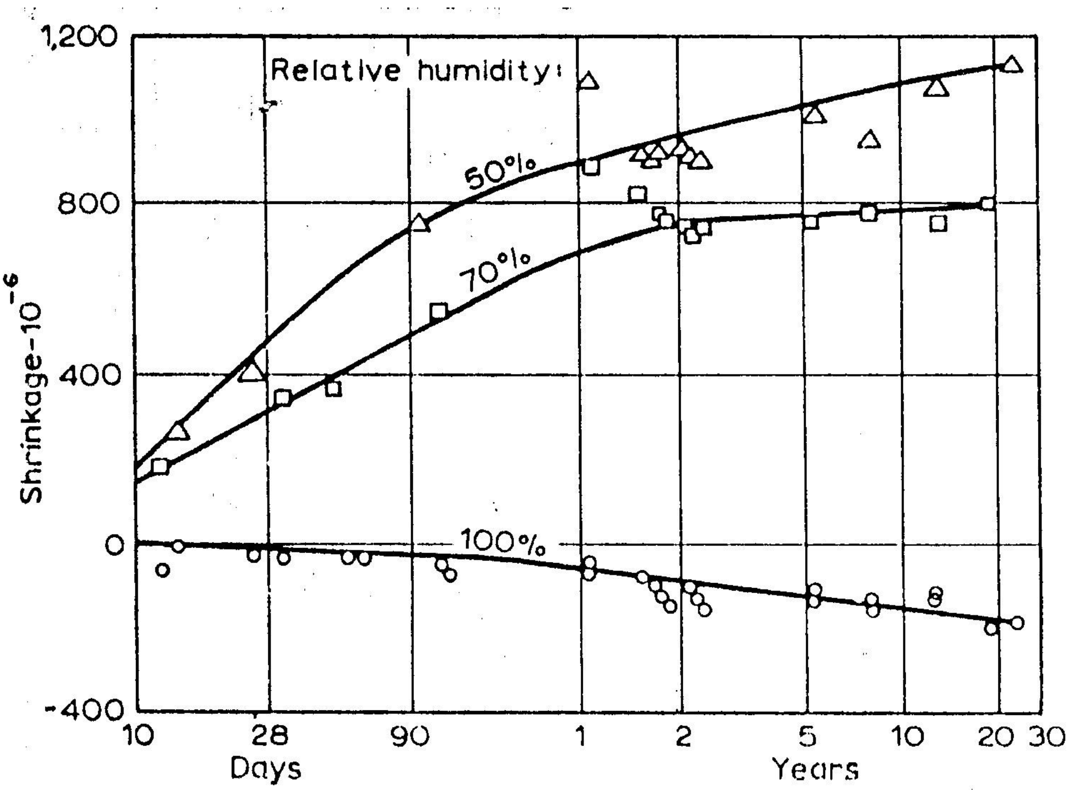


Fig. (2-4): Relation between shrinkage and time for concrete stored at different relative humidities [3].

Neville [3] states that the magnitude of shrinkage is independent of the rate of drying except that transferring specimens directly from water to a very low humidity can lead to fracture.

2.3.7 Temperature

It is well know that increasing concrete temperature after casting increases the evaporation of the water therefore shrinkage increases.

2.3.8 Influence of Chemical Admixtures

Chemical admixtures have varying effects on the drying shrinkage of concrete. Obviously, any admixture which increases water requirement of a mix, can generally be expected to lead to increased shrinkage and those, which decrease water requirement of mix , decrease the shrinkage [1].

Al-Nassar [23] studied the effect of some admixtures on dimensional changes and cracking of concrete. Four types of chemical admixtures were used: super plasticizer, plasticizer, water proofing and BVD. He found that the development of shrinkage is affected by the type and amount of admixture.

Shah et al. [24] used ring specimens to test for restrained shrinkage. The inner diameter of the ring was 305 mm and the outer diameter was 375 mm. Free srinkage was also measured on 100 x 100 x 400 mm prism specimens. The addition of shrinkage reducing admixtures (SRA) greatly improved the reduction of free shrinkage. An equal amount of water was removed when the SRA was added. The addition of the SRA caused a delay in the restrained shrinkage cracking. Typical specimens cracked at 48 days or more.

2.4 Shrinkage Induced Cracking

In a structure, concrete is always under same degrees of restraint, either externally (by the foundation or by another part of structure) or internally (by reinforcing steel embedded in concrete and the rigid of concrete aggregate).

The combination of shrinkage and restraint develops tensile stresses. When the induced strain exceeds the allowable tensile strain of concrete, cracking takes place. Alternatively, when the developed stress exceeds the tensile strength of concrete, cracking occurs as shown in Figure (2-5).

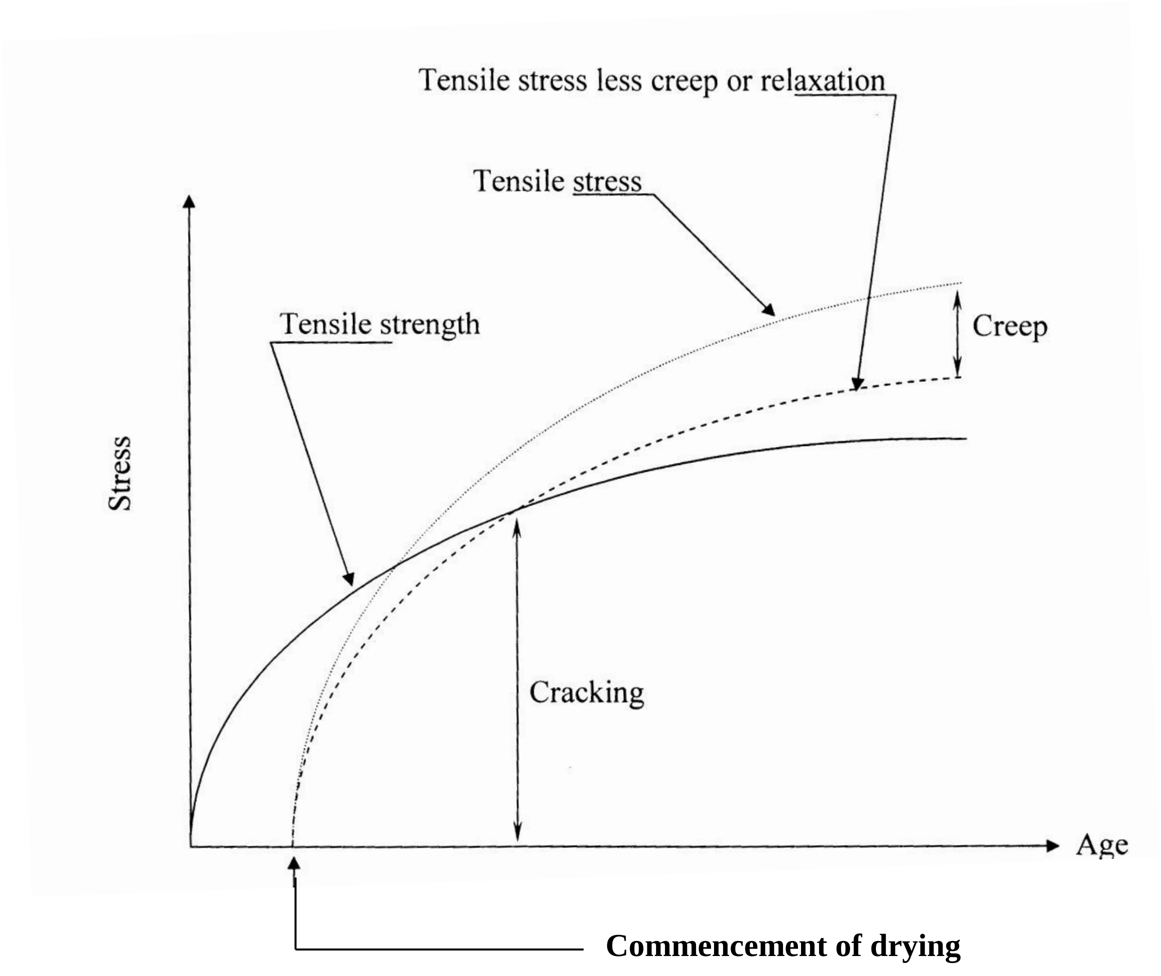


Fig.(2-5): Sketch of crack development (stress wise) [25].

The magnitude of tensile stress development during drying of the concrete influenced by a combination of factors such as:

i – The amount of shrinkage
ii- The degree of restraint.
iii- The modulus of elasticity of the concrete.
iv- The creep or relaxation of concrete.

2.4.1 Plastic Shrinkage Cracking

Plastic shrinkage cracks are the most dangerous cracks that develop within the first few hours after placing. When the rate of evaporation exceeds the rate at which bleeding water rose to the surface, plastic shrinkage cracks were likely to occur. The width of plastic shrinkage cracks may reach 6 mm, so they can result in serious problems.

Lerch [7] from his sit investigation concluded that the cracks were usually almost a straight line without any symmetry of pattern which he called craze cracks.

According to ACI 305 [8] the risk of plastic shrinkage cracks is considered critical at combination of temperature and relative humidity, such as 41^{o}C and 90% relative humidity, 35^{o}C and 70% relative humidity, 24^{o}C and 30% relative humidity. Typical plastic shrinkage cracks are parallel to one another and have considerable depth.

Samman et, al. [26] compared plastic shrinkage cracking of normal and high performance concrete. They concluded that low-strength concrete mixes containing a greater amount of mixing water yielded maximum rate of evaporation, however their cracking behavior was much less severe than that of the high –strength mixes, due to low restraint to the shrinkage of concrete from low strength concrete if compared with high strength concrete.

2.4.2 Restrained Shrinkage Cracking

Restraint acts to hinder the change in dimension due to volume change, thus producing elastic strain within the concrete member [27]. Normally, restraint conditions that will induce compressive stress in concrete are not considered in design because of the ability of concrete to withstand compression. On the other hand, restraint condition that induce tensile stresses are of main concern because of the low tensile strength of concrete. The degree of restraint depends largely on relative dimensions, strength, creep and modulus of elasticity of concrete and that of the restraining object [27]. The induced stresses in concrete due to restraint tends to decrease in direct proportion to the decrease in stiffness of the restraining part.

Restraint occurs at the boundaries and within the concrete member, can be divided into external end restraint (which is the main topic in that study), external continuous restraint and internal restraint [28]. External end restraint is typical for concrete element whose restraint to volume change remains concentrated at fixed location (at the end) with no or minimum base restraint. When an end restrained member having a uniform cross-section contract, uniform tension develops a long its length. As the developed-tensile strain exceeds the tensile strain capacity of concrete, cracks which extend through the whole section may form. External continuous restraint acts along a contact surface between member and its surroundings, as in the case of raft foundation cast on a hard base.

In addition to internal restraints caused by aggregate and reinforcement, some restraint is caused by temperature gradients within the concrete. The warmer concrete in the interior of the mass provides restraint as the concrete in the periphery of the mass cools at different rate due to heat transfers to its surroundings. The degree of internal restraint depends upon the total quantity of heat generated, the severity of the thermal gradient, the thermal properties of the concrete, and thermal boundary condition.

Most researchers [27] did not take into consideration difference between end restraint or base restraint. Test methods commonly used for measuring shrinkage cracking of concrete are: bar test, plate test, and the ring type specimens for restrained shrinkage cracking test. All of these method have several drawbacks, in particular, the difficulty of providing a constant restraint. Al-Rawi (29) used (I-shaped) molds having a channel section to study shrinkage crack spacing and crack width, and semi-similar molds were used in this work.

2.4.2.1 End-Restrained Shrinkage Cracking

Since the restraining edges exist only at the member ends, the restraint in these members will be uniform, accordingly, a uniform state of tensile strain will develop in the members as it shrinks or contracts. The member cracking will begin to propagate at the weakest section existing at any position within the member length [30].

Al-Rawi [29] used concrete reinforced with deformed bars and welded wire mesh. He found that using the deformed bar reinforcement can control both the minimum crack spacing and maximum crack width. He also derived a formula for the minimum crack spacing, using a new model which was believed to resemble field conditions as follows:

$$S_{\min} = 0.85k\frac{d}{\rho} \qquad (2\text{-}3)$$

Where:

S_{min} : the minimum crack spacing.

$$k = \begin{cases} 0.8 \text{ for indented deformed bars} \\ 0.67 \text{ for ribbed deformed bars} \end{cases}$$

d : is the bar diameter and ρ is steel ratio.

The width of crack at the onset of cracking (w_i) is :

$$w_i = \frac{2}{3} S_{max} \times e_{\mu 1t} \qquad (2\text{–}4)$$

The maximum crack final (w_{max}) is:

$$w_{max} = S_{max} \times \left[e_{shr} - \left(creep_1 + loss\ \ of\ \ restraint \right) - \left(e_{ult} + creep_2 \right) / 2 \right] \qquad (2\text{-}5)$$

Where:

(S_{max}) : maximum crack spacing.

(e_{ult}) : elastic tensile strain capacity of concrete.

(e_{shr}) : final shrinkage strain.

$Creep_1$: creep prior to cracking and

$Creep_2$: creep after cracking.

Kadhum [31] presented equation, for the prediction of minimum crack spacing, S_{min} in slab subjected to end restraint:

$$S_{min} = 0.85 k \frac{d}{\rho + \rho R} \qquad (2\text{-}6)$$

For two and three end restrained from free edge,

$$\rho R = 0.9 - 1.1 \left(\frac{1}{L} \right)^{0.6}$$

k : a constant depending on the type of reinforcement which can be taken as (0.8) for indented deformed bar.

d : bar diameter.

ρ : steel ratio.

$\rho R =$ effect of end restraint as a ratio.

L : slab length or width.

2.4.2.2 Base Restrained Shrinkage Cracking

A concrete wall cast on a continuous concrete base is a typical example for base restrained concrete members. The restraint in the wall is not uniform through the wall height but varies from point to point within the wall. The magnitude of the restraint depends on several factors, these factors including the wall's L/H (length / height ratio), the position of the point in consideration within the wall itself, wall and base dimensions, degree of fixity between the wall and the base, and amount and distribution of reinforcement.

Al-Rawi and Kheder [30] investigated the combining effects of the base restraint and the reinforcing steel in distributing volume change cracking. He suggested the following equation for prediction of minimum crack spacing (S_{min}) and maximum crack width (w_{max}) in base restrained concrete members:

$$S_{\min} = \left(\frac{k_1\, d\, H}{\rho H + k_1 d} \right) \qquad (2\text{-}7)$$

Where:

k_1 : factor equals 0.57 for deformed bars, 0.68 for indented bars, and 0.85 for plain bars.

d : bar diameter

ρ : steel reinforcement ratio.

H : wall height.

$$W_{\max} = S_{\max} \left[k \left(R_b - 0.8 R_a \right) e_{sh} - e_{ult} / 2 \right] \qquad (2\text{–}8)$$

Where:

$k = 1 - \bar{c}$

R_a = degree of restraint after cracking.

R_b = degree of restraint before cracking.

S_{max}= maximum crack spacing.

e_{sh}=free shrinkage.

e_{ult}: elastic tensile strain capacity of concrete.

Assuming the sum of creep strain before cracking (cb) and the average value of creep strain after cracking (ca) to be $\bar{c}$ (constant) of the total net shrinkage, where $\bar{c}$ equals 0.4 for reinforced concrete walls and 0.25 for plain concrete walls.

2.5 Factors which Affect Cracking Resistance

2.5.1 Creep or Relaxation of Concrete

Creep is a slow increase of strain (due to stress) under a sustained load. According to Neville [3], if the restraints are such that a stressed concrete specimen is subjected to constant strain, creep will be expressed as a progressive decrease in stress with time known as (relaxation).

Al-Rawi [25] measured creep under shrinkage cracking conditions, he assumed creep to be the difference between tensile strain capacity and elastic tensile strain capacity.

The basic effect of creep on cracking tendency of concrete is to delay or prevent the cracking of concrete through delaying the shrinkage strain propagation and preventing the stage at which tensile strain capacity is exceeded.

Many factors which affect creep such as; relative humidity, W/C ratio, mix proportion, age of concrete, ambient temperature. An additional factor that affects the creep of concrete is the (SO_3) content of cement. This factor was studied by Alexander et al[32] and they concluded that the effect of (SO_3) content in cement on creep resembles its effect on drying shrinkage and there is an optimum (SO_3) content above or below which creep increases. They, also stated that the (SO_3) content for minimum creep was at least (0.6) higher than that for minimum drying shrinkage.

2.5.2 Tensile Strain Capacity

The tensile strain capacity is the maximum strain that concrete can sustain in tension before cracking occurs. In this case, it is defined, as the total shrinkage required to induce cracking. According to Al-Rawi [25] the amount of strain which is instantly relived due to elastic recovery of restraint concrete upon cracking is termed elastic tensile strain capacity.

The tensile strain capacity is normally assessed by testing the concrete in flexure or in direct tension.

Houk and others [33] reported that the tensile strain capacity is higher in flexural test 230 microstrain than in direct tension 130 microstrain ,possibly because of the "weakest link" theory. They also reported that the rate of straining significantly affected the tensile strain capacity.

Lee and Lamb[34] reported that tensile strain capacity as measured in a direct test at a progressively increasing stress is of the order of 100 microstrain while the order of 200 microstrain will be reached if the rate of strain is controlled.

B.S Code 5337 [35] doubles the typical strain capacity for mature concrete (from 100 to 200 microstrain) to allow for age and creep. Houk et al. [33] reported that tensile strain capacity increased some 50 percent with increase in age from 3 to 28 days. Other researchers such Hunt [36] reported that no significant effect of age on values of tensile strain capacity.

There is an agreement that the tensile strain capacity of concrete depends on the mix proportion, in particular on the shape, type and size of the aggregate. It was found by Lee and Lamb [33] that the crushed type aggregate has the beneficial effect on the strain capacity of concrete by increasing from 95 * 10^{-6} for rounded to 139 * 10^{-6} for the crushed type.

Al-Rawi [25] reported an increase in the elastic tensile strain capacity of mortar beam by 16 % when curing time was increased from 3 to 7 days.

2.6 Cracking Time

Cracking time is the time required for first crack to occur. The time of the first crack is dependent on the same factors that influence the cracking tendency of concrete (i.e., degree of restraint, shrinkage, creep, tensile strain capacity … etc). The effect of these factors is complex, because of that many factors reduce the shrinkage but at the same time reduce the strength or reduce the tensile strain capacity, so the final effect may be positive or negative.

Al-Rawi [25] reported that the cracking time depends on both shrinkage and tensile stain capacity. It increased with the decrease in W/C ratio (mix preparations being unchanged), with increase in normal curing time and amount of crushed coarse aggregate.

2.7 Effect of Sulphates

2.7.1 Introduction

Most of the aggregates used in Iraq for concrete are sea deposits, which have become contaminated with sulphates due to the tropical dry climate. These sulphates are the source of the problem of internal sulphate attack in concrete [5,6,36].

When the amount of internal sulphates exceeds a certain limit, internal stresses will develop due to the formation of calcium sulphoaluminate and gypsum. The consequences of sulphate attack include not only destructive expansion and cracking, but also loss of strength of concrete due to loss of cohesion in the hydrated cement paste and the adhesion between cement paste and the aggregate particle [3].

2.7.2 Effect of Sulphates on Concrete Properties

2.7.2.1 External Attack

External sulphate attack is a chemical reaction between sulphates usually in ground water or soil and concrete.

External sulphate attack is often said to a rise from each of two major sulphate reaction : (1) the sulphate ions react with (C_3A) and its hydration products to form ettringite : (2) the sulphate ions react with calcium hydroxid to form gypsum. There is a wide agreement that the formation of ettringite results in expansion, but the idea that gypsum formation leads to any expansion is controversial [37]. The theories either supporting this idea are not well established. However Tian et al [37] suggested that gypsum formation during sulphate attack is expansive, but the exact mechanism is not clear. The results of these findings indicate that expansion and cracking of Portland cement concrete during sulphate attack should probably not be exclusively attributed to ettringite formation.

External sulphate attack is affected by the composition of cement. Rasheeduzzafar [38] reported that C_3S/ C_2S is also important. Cement with high C_3S/ C_2S ratios also are prone to sulphate attack of a softening type caused by gypsum formation.

As several researchers have shown that limitation on (C_3A) content is not the ultimate answer to the problem of external sulphate attack and they suggested other solutions such as the use of type V cement and a low w/c ratio produced a dense impermeable concrete and the use of blended cement made with fly ash, silica fume and blast furnace slag.

2.7.2.2 Internal Attack

Many researchers have studied the effect of internal sulphate attack.,They believed that the formation of the calcium sulphoaluminates in an early stage, when concrete is still plastic expansion does not cause any appreciable disruption or reduction in strength, because the formation of the sulphoaluminates is not associated with the development of the internal stresses, due to fresh concrete plasticity, but internal stresses will develop due to the formation of calcium sulphoaluminates in the hardened cement mix. Mansour [39] studied the effect of sulphates in the ingredients of concrete mix on the properties of concrete. He investigated the effect of sulphate reactions on compressive strength of hardened concrete, velocity of ultrasonic waves, and expansion of concrete. He was in agreement with other researchers that the effect of sulphates on the various tested properties of concrete was found to depend on the amount and type of sulphates which exist in the concrete mix.

Ali [40] found out that the sulphate content in sand could be increased without significant loss in strength provided that the sulphate content in cement is reduced.

Shallal [41] concluded that (for cement containing 5% pozzolana) the effect of sulphates content in cement on concrete compressive strength,, expansion, and ultrasonic pulse velocity (U.P.V) is almost the same as the effect of sulphates content in sand. Thus, the compressive strength, expansion, and (U.P.V) of concrete is mainly depended on the total of sulphates in the mix. The sulphates content of sand used in concrete can, therefore, be raised substantially by reducing the sulphates content of cement.

Al-Rawi [42] investigated the effect of the gypsum content of cement on several engineering properties of concrete cured by accelerated and normal methods. He stated that increased gypsum content results in a significant decrease in the slump of concrete and that there is an optimum gypsum content, considerably higher for accelerated cured concrete than for normally cured concrete, at which maximum strength is obtained. The optimum gypsum content under accelerate curing conditions may be used without risk of reduction in the durability of concrete caused by excessive, delayed expansion.

According to Lerch [43], for each cement there is an optimum gypsum content which produces the highest strength and the lowest drying shrinkage.

Salman [44] found out that the drying shrinkage of concrete decreases and the tensile strain capacity of concrete increases as the gypsum content in concrete is increased.

Al-Rawi and Abdul-Latif [45] suggested a new test called "Compatibility test" to investigate the possibility of using sands with relatively high (SO_3) contents with suitable cement without deleterious effect on concrete. The work was carried out on seven cements, three ordinary Portland cement, three sulphate resisting cements and one white cement. The sand used had SO_3 contents between 0.18% and 1.5% and the mix is designed to give a compressive strength of 30 MPa at 28 days. The results show that the SO_3 content in sand gives the maximum concrete strength which differs from one cement to the other ranging from (0.18% to 1.5%) depending on the chemical composition and fineness of cement.

Suhaila Mater [46] reported that, for low sulphate levels ranging between (0.11-0.5) % by weight of sand, the compressive strength of concrete decrease with the increase of volume fraction of steel fibers, but for high sulphate levels ranging between (1-2)% by weight of sand, there is an increase in compressive strength with the increase in fibers volume fraction.

AL-Rawi et al [47], stated a new method for calculating the effective sulphates in concrete through their work on set of concrete mixes made with both cement and sand containing varying percentages of sulphates in the form of gypsum. These concretes were tested for compressive strength and length change. A second set of concrete mixes was made with both sand and gravel containing different percentages of sulphates. Again they were tested for compressive strength and length change. The results of the first set of concrete mixes showed that sulphates in cement have much more harmful effect on concrete than sulphates in sand, probably because of the fine particle size distribution of cement compared with sand. The results of the second set of concrete mixes showed that sulphates in sand have much more harmful effect on concrete as compared with sulphates in gravel.

Abdul Latif [48], concluded that each type of cement has certain behavior in relation to the increase of (SO_3) percent in sand and this behavior depends on number of factors such as SO_3% in cement, fineness,

C_3A content and soundness that specifies optimum gypsum content for each case. Since this would not agree with the limits specified in 1QS 45-1984.

Yousufani [49] concluded that increasing the percentage of sulphate increases the creep of concrete under deflection.

Abood [50] found that the optimum values of SO_3 for minimum creep are 3.82% and 3.98% for medium richness and rich mixes respectively which were less than that required for the highest compressive strength. He also, found that the optimum (SO_3) content for minimum creep increased to reach (4.9%) when the curing period under water was reduced from 28 to 14 days and correspondingly increasing the drying period from 7 to 21 days. On the other hand, the amount of creep diminished when increasing the water curing period.

Al-Zaiwary [51] followed the performance of concrete specimens having various proportions of combined sulphate and excess fine particles (<75 µ) in the sand. He found that 10% fine particles, made of sand, silt, and clay (illite) added to a sulphate bearing fine aggregate, show no appreciative destructive effect on concrete properties. On the contrary, his experiments have indicated some improvement in the compressive strength of concrete.

2.7.3 Expansion of Concrete Accompanied to Sulphates Attack

Gypsum from a different interior sources (cement, sand, gravel) reacts with some components of cement specially Tricalcium Aluminate (C_3A). Such reaction produces calcium sulphoaluminate (Ettringite) $3CaO.Al_2O_3.3CaSO_4.31\ H_2O$. [52]. The volume of this product is 227% of the volume of reactant. The hydration process of the calcium silicate yields calcium hydroxide which react with sulphate to produce the gypsum. The volume of gypsum is 124% of the volume of reactant. These volumetric changes accompanied by interior stresses which caused strength reduction and disintegration [3,4].

$$3CaO.Al_2O_3 + 3CaSO_4.2H_2O + 25H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O$$

$$Ca(OH)_2 + Na_2SO_4 10H_2O \rightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O$$

Many researchers found that the sulphate reaction is usually accompanied by expansion.

Hobbs [53] found a general relation for expansion and showed that the expansion increases with increasing SO_3 over a certain amount (this amount depends on the type and fineness of cement).

Salman [44] verified what is found by Hobbs and found that the expansion depends on the amount of added gypsum.

Al-Qaisi [54] reported that expansion increases with the increase in the fineness of the added natural gypsum. For low and high strength mixes, he also concluded that the temperature affected the expansion of all mixes immersed in water. The results also showed that increasing the mixing time from (5) to (30) minutes would increase the expansion.

Al-Kadhimi [55] concluded that due ettringite formation, cement mortar (1:2, cement : aggregate) of sulphate resisting cement immersed continuously in water show much lower linear expansion than similar cement mortar made with ordinary Portland cement.

Zari [56] found that expansion is not always an indication of deterioration, since expansion in some ordinary Portland cement (OPC) concrete mixes was associated with again in compressive strength. He also concluded that the (OPC) concrete showed better resistance to sulphates than sulphate resisting Portland cement (SRPC). This was attributed to higher (C_3A) content, which gives large earlier reactions in (OPC) Thus, the product would not induce large internal stresses.

Manasor [39] found that the length changes increase with increase of sulphates for all ages.

Taylor et al. [57] noted that the expansion from delayed ettringite formation is insignificant with sulphate – resisting Portland cements and this may be related to low value of Al_2O_3/Fe_2O_3 ratio in such cements.

Yousif [58] reported that expansions associated with lean mixes were high, especially for high sulphate content and such mixes did not show excessive cracking. He attributed this to the lesser formation of sulphoaluminates, lower modulus of elasticity , higher creep and voids content for such mixes as compared with medium to rich mixes. He also reported that the use of ordinary Portland cement with low and medium sulphates in concrete ingredients gives better results for compressive strength than sulphate resisting cement, due to the faster relieve from sulphate attack after long curing period. Although for high percentages of sulphates the sulphate resisting cement is better than ordinary Portland cement to resist internal sulphate attack.

2.7.4 Mechanism of Expansion Associated with Ettringite Formation

Neville [3] stated that, the mechanism of this expansion is still debated, where there are two principal schools of thought. Mather [59] and Renhe et al [60] adopted the ettringite crystal growth pressure theory, they are of the opinion that the reaction between calcium sulphate and C_3A is top chemical, that is, it is a solid state reaction, not involving solution and re-precipitation which would allow movement of the newly formed product away from the original location. Such movement would not result in the development of pressure. If the product of the top chemical occupies larger volume than the volume of the two original compounds, the expensive and disruptive forces are created. In the case of reaction between calcium sulpahte and $Ca(OH)_2$, there is no overall increase in volume. But, because of the differences in the solubility of C_3A, there is a local increase in volume and , at the same time, an increase in porosity else where. This former hypothesis suggests that pressure from ettringite crystals growing in preformed microcracks in the transition zone between the cement paste and the aggregate widens these cracks and causes the observed expansion. This theory was disputed by Johansen et al [61] and Taylor [62], who suggested that the degree of supersaturation of ettringite in the pore solution of the cementitious material was insufficient to generate sufficient crystal growth pressure to achieve this expansion. Diamond [63], however, suggested on the basis of the basic concepts of fracture mechanics that a modest degree of ettringite supersaturation is enough for ettringite growth to extend the cracks, because the stress concentration factor at the tip of a long crack in concrete is large as a result of its quasi brittle nature.

The second school of thought, whose chief protagonist is Mehta [64]. He adopted the uniform past expansion theory and attributes the development of expansion forces to the swelling pressure induced by absorption of water by originally colloidal ettringite which precipitates in the solution in the presence of time. The formation of ettringite is thought to be the case of expansion. Ettringite can also form from the reaction between sulphate and C_4AF, but this ettringite is nearly amorphous and no damaging explanation has been reported.

This uniform paste expansion theory suggests that expansion of the cement paste matrix occurs, leaving gaps around the aggregate grains. Subsequently, newly crystallizing ettringite rapidly fills the cracks produced by this expansion to result in ettringite band formation. On this basis, therefore, ettringite band formation dose not contribute directly to the observed expansion.

Taylor [65] stated that the rate and ultimate extent of expansion depends on factors of three kinds. These are :

1- Chemistry, which determines the amount of ettringite formed.

2- Paste microstructure, which determines the stresses that can result from its formation.

3- Concrete or mortar microstructure which determines how the material responds to those stresses.

The relations between the rate and the ultimate extent of expansion are probably complex. On the one hand, increased hydration decreases the permeability of the concrete. This may explain why, although ultimate expansions from DEF are high for materials of low water / cement ratio, the rates of expansion in such materials can be very low, on the other hand, a low rate of expansion may increase the extent to which the expansive forces are relieved by creep and there by decrease the ultimate expansion.

Lawrence [66,67], reported that the increases in alite content or fineness and decrease in water / cement ratio all tend to increase the ultimate expansion, and the increases in curing time or temperature within normal limits also increase expansion.

2.7.5 Conditions of the Internal Sulphate Attack

There are three conditions for the internal sulphate attack to take place.

1. It needs preliminary microcracks where deposition of ettringite crystals can occur.
2. It occurs in a sulphate –free environment for the late sulphate release from gypsum-contaminated aggregates, sulfure-rich clinker phase and /or high-sulphate cement.

3. It occurs in a moist environment favoring diffusion of SO_4 and other reacting ions (Ca++ and aluminate) through water – saturated capillary pores [68].

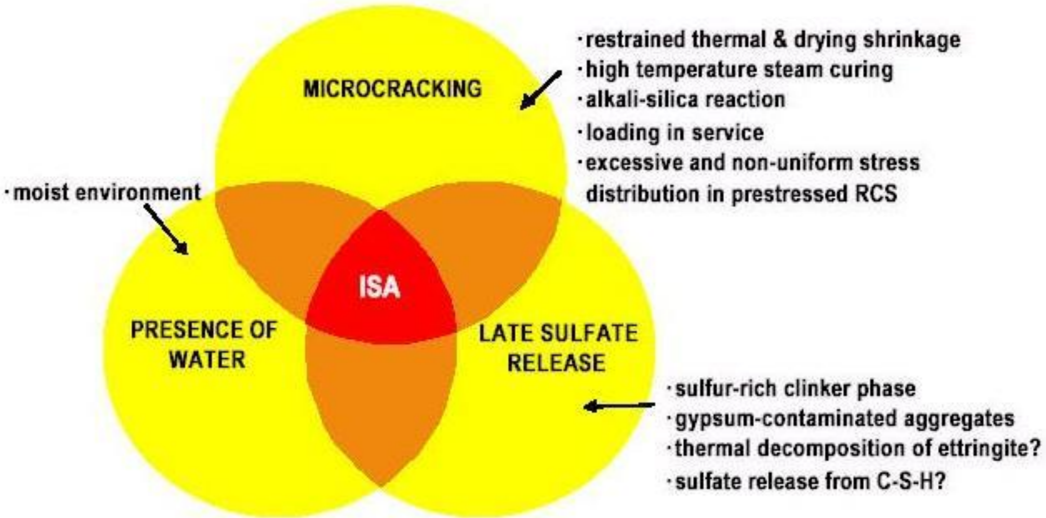


Fig.(2-6): Show the ternary representations of the (DEF) related to (ISA) [68].
DEF: Delayed Ettringite Formation.
ISA: Internal Sulfate Attack

CHAPTER 4

RESULTS AND DISCUSSION

The results of the present experimental work include the following characteristics of the concrete:

4.1 Free Shrinkage Test

By using the steel mold described in chapter three (concrete beam with a gap at its middle to ensure free movement) free shrinkage was measured for all mixes, and plotted in Figures (4-1a) to (4-8b).

It can be seen from these Figures that the free shrinkage increases with the age progress for all mixes, but with different rates and different evaporation intensity. The reason for high initial rate of shrinkage can be expected from the diffusion theory of drying that is the shrinkage is influenced strongly by the moisture loss. The moisture will be evaporated initially from the surface and near the surface with a high rate. This is due to the high diffusion coefficient of the moisture from the surface as a vapor.

The data indicates that the addition of sulphates in all percentages decreases the shrinkage of concrete at early ages. This is attributed to the volumetric changes (expansion) due to the formation of excessive amount of ettringite in mixes with sand of high percentage of surphate 1.5%. Hence, when the specimen was subjected to drying condition and it began to shrink, a part of shrinkage would be spent to retrieve the real length and the formation of small amount of ettringite in mixes with sand of low percentages of sulphate 0.5%, 1%. This would produce a denser concrete with lower permeability which reduces the withdrawal of water from the specimens subjected to drying conditions and subsequently reduces the drying shrinkage at early and later ages. This result was in line with the results reported by Abood [50].

The addition of sulphates in high percentage (1.5% by weight of sand) would increase the shrinkage at the later ages due to the delayed ettringite formation which produces interior microcracks that increase the rate of withdrawal of water and consequently drying shrinkage strain. This is in agreement with what was reported by [76].

The effect of drying period and the percentage of sulphate content on the free shrinkage of concrete with OPC and sand of zone 2 and moist cured for 3 days is presented in Figures (4-1a) and (4-1b) respectively. From these Figures, it is evident that the optimum sulphate content was 1% by weight of sand (total SO_3 in mix = 4.03 % by weight of cement). The excess sulphate content to that of the optimum value would increase the free shrinkage strain.

Figures (4-2a) and (4-2b) show the relationship between the same previous variables but with 28 days moist curing. From these Figures it can be seen obviously that increasing the curing period decreases the shrinkage strain of the concrete containing a percentage of sulphate lower than or equal to the optimum value and increases it at the higher values. This result agreed with what is reported by Hansen and Abood [77, 50].

It is worth of mentioning that the optimum sulphate content was not affected by the curing period. A similar effect of drying period and different sulphate content with different curing condition can be noticed in Figures (4-3a), (4-3b), (4-4a), (4-4b) which represent the effects of drying period and the percentage of sulphate content in sand on the free shrinkage of concrete with SRPC and sand of zone 2 and moist cured for 3 and 28 days respectively. From these Figures it can be seen that the optimum sulphate content is 1% by weight of sand (total SO_3 in mix = 3.73% by weight of cement) and increasing the sulphate content over the optimum value will increase the free shrinkage strain. It can be noticed that this value of total SO_3 in the SRPC mix is lower than that of the mix with OPC. This can be attributed to the low C_3A content in the SRPC.

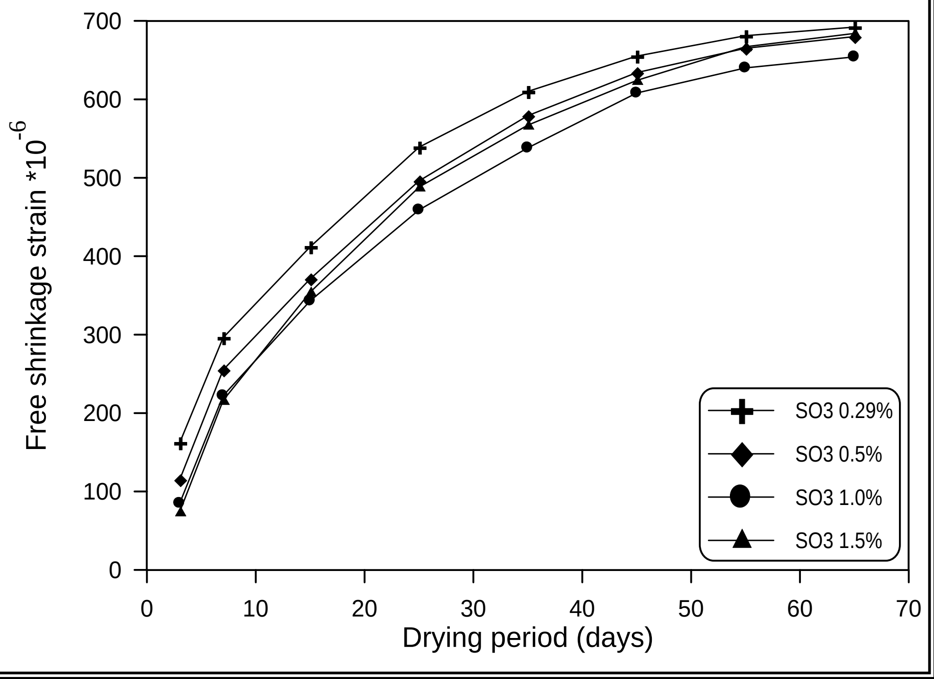
The relationships between the drying period and the different sulphate content in sand and the free shrinkage strain of concrete with OPC and sand of zone 4 and moist cured for 3 days are illustrated in Figure (4-5a) and Figure (4-5b) respectively. From these Figures it is obvious that the optimum sulphate content is 1% by weight of sand (total SO_3 in mix = 3.84% by weight of cement) and the excess sulphate to that of the optimum value will increase the free shrinkage strain.

It can be noticed that the previous optimum value of total SO_3 in the mix is lower than that of the mix with OPC and sand of zone 2. This may be due to the higher effectiveness of sulphates in the finer sand. Thus, the greater amount of ettringite will be formed at the earliest ages which reduces the formation of delayed ettringite.

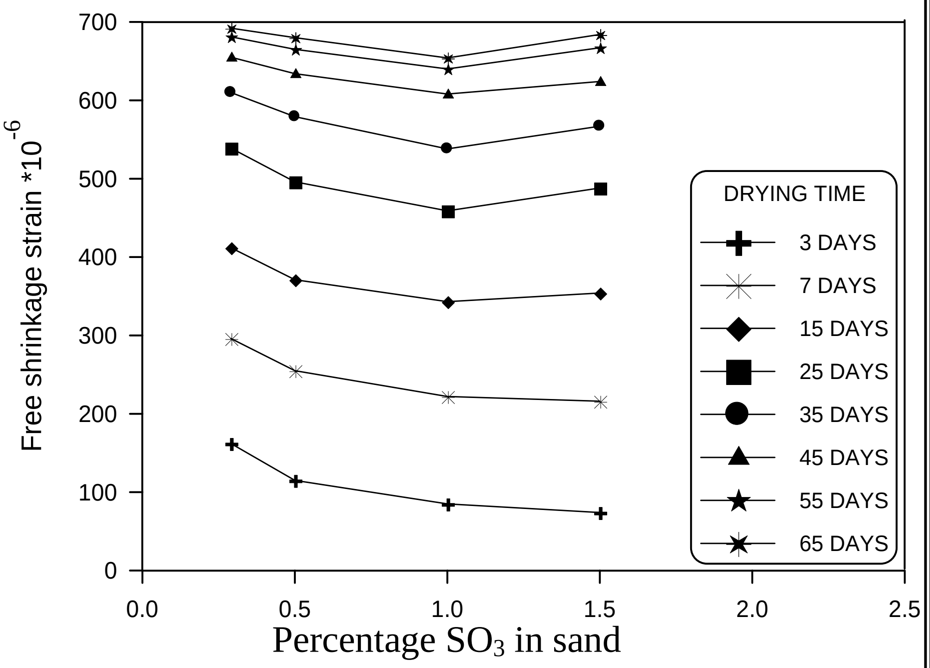
Figure (4-6a) and Figure (4-6b) , show the relationship between the same previous variables but for 28 days moist cured specimens. From these Figures it is evident that increasing the curing period reduces the free shrinkage strain of concrete with sulphate content lower than or equal to the optimum value and increases the shrinkage at the higher values. It can be seen that the optimum sulphate content did not affected by the curing period.

The Figures (4-7a) and (4-7b) illustrate the effect of drying period and the percentage of sulphate content in sand on the free shrinkage of concrete with SRPC and sand from zone 4 and moist curing for 3 days. From these Figures it can be seen that the optimum sulphate content is 1% by weight of sand (total SO_3 in the mix=3.55% by weight of cement) and increasing the percentage of sulphate content over this optimum value will increase the free shrinkage strain. It can be noticed that the optimum sulphate content in question is lower than that of the mix with SRPC and sand from zone 2, this may be due to the higher effectiveness sulphates in finer sand than coarser, the above optimum value was also lower than that of the mix with OPC and sand of zone 4, this can be attributed to the low C_3A content in the SRPC.

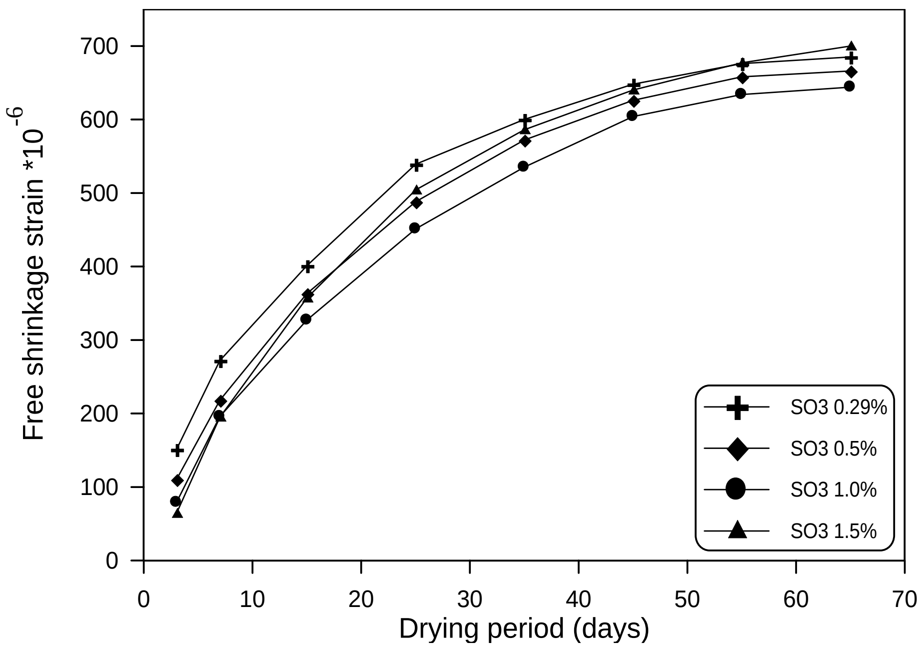
The effect of drying period and the percentage of sulphate content (by weight of sand) on the free shrinkage of concrete with SRPC and sand of zone 4 and moist curing for 28 days illustrated in Figures (4-8a) and (4-8b) respectively. From these Figures it can be seen that the optimum sulphate content is 1% by weight of sand (total SO_3 in mix = 3.55%) by weight of cement). This optimum value is lower than that of the mix with SRPC and sand of zone 2 at the same curing period. It is also lower than that of the mix with OPC and sand of zone 4.



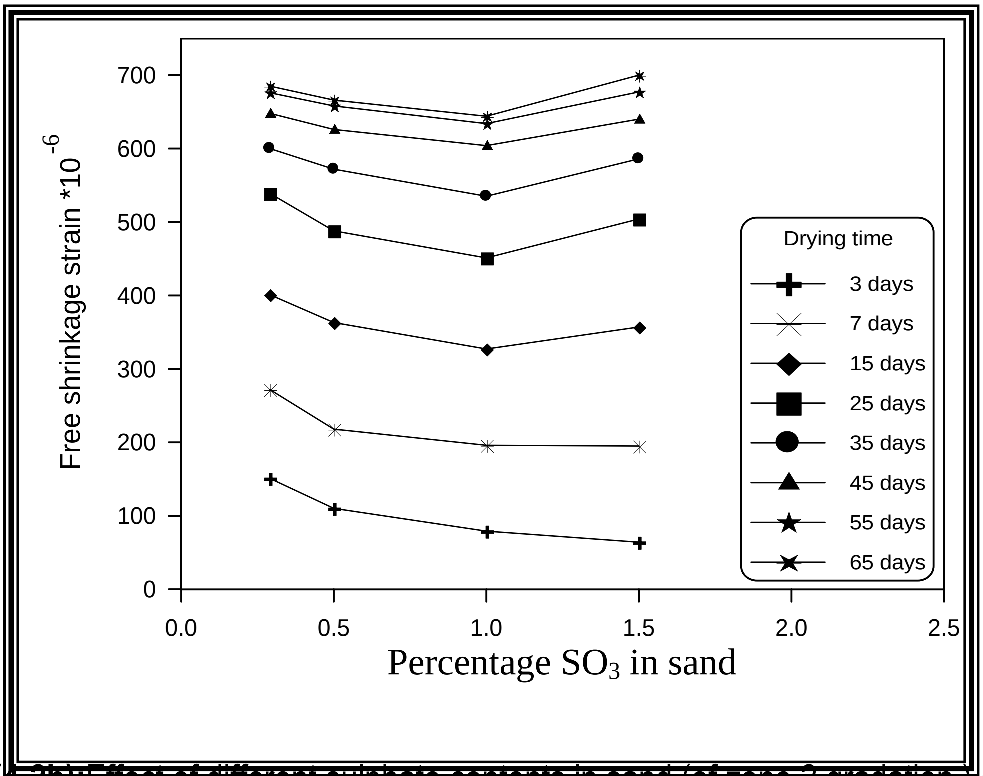
Fig(4-1a): Effect of drying time on free shrinkage strain of concrete containing OPC and sand from zone 2 with different sulphate contents, (3 days moist curing)



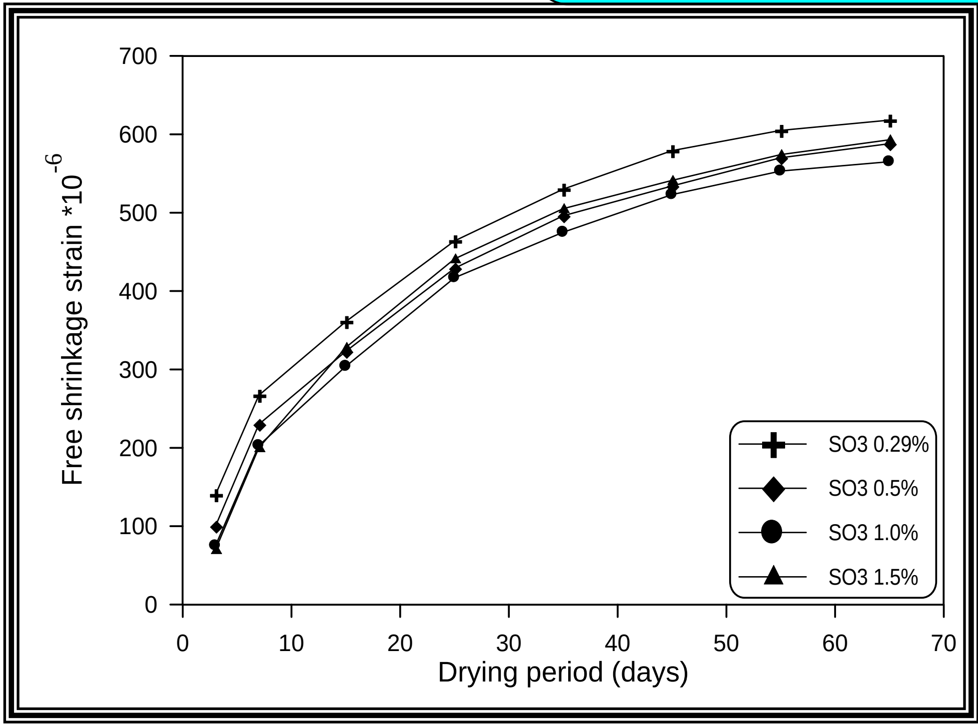
Fig(4-1b): Effect of different sulphate contents in sand (of zone 2 gradation) on the free shrinkage strain of concrete with OPC ,(3 days moist curing).



Fig(4-2a): Effect of drying time on free shrinkage strain of concrete containing OPC and sand from zone 2 with different sulphate contents, (28 days moist curing) .

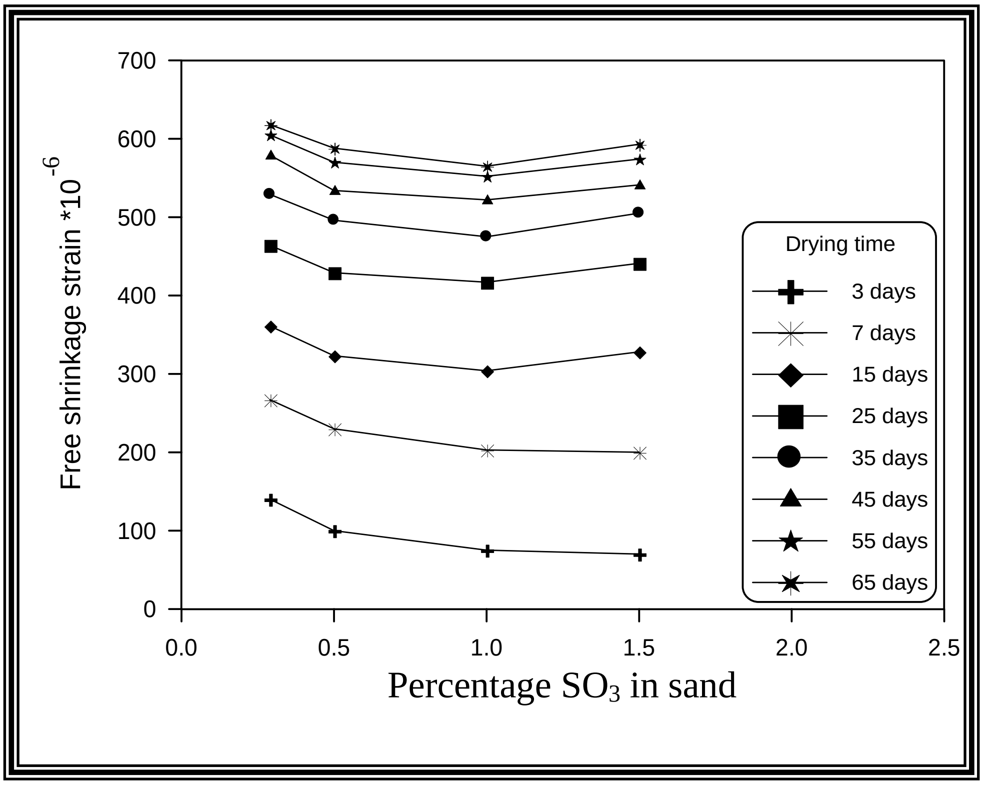


Fig(4-2b): Effect of different sulphate contents in sand (of zone 2 gradation) on the free shrinkage strain of concrete with OPC ,(28 days moist curing).

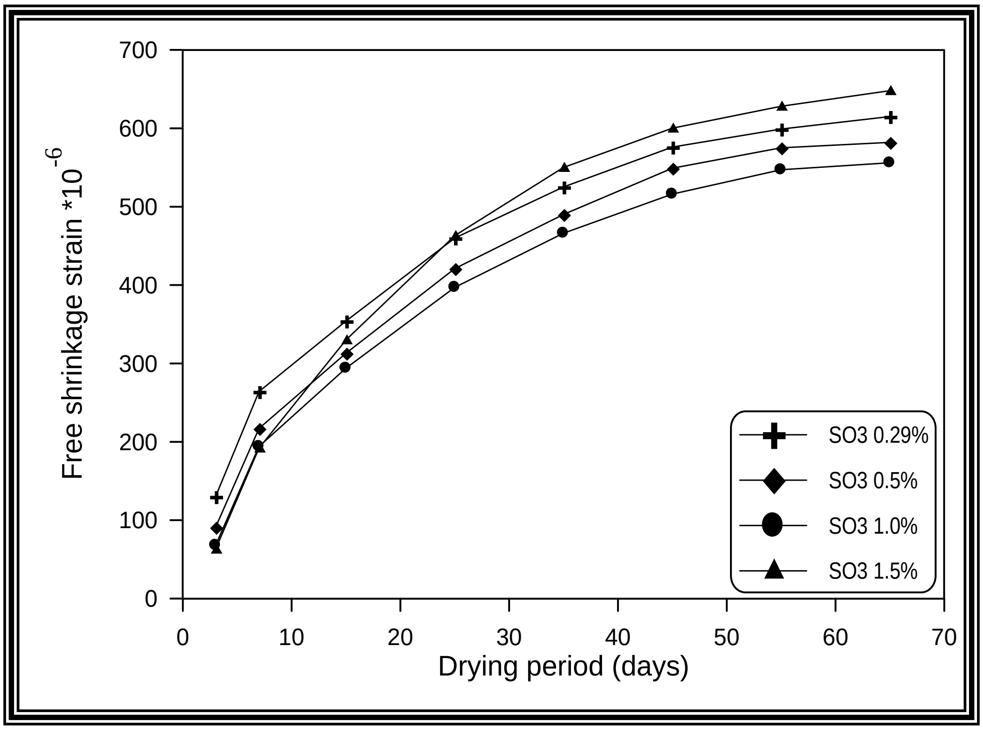


Fig(4-3a): Effect of drying time on free shrinkage strain of concrete containing SRPC and sand from zone 2 with different sulphate contents, (3 days moist curing)

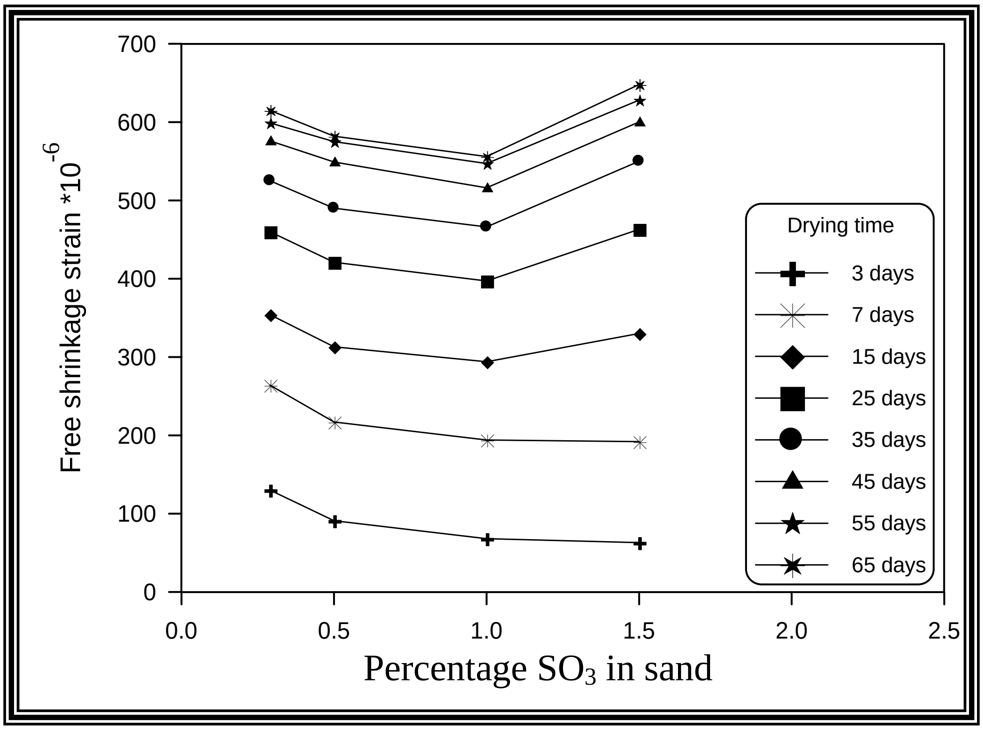
.



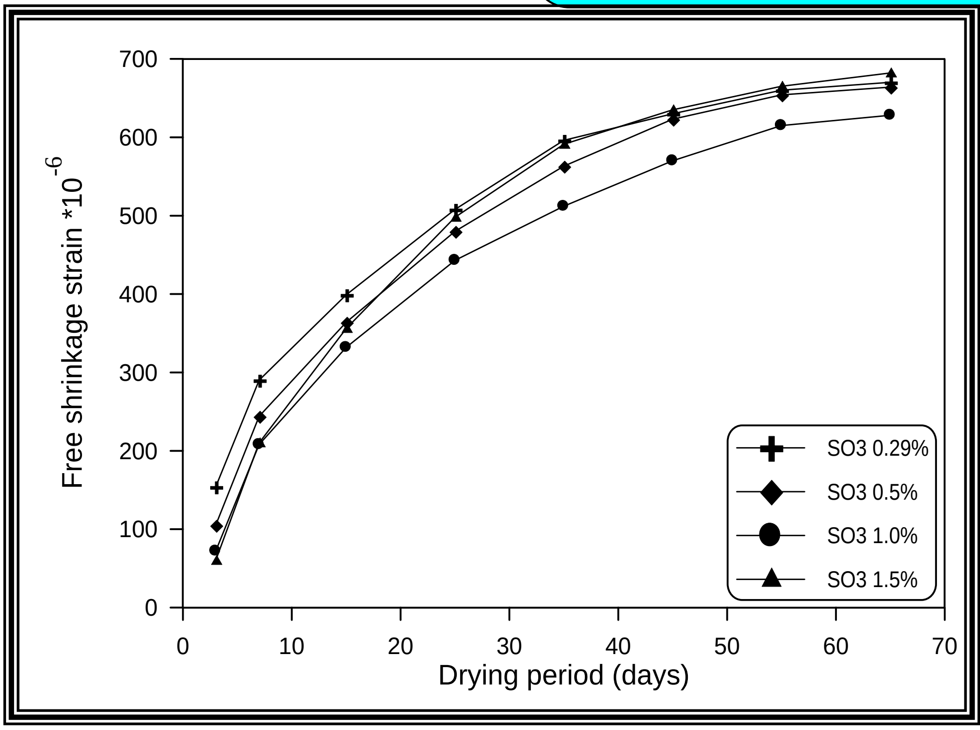
Fig(4-3b): Effect of different sulphate contents in sand (of zone 2 gradation) on the free shrinkage strain of concrete with SRPC , (3 days moist curing).



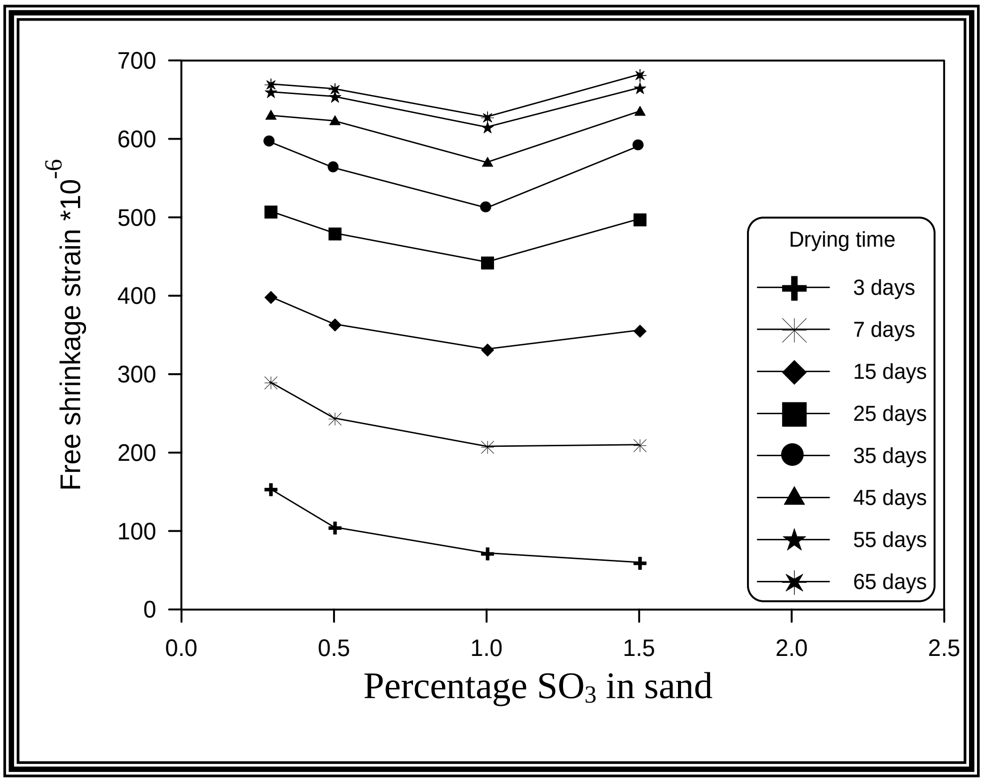
Fig(4-4a): Effect of drying time on free shrinkage strain of concrete containing SRPC and sand from zone 2 with different sulphate contents, (28 days moist curing) .



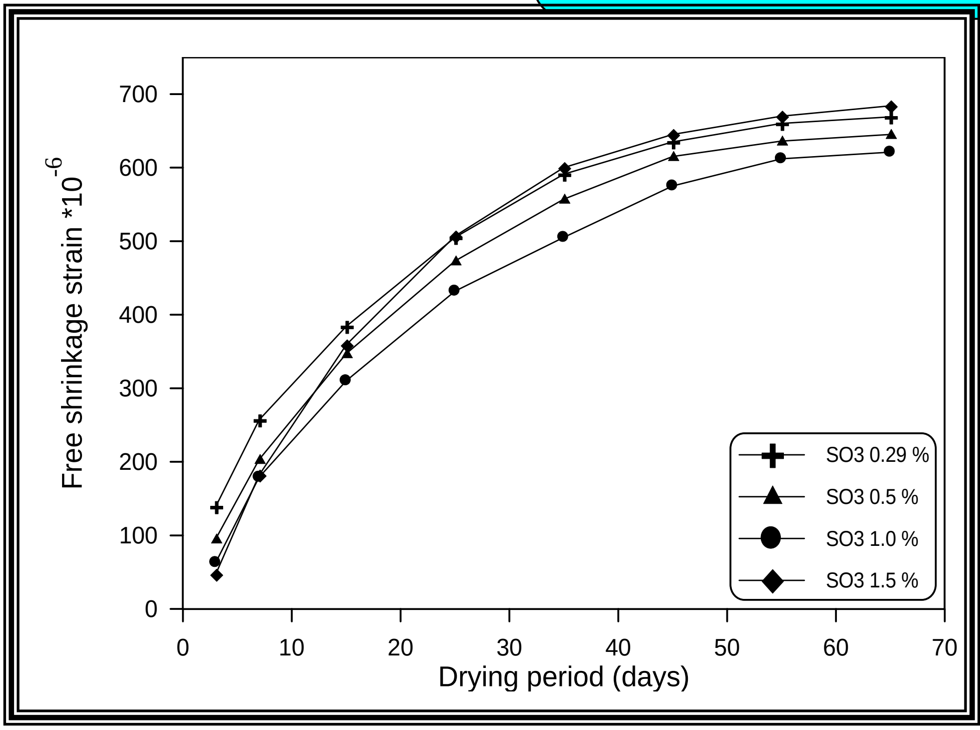
Fig(4-4b): Effect of different sulphate contents in sand (of zone 2 gradation) on the free shrinkage strain of concrete with SRPC , (28 days moist curing).



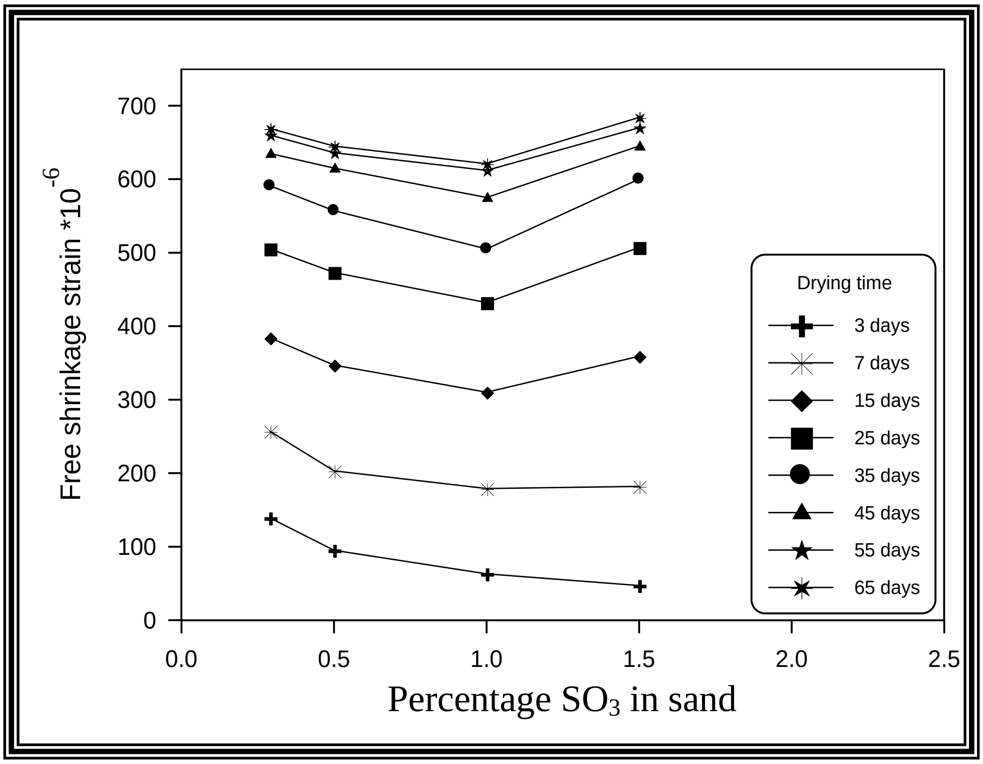
Fig(4-5a): Effect of drying time on free shrinkage strain of concrete containing OPC and sand from zone 4 with different sulphate contents, (3 days moist curing) .



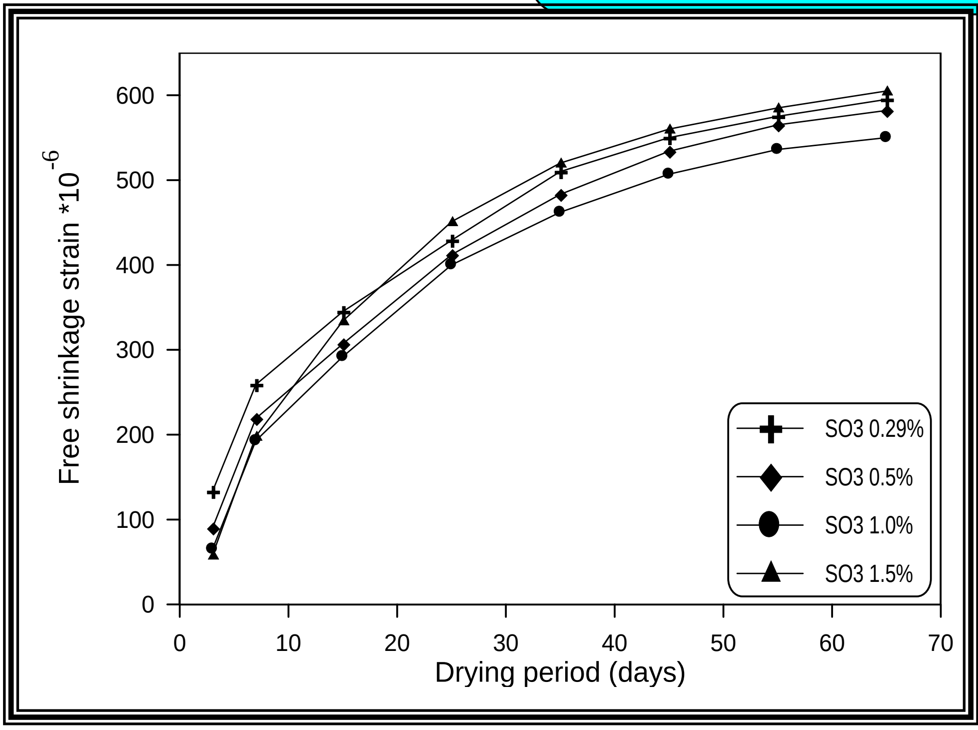
Fig(4-5b): Effect of different sulphate contents in sand (of zone 4 gradation) on the free shrinkage strain of concrete with OPC , (3 days moist curing)



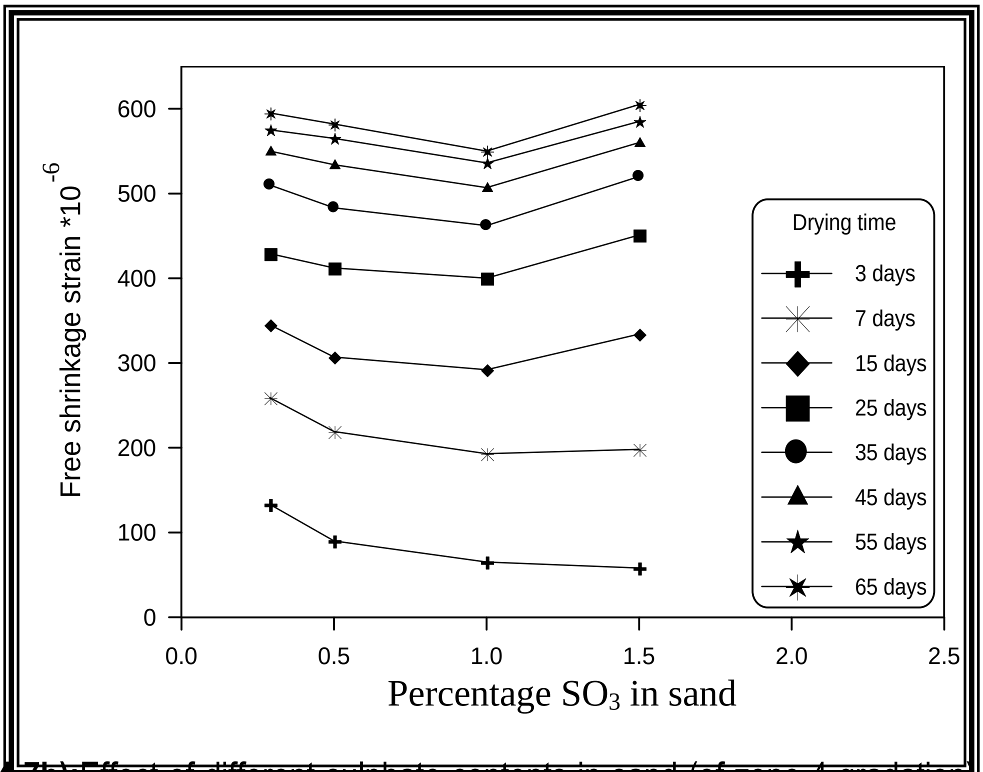
Fig(4-6a): Effect of drying time on free shrinkage strain of concrete containing OPC and sand from zone 4 with different sulphate contents, (28 days moist curing) .



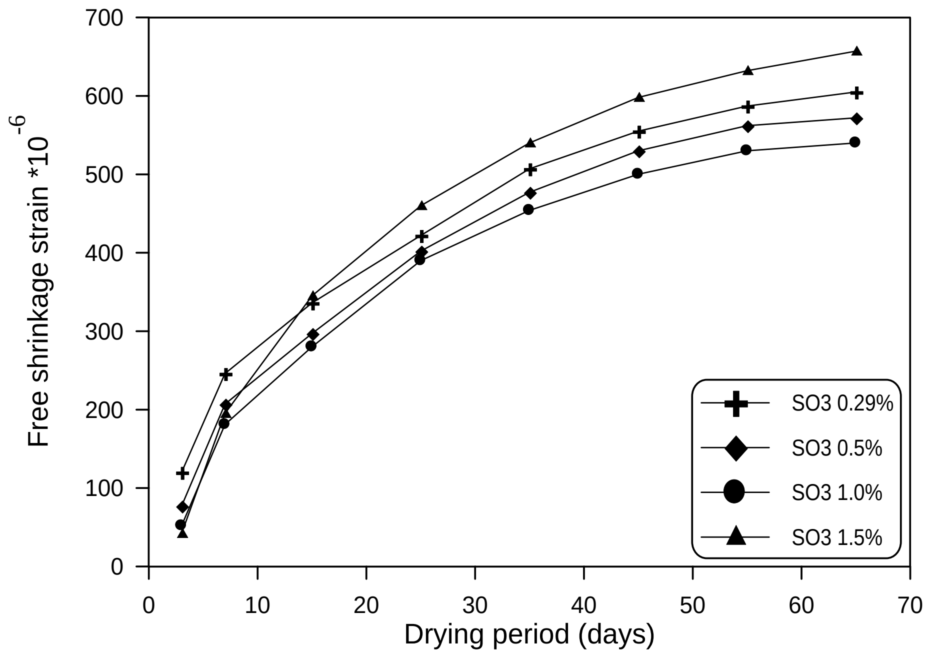
Fig(4-6b): Effect of different sulphate contents in sand (of zone 4 gradation) on the free shrinkage strain of concrete with OPC , (28 days moist curing) .



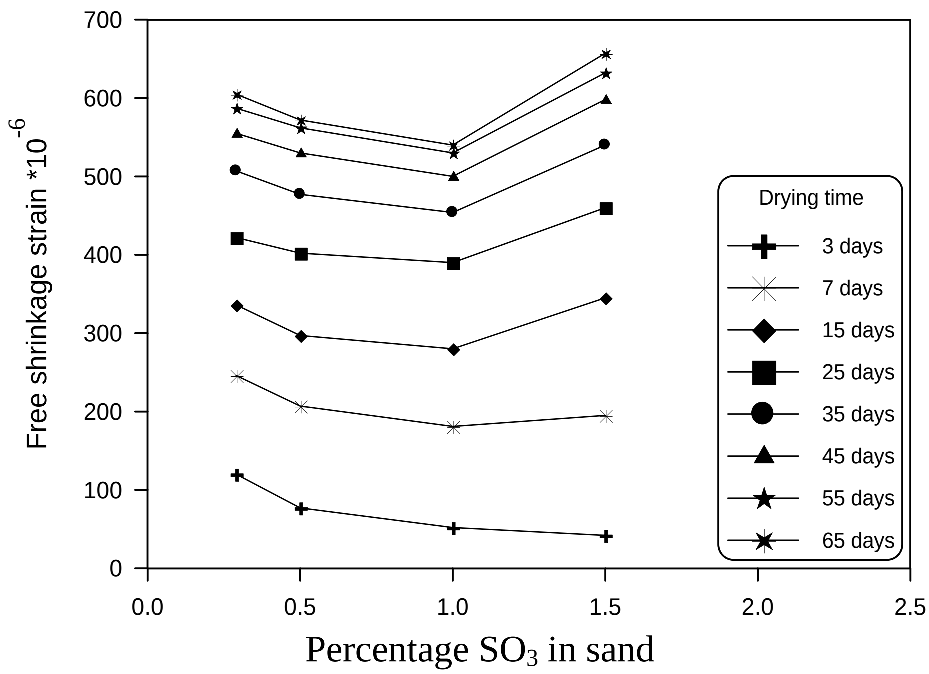
Fig(4-7a): Effect of drying time on free shrinkage strain of concrete containing SRPC and sand from zone 4 with different sulphate contents, (3 days moist curing) .



Fig(4-7b): Effect of different sulphate contents in sand (of zone 4 gradation) on the free shrinkage strain of concrete with SRPC , (3 days moist curing).



Fig(4-8a): Effect of drying time on free shrinkage strain of concrete containing SRPC and sand from zone 4 with different sulphate contents, (28 days moist curing) .



Fig(4-8b): Effect of different sulphate contents in sand (of zone 4 gradation) on the free shrinkage strain of concrete with SRPC , (28 days moist curing).

The results of cracking time and free shrinkage strain at that time and other drying shrinkage data are listed in Tables (4-1), (4-2), (4-3) and (4-4). From Table (4-1), it can be noticed that the free shrinkage strain (at cracking date) of the concrete with OPC and sand of zone 2 increases with increasing the percentage of sulphate content in sand. Salman [44] proved experimentally the soundness of this fact.

It can be noticed also, that increasing the curing period increases the free shrinkage strain at the cracking time, this confirms what is found by Al-Rawi [25]. This may be due to the increase in concrete strength with increasing the curing period. Neville [3] stated that the hydrated cement paste becomes stronger with age and it is able to attain a larger fraction of its shrinkage tendency without cracking. The increment of the free shrinkage with increasing the curing period to 28 days compared with 3 days of curing was more pronounced at the high level of SO3 content, where it was about 10.2 percent for SO3 of 0.29 percent (by weight of sand) while it was about 12.5 percent for SO3 of 1.5 percent (by weight of sand).

Table (4-1): Drying shrinkage data for specimens with OPC and sand of zone 2.

Specimen designation	SO_3 content % by weight of sand	Curing period (days)	Drying period (days)	Cracking time (days)	Free shrinkage strain $*10^{-6}$ 1	Loss of restraint $*10^{-6}$ 2	Tensile strain capacity $*10^{-6}$ 3=1-2	Elastic tensile strain capacity $*10^{-6}$ 4	Creep strain at cracking time $*10^{-6}$ 5=3-4
AOC_0	0.29	3	65	21	489	89	400	141	259
AOC_1	0.5	3	65	28	520	96	424	150	274
AOC_2	1.0	3	65	38	560	106	454	163	291
AOC_3	1.5	3	65	37	580	113	467	165	302
MOC_0	0.29	28	65	25	539	100	439	161	278
MOC_1	0.5	28	65	36	578	108	470	173	297
MOC_2	1.0	28	65	52	626	120	506	189	317
MOC_3	1.5	28	65	49	653	131	522	195	327

Note : All values of free shrinkage strain ,loss of restraint and elastic tensile strain capacity were measured directly in this study ,while the values of tensile strain capacity **and creep strain were calculated** .

Table (4-2): Drying shrinkage data for specimens with SRPC and sand of zone 2

Specimen designation	SO_3 content % by weight of sand	Curing period (days)	Drying period (days)	Cracking time (days)	Free shrinkage strain $*10^{-6}$	Loss of restraint $*10^{-6}$	Tensile strain capacity $*10^{-6}$	Elastic tensile strain capacity $*10^{-6}$	Creep strain at cracking time $*10^{-6}$

					1	2	3=1-2	4	5=3-4
ASC_0	0.29	3	65	28	484	87	397	141	256
ASC_1	0.5	3	65	35	496	90	406	143	263
ASC_2	1.0	3	65	52	544	101	443	155	288
ASC_3	1.5	3	65	50	554	104	450	157	293
MSC_0	0.29	28	65	37	536	97	439	158	281
MSC_1	0.5	28	65	47	555	102	453	164	289
MSC_2	1.0	28	65	Not cracked					
MSC_3	1.5	28	65	53	625	120	505	182	323

Table (4-3): Drying shrinkage data for specimens with OPC and sand of zone 4 .

Specimen designation	SO_3 content % by weight of sand	Curing period (days)	Drying period (days)	Cracking time (days)	Free shrinkage strain $*10^{-6}$ 1	Loss of restraint $*10^{-6}$ 2	Tensile strain capacity $*10^{-6}$ 3=1-2	Elastic tensile strain capacity $*10^{-6}$ 4	Creep strain at cracking time $*10^{-6}$ 5=3-4
AOF_0	0.29	3	65	24	498	92	406	145	261
AOF_1	0.5	3	65	34	554	105	449	163	286
AOF_2	1.0	3	65	49	589	112	477	174	303
AOF_3	1.5	3	65	47	640	135	505	179	326
MOF_0	0.29	28	65	29	540	100	440	157	283
MOF_1	0.5	28	65	41	591	112	479	173	306
MOF_2	1.0	28	65	60	617	113	504	184	320
MOF_3	1.5	28	65	56	671	137	534	188	346

Table (4-4): Drying shrinkage data for specimens with SRPC and sand of zone 4.

Specimen designation	SO_3 content % by weight of sand	Curing period (days)	Drying period (days)	Cracking time (days)	Free shrinkage strain $*10^{-6}$ 1	Loss of restraint $*10^{-6}$ 2	Tensile strain capacity $*10^{-6}$ 3=1-2	Elastic tensile strain capacity $*10^{-6}$ 4	Creep strain at cracking time $*10^{-6}$ 5=3-4
ASF_0	0.29	3	65	32	485	87	398	140	258
ASF_1	0.5	3	65	39	504	92	412	146	266
ASF_2	1.0	3	65	61	545	102	443	157	286
ASF_3	1.5	3	65	56	586	120	466	165	301
MSF_0	0.29	28	65	37	517	96	421	149	272
MSF_1	0.5	28	65	48	540	101	439	158	281
MSF_2	1.0	28	65	Not cracked					
MSF_3	1.5	28	65	62	650	130	520	190	330

From Table (4-2), the results indicate that the free shrinkage strain of the concrete with SRPC and sand of zone 2 increases with increasing the curing period, this increment increases with increasing the sulphate content in sand, where it is about 10.7 percent for SO3 of 0.29 percent (by weight of sand) while it is about 12.8 percent for SO3 of 1.5 percent (by weight of sand these rates of increment were higher than that of concrete with OPC and sand) of zone 2 this can be attributed to the rise in concrete strength.

The free shrinkage strain of the concrete with OPC and sand of zone 4 increased with increasing the percentage of sulphate content in sand (by weight) as shown in Table (4-3). It can be noticed that increasing the curing period to 28 days increases the free shrinkage strain at the cracking time compared with 3 days curing, the magnitude of this increase decreases with increasing the sulphate content up to the optimum value of sulphates and then this increment increases where it was about 8.4%, 6.6%, 4.7%, 4.84% for SO3 of 0.29%, 0.5%, 1.0%, 1.5% (by weight of sand) respectively. This may be attributed to the higher activity of the finer sulphates so the greater part of the SO3 would react at the earlier age of hydration, thus, increasing the curing period leads to hydrate the small residual part of SO3.

The results in Table (4-4) show the same trend as in Table (4-3). When SRPC was used instead of OPC but with higher rates of increments, these rates were about 6.6%, , 7.14%, and 10.92% for SO3 of 0.29%, 0.5% and 1.5% (by weight of sand) respectively.

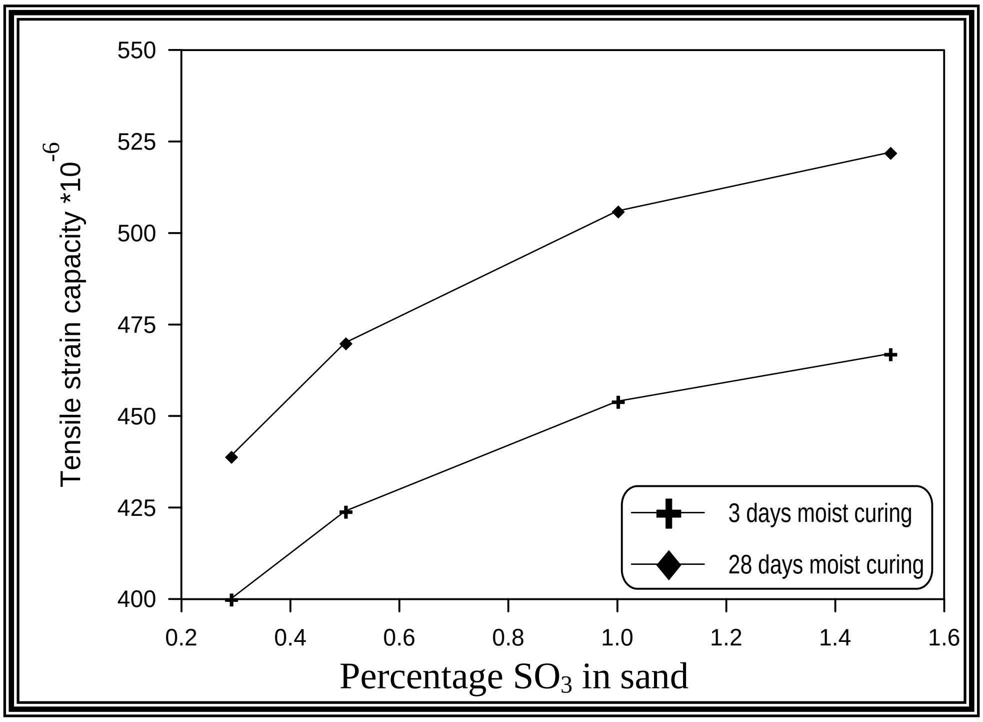
4.2 Restrained Shrinkage Test

These tests were conducted under the drying conditions in laboratory. The results of the direct determination of loss in restraint and other properties investigated under restrained shrinkage conditions are given in Tables (4-1), (4-2), (4-3) and (4-4).

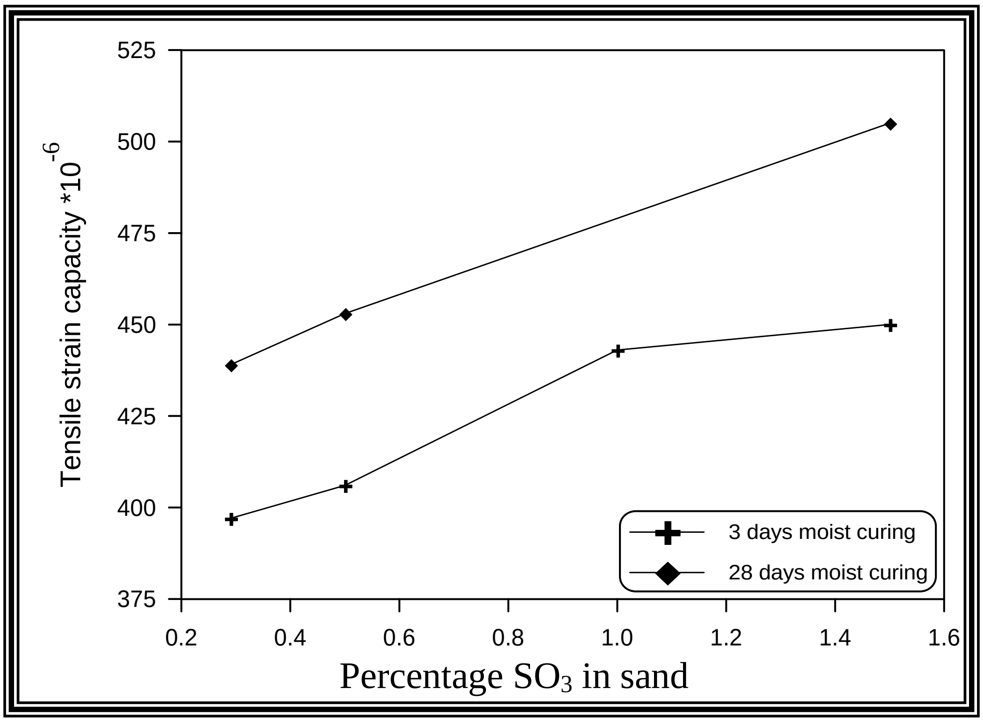
4.2.1 Tensile Strain Capacity

The determination of tensile strain capacity was based on the restrained model presented by Al-Rawi [25]. The results are given in Tables (4-1) to (4-4) and in Figures (4-9) to (4-12).

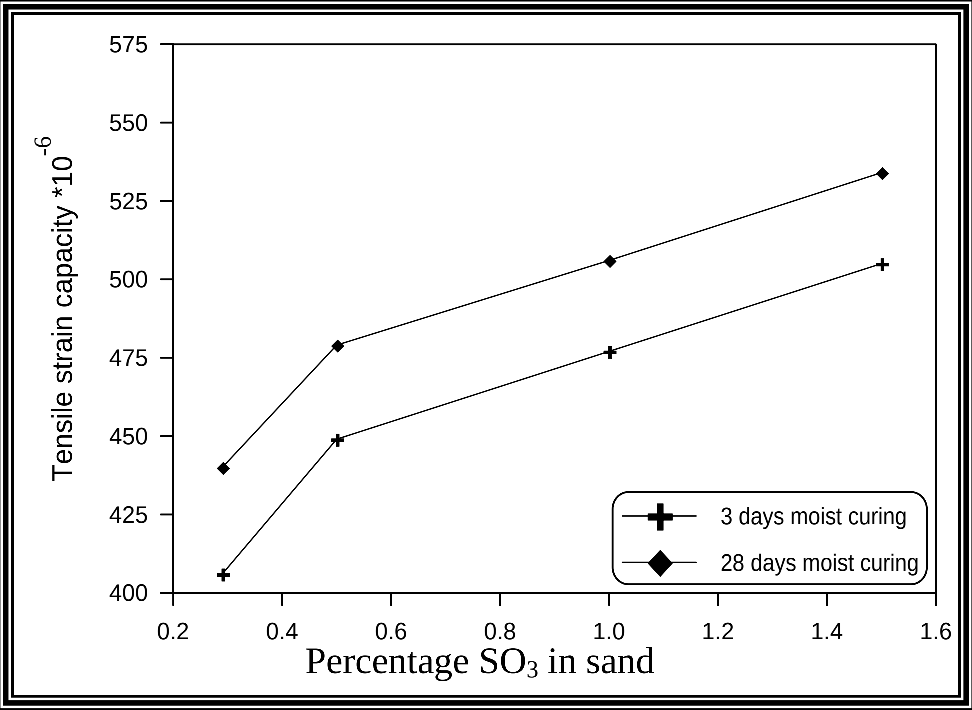
In general, when the sulphate content increases the tensile strain capacity of concrete increases too.



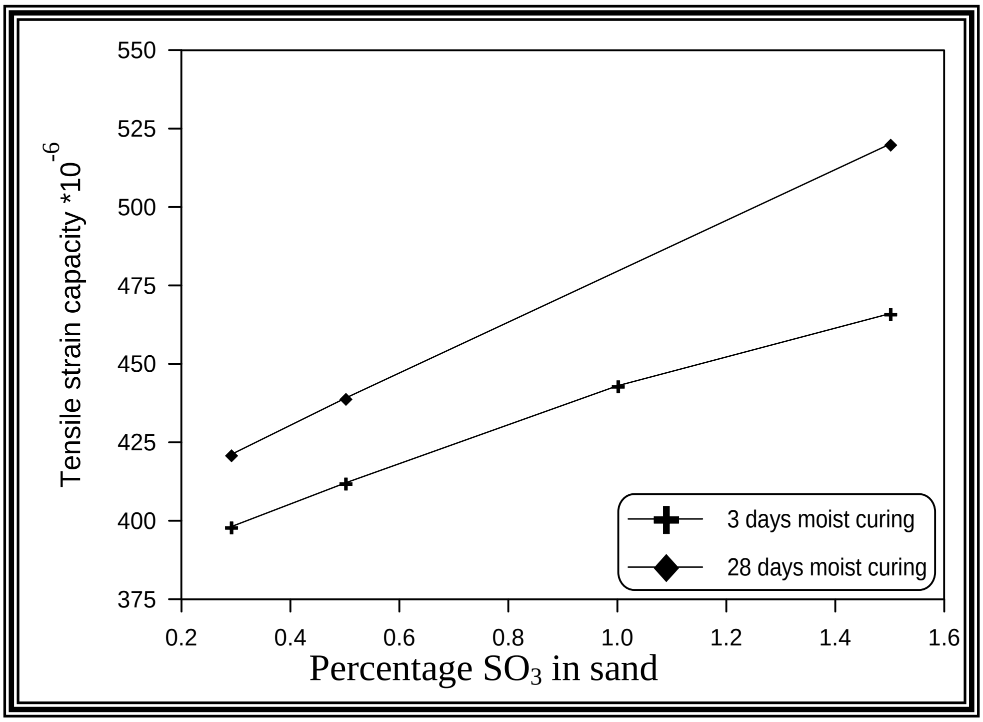
Fig(4-9): Effect of different sulphate contents in sand (of zone 2 gradation) on the tensile strain capacity of concrete with OPC .



Fig(4-10): Effect of different sulphate contents in sand (of zone 2 gradation) on the tensile strain capacity of concrete with SRPC .



Fig(4-11): Effect of different sulphate contents in sand (of zone 4 gradation) on the tensile strain capacity of concrete with OPC .



Fig(4-12): Effect of different sulphate contents in sand (of zone 4 gradation) on the tensile strain capacity of concrete with SRPC .

This increase in tensile strain capacity can be attributed to the expansion of concrete, thus leading to delay the occurrence of drying shrinkage. Therefore, the concrete sustain more strain in tension before cracking, as the amount of gypsum was increased. This behavior is in line with the previous literature [44, 76].

Table (4-1) and Figure (4-9) show the effect of sulphate content in sand (by weight) on the tensile strain capacity of concrete with OPC and sand of zone 2. It can be noticed that the tensile strain capacity increases with increasing the sulphate content in sand and with increasing the curing period to 28 days compared with 3 days curing. The percentages of these increments were 9.72%, 10.8%, 11.45% and 11.77% for mixes containing 0.29%, 0.5%, 1.0% and 1.5% sulphate in sand, respectively.

The results in Figure (4-10) and Table (4-2) show the same trend as in Figure (4-9) and Table (4-1) when SRPC was used instead of OPC but the rates of increment were about 10.7%, 11.89% and 12.22% for mixes containing 0.29%, 0.5% and 1.5% sulphates in sand, respectively. It is clear that the effect of increasing the curing period was more pronounced for mixes containing SRPC than those containing OPC.

The relationship between the different sulphate contents in sand and the tensile strain capacity of concrete with OPC and sand of zone 4 is presented in Figure (4-11) and Table (4-3). From these Figure and Table it can be noticed that increasing the sulphate content in sand and increasing the curing period have led to increase the tensile strain capacity. The percentages of these increments were about 8.37%, 6.68%, 4.61% and 5.74% for mixes containing 0.29%, 0.5%, 1.0% and 1.5% sulphates, respectively. It is obvious that increasing the fineness of sulphates decreases the effect of curing period on the tensile strain capacity associated with increasing the sulphate content (for concrete containing OPC). This may be attributed to the fact that finer sulphates has a higher reactivity. Hence, a greater part of sulphate would react at the early ages, thus leaving the remaining lower part of sulphates to react with curing time.

The results in Figure (4-12) and Table (4-4) show the same trend as in previous Figures and Tables, while the values of increment were about 5.77%, 6.55% and 11.58% for mixes containing 0.29%, 0.5%, and 1.5% sulphate, respectively. From these results it can be said that increasing the fineness of sulphates enhances the effect of curing period on tensile strain capacity associated with increasing the sulphate content (for concrete containing SRPC). This behavior was expected because increasing the fineness of sulphates leads to react only a limited amount of sulphates due to existing a limited amount of C_3A in this type of cement. Thus increasing the curing period would allow more amount of sulphates to react with the aluminate ions $(Al)^{+++}$ from C_4AF compound [78].

4-2-2 Elastic Tensile Strain Capacity

Elastic tensile strain capacity of concrete was obtained directly by measuring the immediate movement after cracking of concrete on channel shape beams. The test results are summarized in Tables (4-1) to (4-4).

Table (4-1) shows the effect of sulphate content in sand on the elastic tensile strain capacity of concrete, with OPC and sand of zone 2. It is obvious that increasing the sulphate content causes a slight increase in elastic tensile strain capacity of concrete while increasing the curing period causes further increase in it. The percentages of these increments were about 14.18%15.33%, 15.95% and 18.18% for mixes containing 0.29%, 0.5%, 1.0% and 1.5%sulphate, respectively. The reason for such behavior could be due to the increase in shrinkage strain at cracking time.

The results in Table(4-2) show the same trend as in Table (4-1), when SRPC was used instead of OPC but the rates of increment were about

12.05%, 14.68% and 15.92% for concrete containing SO_3 0.29%, 0.5% and 1.5% by weight of sand respectively.

Tables (4-3) and (4-4) show the results for concrete mixes with sand from zone 4 were used instead of that from zone 2. the results indicated that higher percentage of sulphate content in sand causes a slight increase in elastic tensile strain capacity and progressive hydration increases it when OPC or SRPC were used in concrete, but this increase differs from previous mixes. The increase was in rates of 8.2%, 6.13%, 5.7% and 5.02% for concrete containing SO_3 0.29%, 0.5% and 1.5% respectively when OPC and sand of zone 4 is used, while about 6.4%, 8.2% and15.15% for concrete containing SO_3 0.29%, 0.5% and1.5% respectively when SRPC and sand of zone 4 is used.

The elastic tensile strain capacity was calculated indirectly by determination of splitting tensile strength and modulus of elasticity. It was taken as the splitting tensile strength (as shown in Table (4-5)) divided by the modulus of elasticity (as shown in Table (4-6)). The results are illustrated in Table (4-7). From this Table, it can be noticed that the calculated values of the elastic tensile strain capacity are lower than those measured by the direct method. This is in line with Al-Rawi [25] who found that the elastic tensile strain capacity obtained using the direct method was greater than that from the indirect method.

Table (4-5): Results of the splitting tensile strength (MPa) of the concrete mixes with different SO_3 content.

Specimen designation	SO_3 content % by weight of sand	Total SO_3 content % by weight of cement	Splitting tensile strength (MPa) at age of :			
			3 days Air curing		Continuous water curing	
			28 days	56 days	28 days	56 days
OC_0	0.29	3.07	3.68	3.75	3.71	3.96
OC_1	0.5	3.355	3.72	3.82	3.75	4.02
OC_2	1.0	4.03	3.79	3.9	3.81	4.04
OC_3	1.5	4.70	3.55	3.65	3.51	3.56
SC_0	0.29	2.77	3.72	3.81	3.75	4.0
SC_1	0.5	3.055	3.78	3.87	3.89	4.07
SC_2	1.0	3.73	3.88	3.96	3.9	4.16
SC_3	1.5	4.41	3.77	3.84	3.7	3.76
OF_0	0.29	3.033	3.73	3.82	3.76	4.0
OF_1	0.5	3.28	3.78	3.87	3.79	4.04
OF_2	1.0	3.843	3.8	3.9	3.83	4.07
OF_3	1.5	4.42	3.18	3.32	3.32	3.64
SF_0	0.29	2.733	3.77	3.87	3.82	4.05
SF_1	0.5	2.973	3.86	3.97	3.92	4.1
SF_2	1.0	3.55	3.9	4.0	3.93	4.16
SF_3	1.5	4.12	3.75	3.82	3.71	3.92

,,,,,

Notations as in Table (3-1).

Table (4-6): Results of the modulus of elasticity (MPa) at 28 days age of moist curing.

Percentage SO_3 in sand (by weight)	Modulus of elasticity (MPa)			
	Sand of zone 2		Sand of zone 4	
	OPC	SRPC	OPC	SRPC
0.29	30500	30750	30900	31250
0.5	31000	32115	31310	32315
1.0	31835	32260	31910	32460
1.5	28850	30300	27230	30050

Table (4-7): Results of the calculated elastic tensile strain capacity of the concrete mixes with different SO_3 content in sand (by weight) and cured in water till the testing time of 28 days .

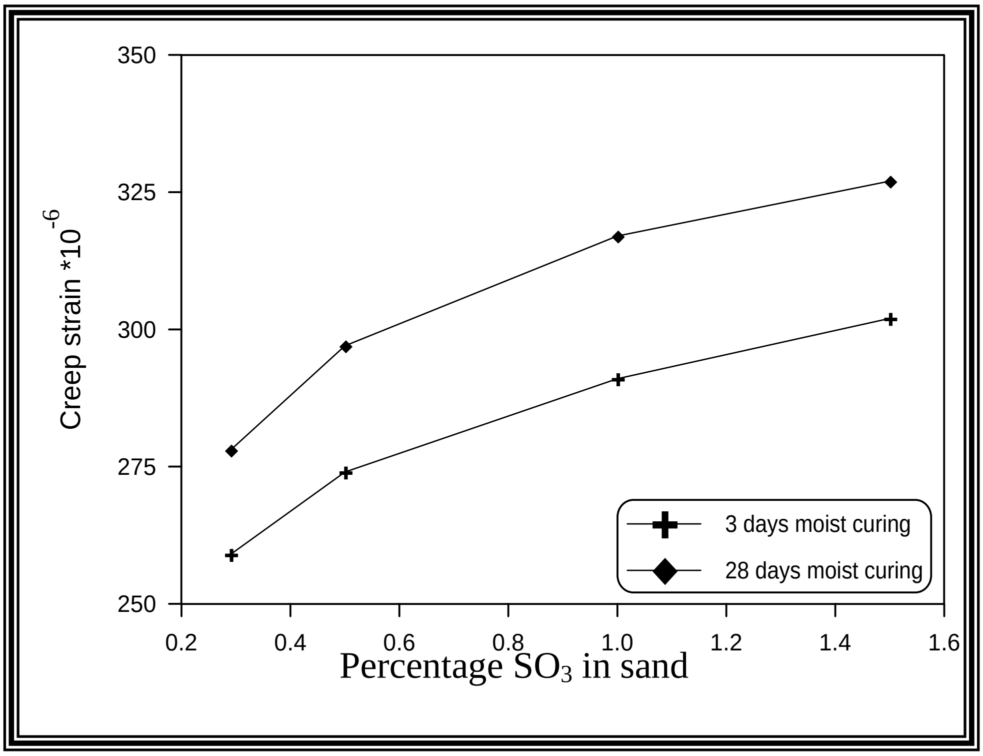
Specimen designation	SO_3 content % by weight of sand	Elastic tensile strain capacity $*10^{-6}$
OC_0	0.29	121.63
OC_1	0.5	120.96
OC_2	1.0	119.67
OC_3	1.5	121.66
SC_0	0.29	121.95
SC_1	0.5	121.12
SC_2	1.0	120.89
SC_3	1.5	122.1
OF_0	0.29	121.68
OF_1	0.5	121.04
OF_2	1.0	120.02
OF_3	1.5	121.92
SF_0	0.29	122.24
SF_1	0.5	121.3
SF_2	1.0	121.07
SF_3	1.5	122.44

Note : calculated elastic tensile strain capacity= splitting tensile strength (MPa) / modulus of elasticity (MPa) .

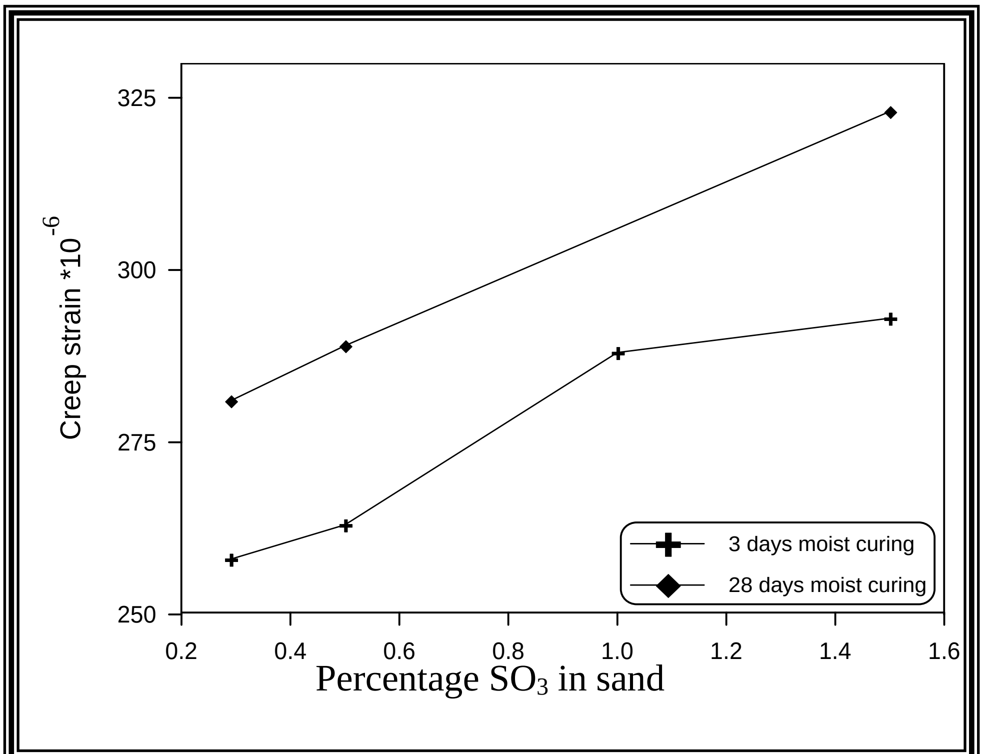
4-2-3 Creep

Creep strain of concrete subjected to restrained shrinkage was calculated as the difference between the tensile strain capacity and the elastic tensile strain capacity.

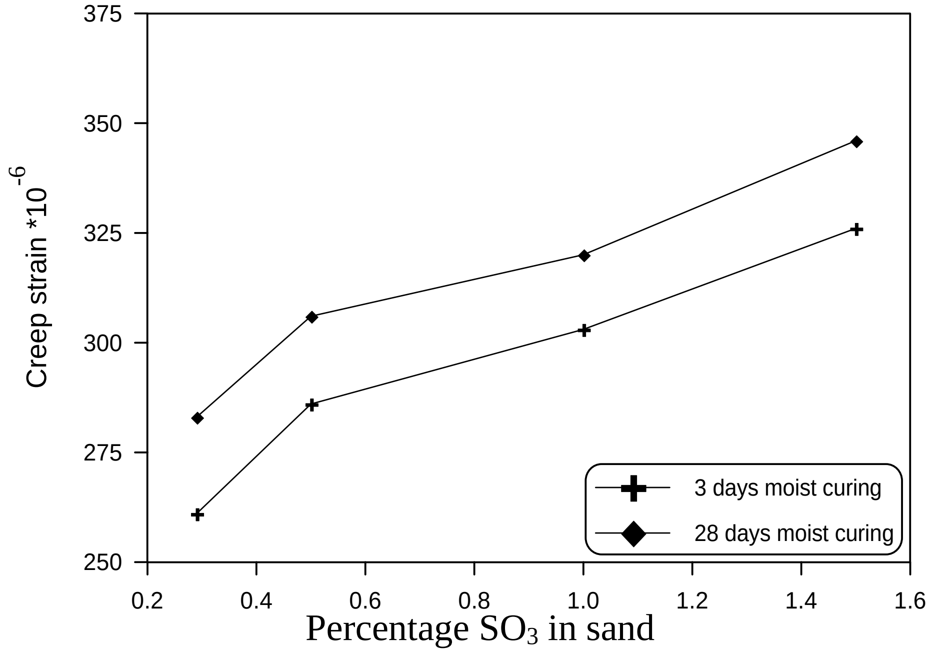
Tables (4-1) to (4-4) and Figures (4-13) to (4-16) show the relation between the creep strain and the percentage of sulphate content in sand.



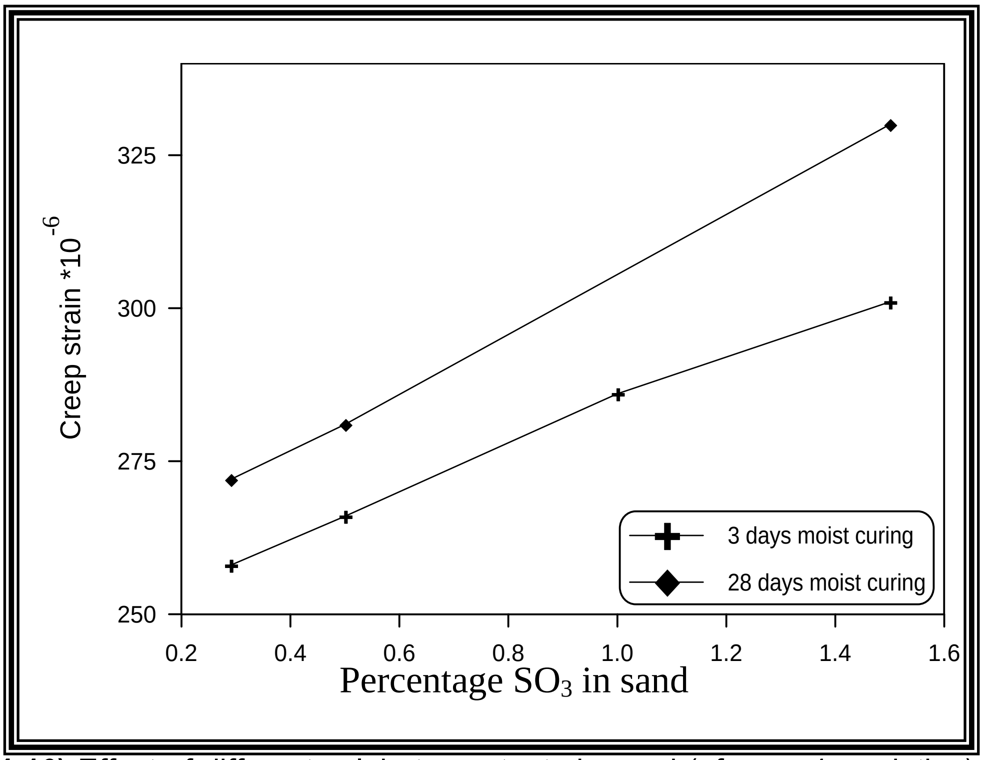
Fig(4-13): Effect of different sulphate contents in sand (of zone 2 gradation) on the creep strain of concrete with OPC.



Fig(4-14): Effect of different sulphate contents in sand (of zone 2 gradation) on the creep strain of concrete with SRPC .



Fig(4-15): Effect of different sulphate contents in sand (of zone 4 gradation) on the creep strain of concrete with OPC .



Fig(4-16): Effect of different sulphate contents in sand (of zone 4 gradation) on the creep strain of concrete with SRPC .

Table (4-1) and Figure (4-13) present this relationship for concrete with OPC and sand of zone 2. it is obvious that the creep strain (at the cracking time) increases with increasing the sulphate content and curing period. The percentages of these increments were about 7.33%, 8.39%, 8.93% and 8.27% for concrete containing SO_3 by 0.29%, 0.5%, 1.0% and 1.5% respectively. This behavior may be attributed to the elongation of cracking time and / or the restrained shrinkage stress with increasing curing period and / or the sulphate content in sand as the creep strain is a function of stress and the duration of its application.

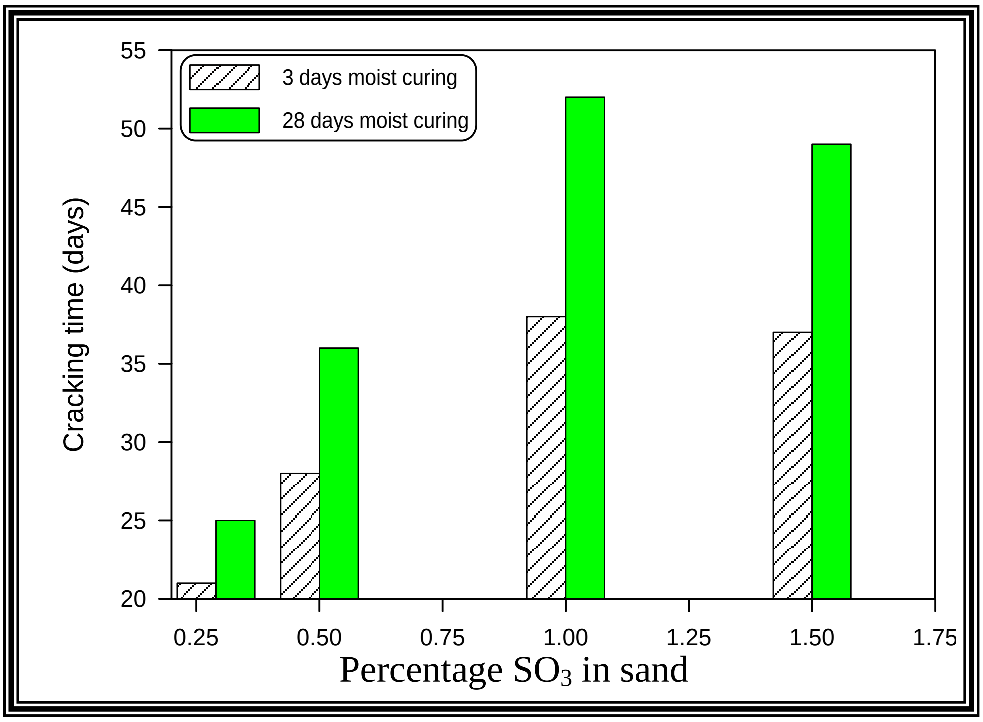
It can be seen that the results tabulated in Tables (4-2) to (4-4) and Figures (4-14) to (4-16) reveal identical trend as for concrete containing OPC or SRPC and sand from zone 2 or zone 4 but with different rates of increment, these rates were about 9.76%, 9.88% and 10.2% for concrete containing SO_3 0.29%, 0.5% and 1.5% respectively when SRPC and sand of zone 2 is used and about 8.4%, 6.99%, 5.6% and 6.13% for concrete containing SO_3 0.29%, 0.5%, 1.0% and 1.5% respectively, where OPC and sand of zone 4 is used, while about 5.4%, 5.6% and 9.6% for concrete containing SO_3 0.29%, 0.5%, and 1.5% respectively when SRPC and sand of zone 4 is used. The results obtained in this work are in agreement with what is found by others [25, 44].

4·3 Cracking Time

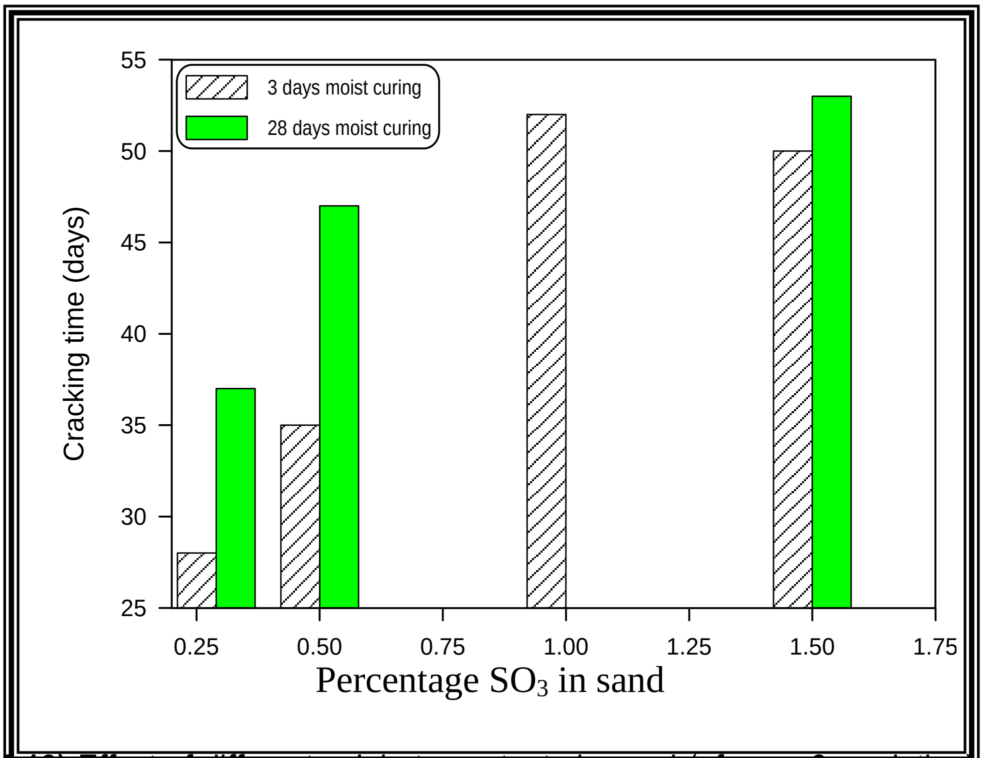
The cracking time can be used as an index for the vulnerability to cracking [79].

Tables (4-1) to (4-4) and Figures (4-17) to (4-20) show cracking time versus percentage of sulphate present in concrete mixes. It can be observed that the cracking time increases with increasing the percentage of sulphate content up to the optimum value of sulphates then it decreases with the higher value of sulphate than the optimum. This may be due to the fact that sulphates would offset early drying shrinkage effects (delay of drying shrinkage), thus, the possibility of cracking at early ages will be reduced, and the time required for cracking will be longer. At the higher level of sulphate 1.5%, a deleterious expansion occurred. That means more microcracks, higher rate of evaporation, faster drying shrinkage and faster cracking and this opinion agrees with what is found by [76].

It has been found that the cracking time depended on C_3A content in concrete mixes, so the use of SRPC had increased the cracking time rather than OPC . Cracking time increased also with increasing the curing period and with increasing the fineness of sulphates used. It is worth to mention that concrete mixes with SRPC and cured for 28 days did not crack through the period of investigation. This result was in line with Al-Rawi [25] who found that increasing the normal curing period increases the cracking time. Salih [80] found that the internal restrained by steel reinforcement did not cause cracking for the 14 days water cured beams. But cracking occurred in the 3 days water cured beams.



Fig(4-17): Effect of different sulphate contents in sand (of zone 2 gradation) on the cracking time of concrete with OPC .



Fig(4-18): Effect of different sulphate contents in sand (of zone 2 gradation) on the cracking time of concrete with SRPC.

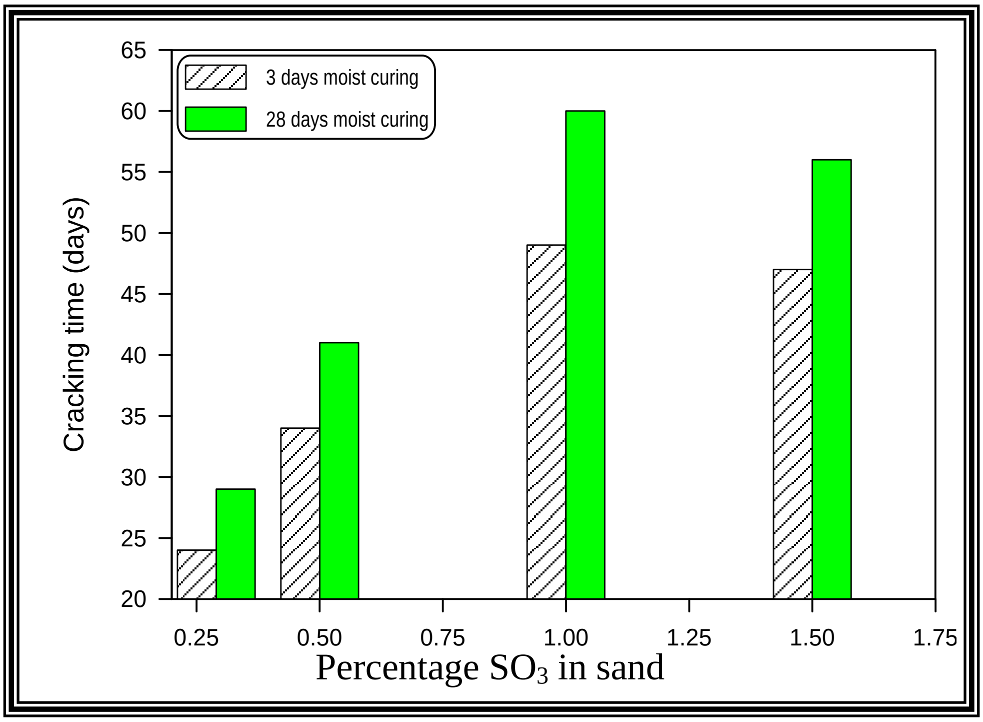
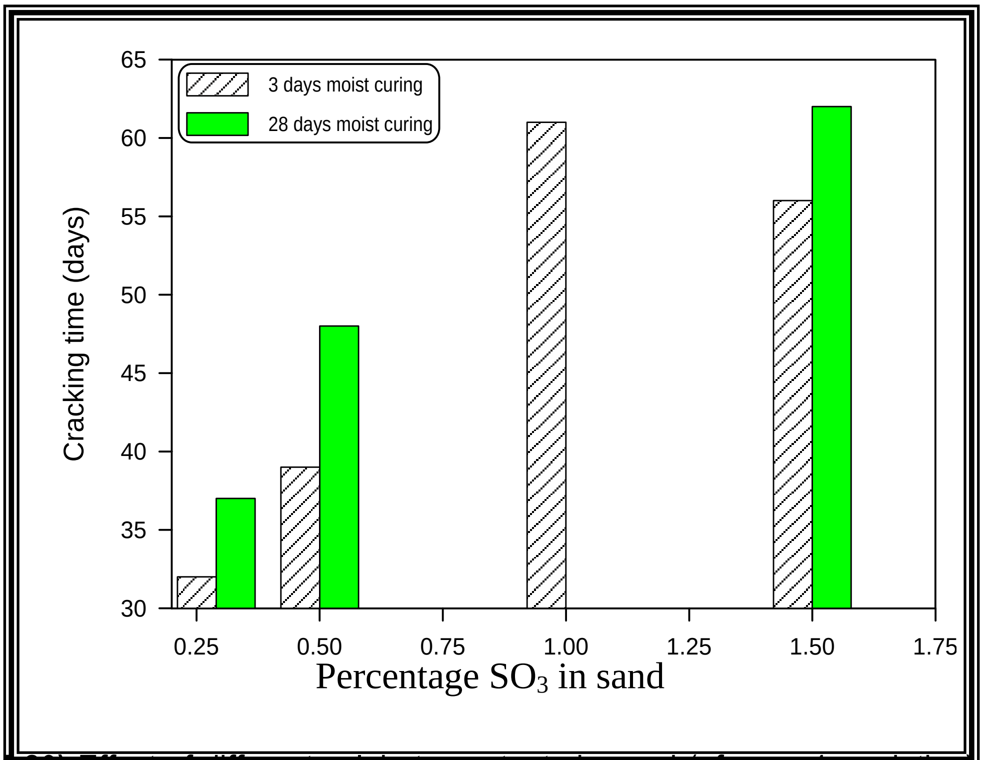


Fig.(4-19): Effect of different sulphate contents in sand (of zone 4 gradation) on the cracking time of concrete with OPC.



Fig(4-20): Effect of different sulphate contents in sand (of zone 4 gradation) on the cracking time of concrete with SRPC .

4.4 Crack Location

Plates (4-1) to (4-8) and Figure (4-21) show the location of crack for some concrete mixes. The results show that cracks occurred within the middle third of the beam rather than at the side thirds. This means that the restrained shrinkage strain is higher at the middle of the beam than at the sides.

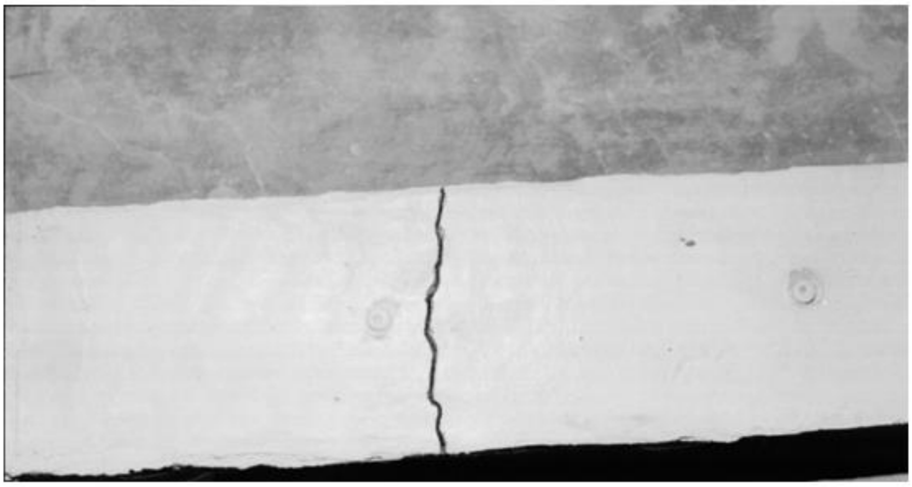


Plate (4-1) The crack location in specimen ASC_2

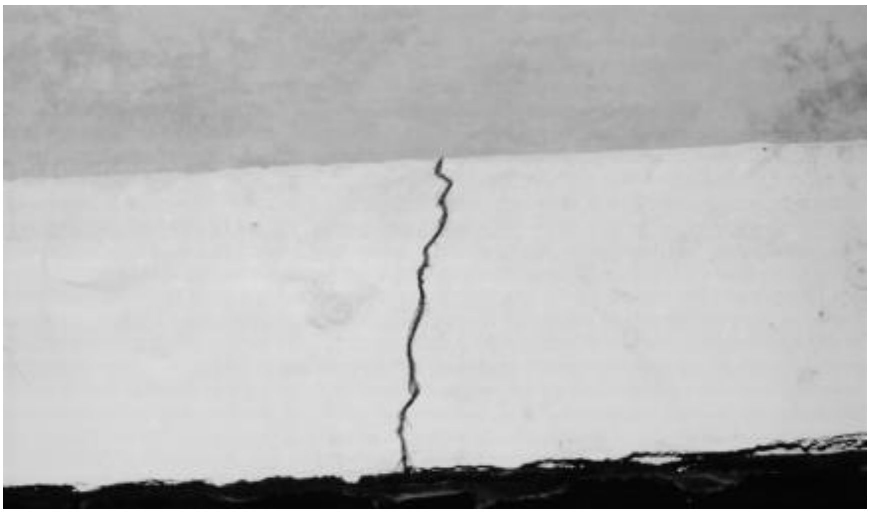


Plate (4-2) The crack location in specimen AOC_2

Plate (4-3) The crack location in specimen MOF $_0$

Plate (4-4) The crack location in specimen ASC_1

Plate (4-5) The crack location in specimen AOF_3

Plate (4-6) The crack location in specimen MOC_2

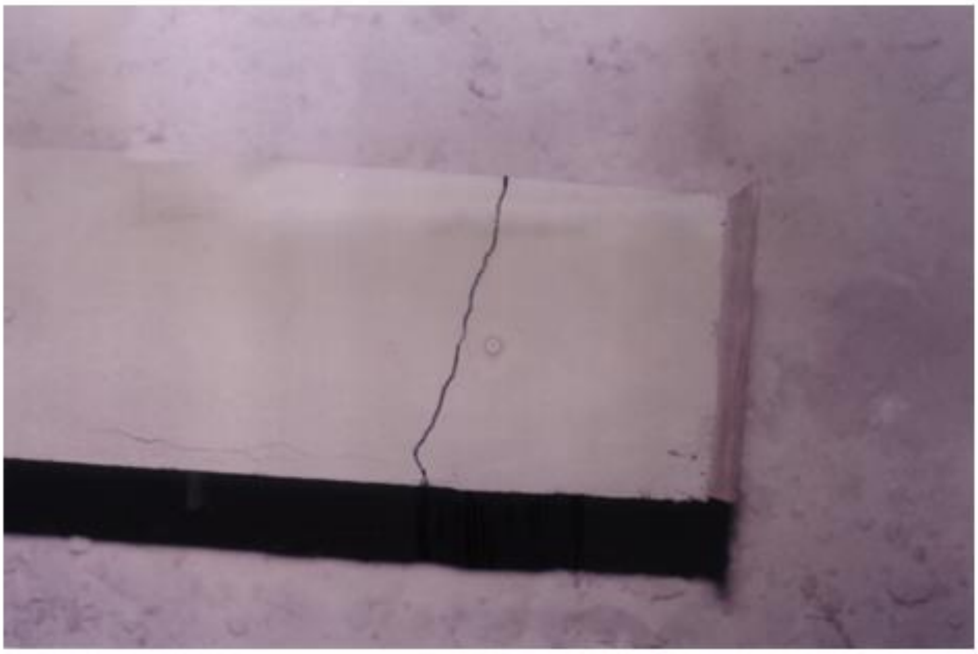


Plate (4-7) The crack location in specimen MOF_3

Plate (4-8) The crack location in specimen MOF_1

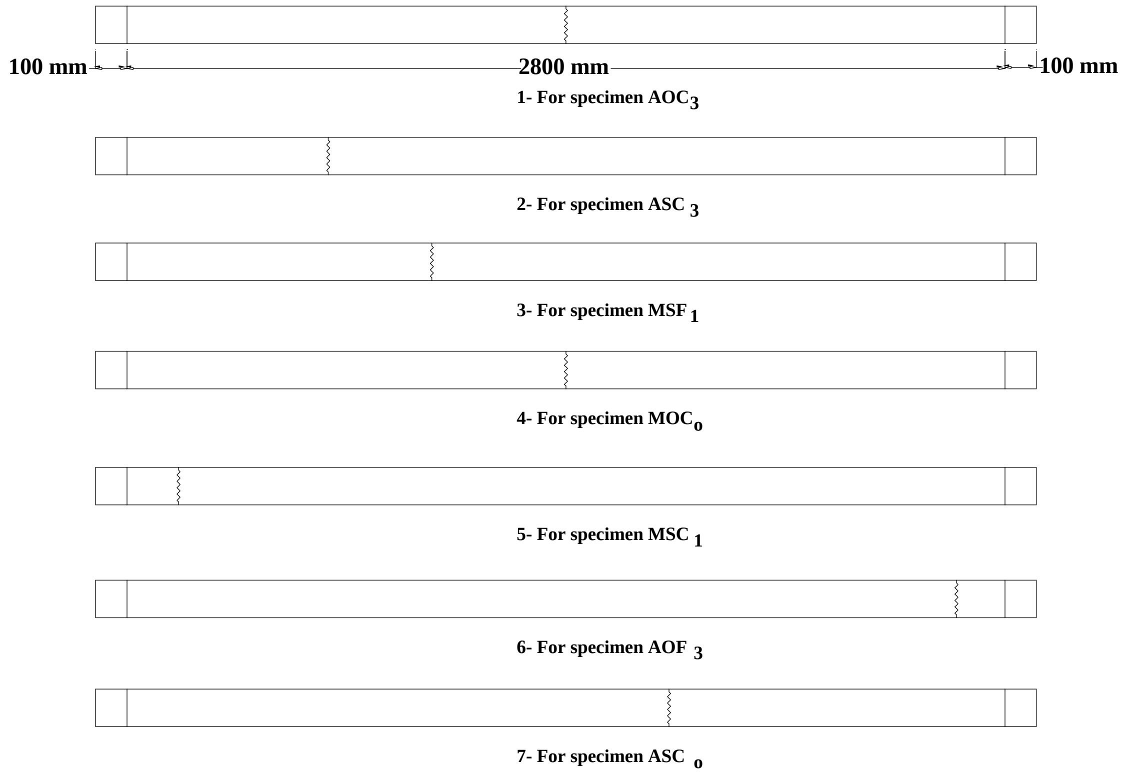


Fig.(4-21) : Location of cracks for some concrete beam specimens.

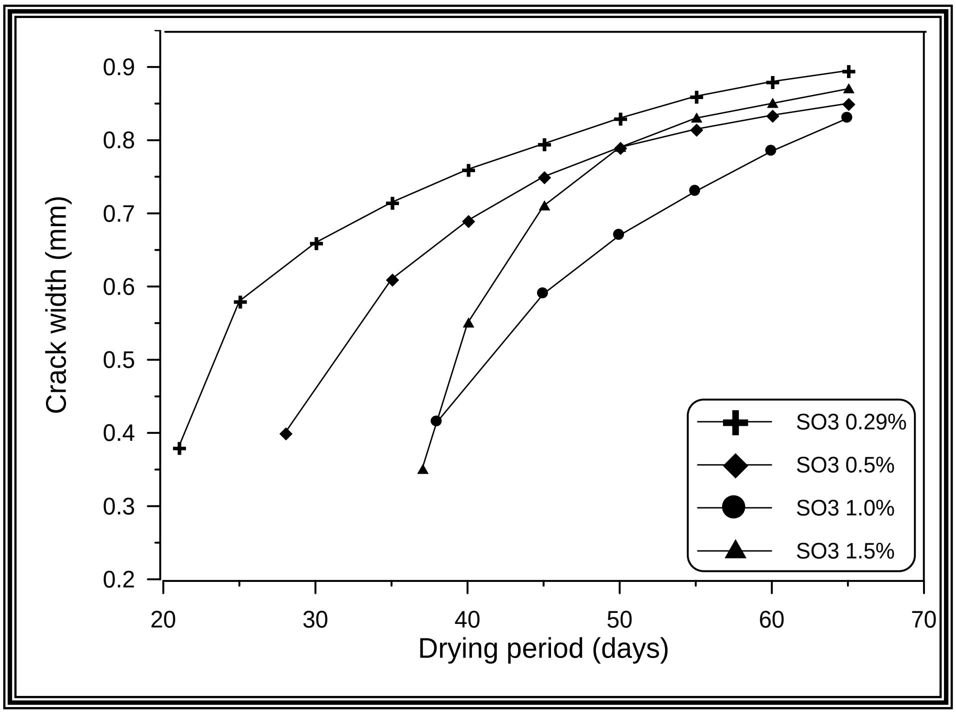
Al-Rawi [25] attributed this behavior to the generation of a strain gradient at the end part which increases the loss of restraint and reduces the possibility of cracking, while at interior zones, higher restrain would be developed due to the build up of friction forces and the absence of strain gradient, so cracks would be expected at the interior zones and away from the ends.

4.5 Crack Development

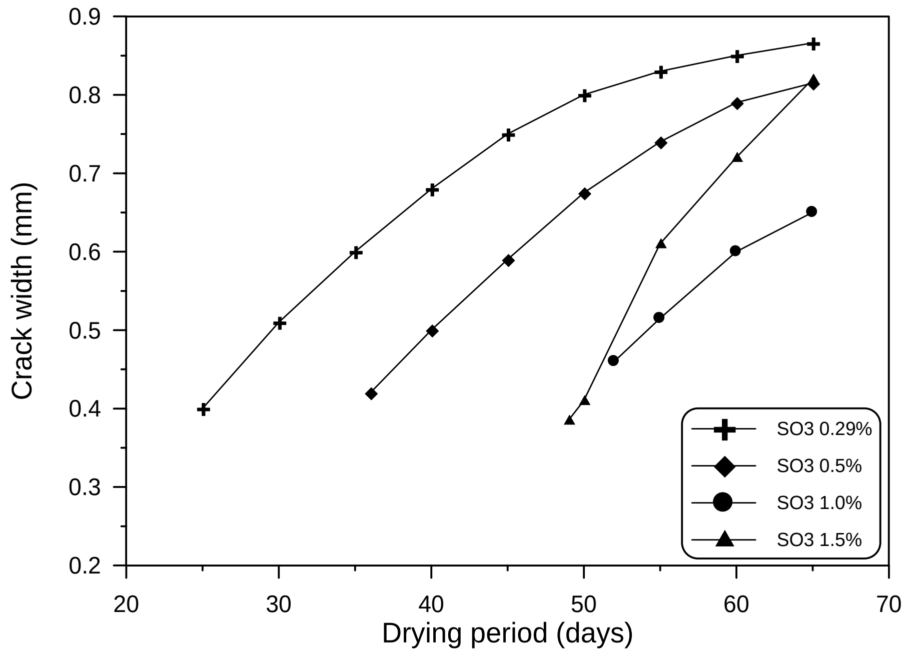
From Figures (4-22) to (4-29) it is clear that increasing sulphate content in sand increases the cracks width at the early ages of crack initiation up to the optimum value and then it decreased depending on the cracking time and the shrinkage strain at that time .It is obvious that the width of cracks at the later ages decreases with increasing the sulphate content in sand up to an optimum value, and beyond this value cracks' width increases .

Using of finer sand which contains different percentages of sulphate in concrete which is cured for 3 and 28 days increases the width of cracks at the early ages of cracking, while at the later ages the finer sand decreases crack' width .

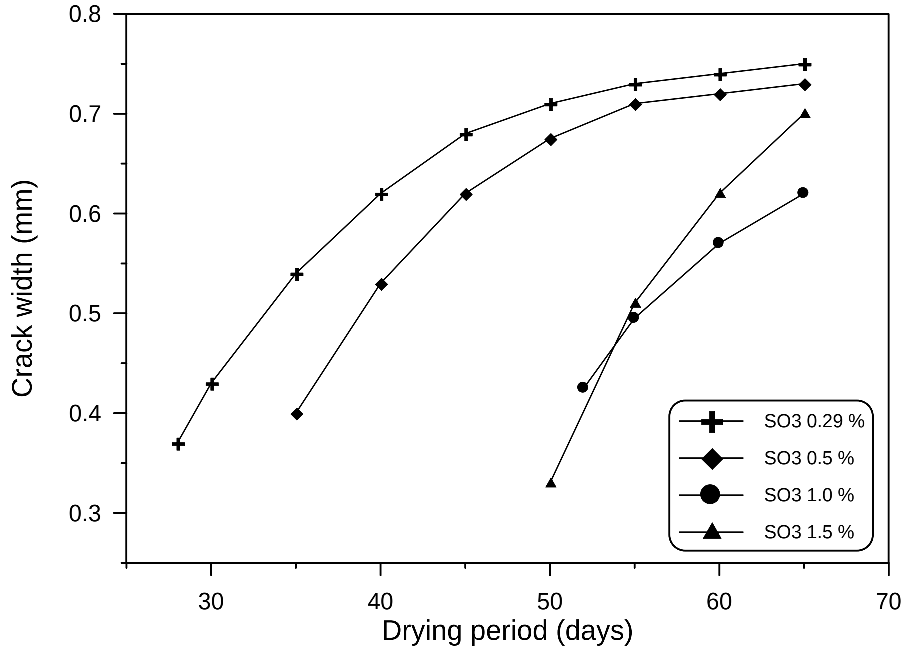
Increasing the curing period increases the cracks' width for all mixes at the early ages of cracking while it decreased the cracks' width at the later ages.



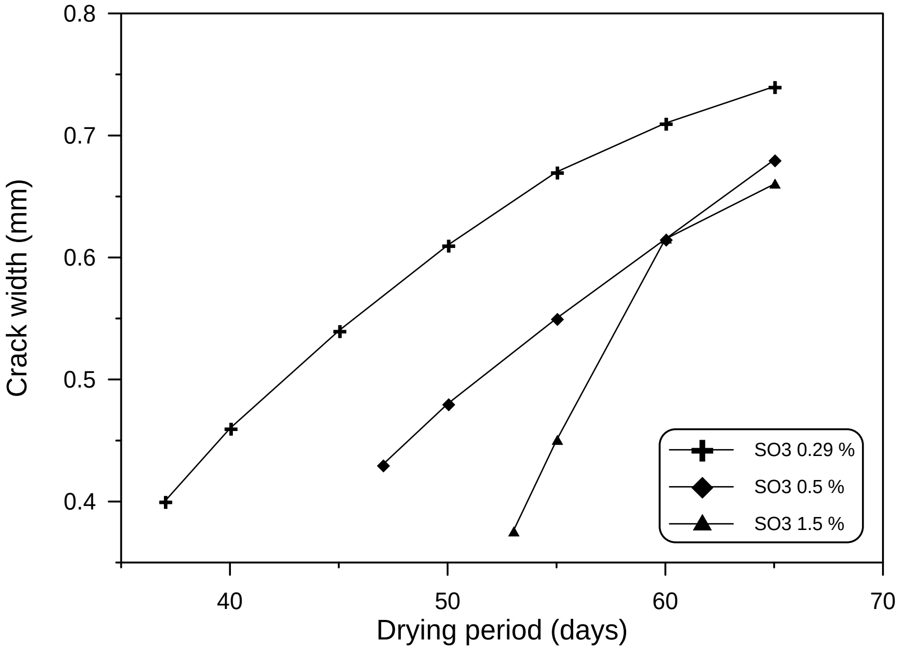
Fig(4-22): Effect of drying period on crack development of concrete containing OPC and sand from zone 2 with different sulphate contents, (3 days moist curing)



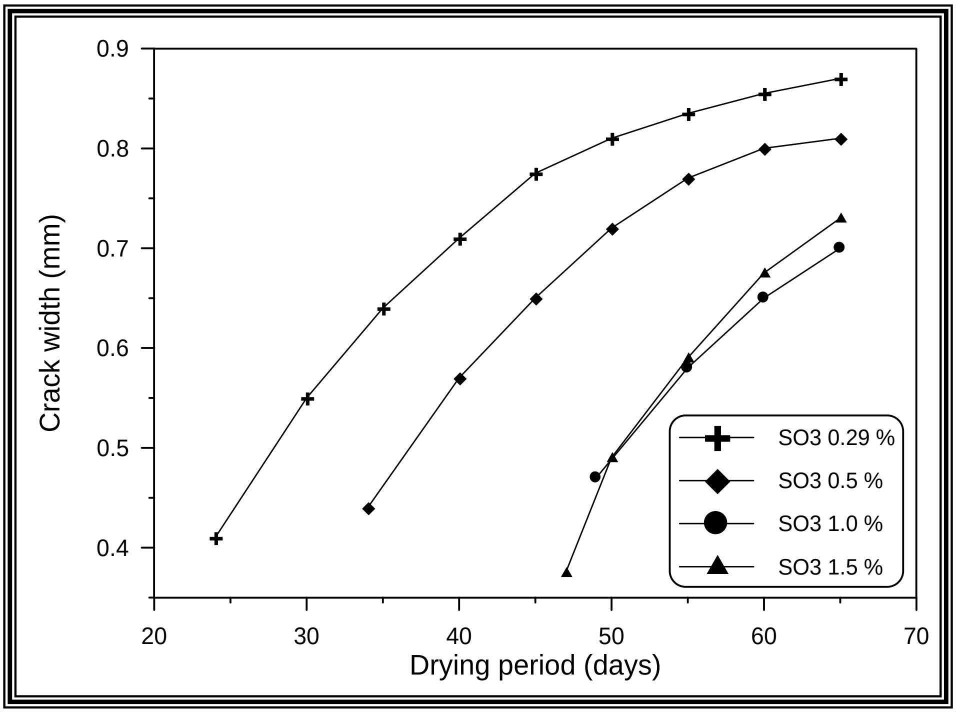
Fig(4-23): Effect of drying period on crack development of concrete containing OPC and sand from zone 2 with different sulphate contents, (28 days moist curing)



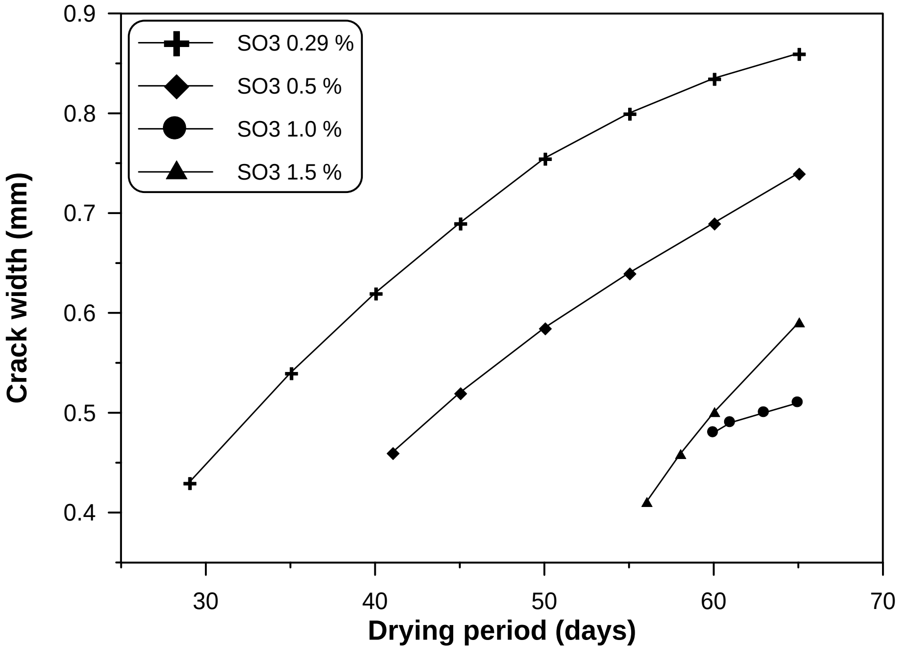
Fig(4-24): Effect of drying period on crack development of concrete containing SRPC and sand from zone 2 with different sulphate contents, (3 days moist curing)



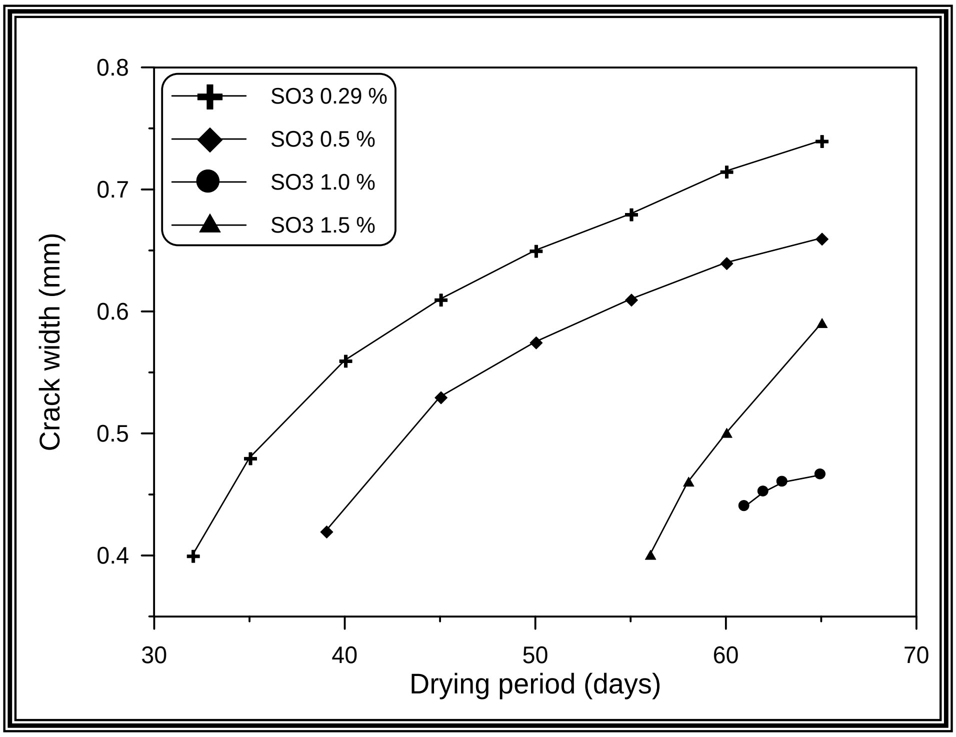
Fig(4-25): Effect of drying period on crack development of concrete containing SRPC and sand from zone 2 with different sulphate contents, (28 days moist curing)



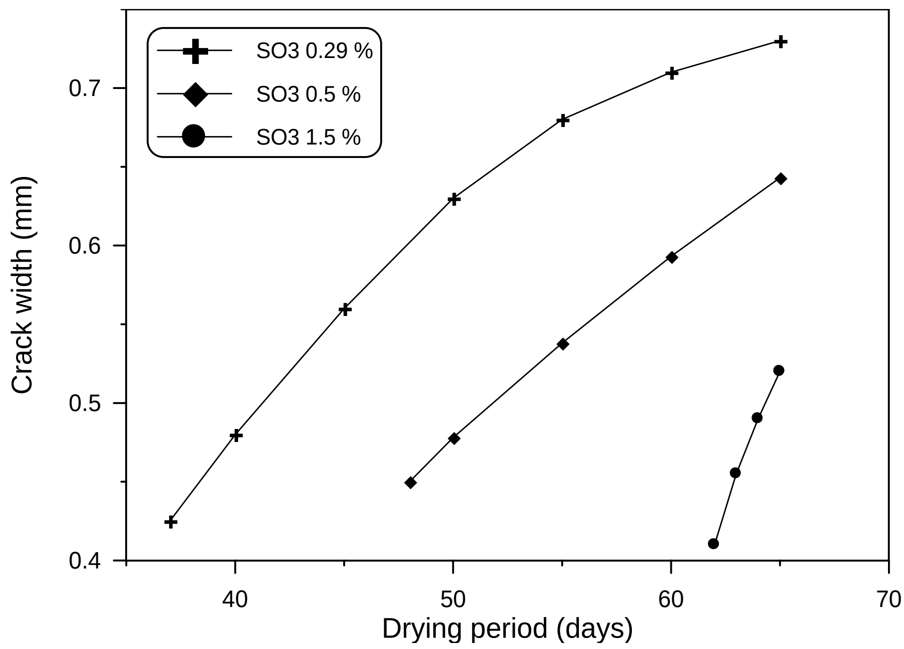
Fig(4-26): Effect of drying period on crack development of concrete containing OPC and sand from zone 4 with different sulphate contents, (3 days moist curing)



Fig(4-27): Effect of drying period on crack development of concrete containing OPC and sand from zone 4 with different sulphate contents, (28 days moist curing)



Fig(4-28): Effect of drying period on crack development of concrete containing SRPC and sand from zone 4 with different sulphate contents, (3 days moist curing)



Fig(4-29): Effect of drying period on crack development of concrete containing SRPC and sand from zone 4 with different sulphate contents, (28 days moist curing)

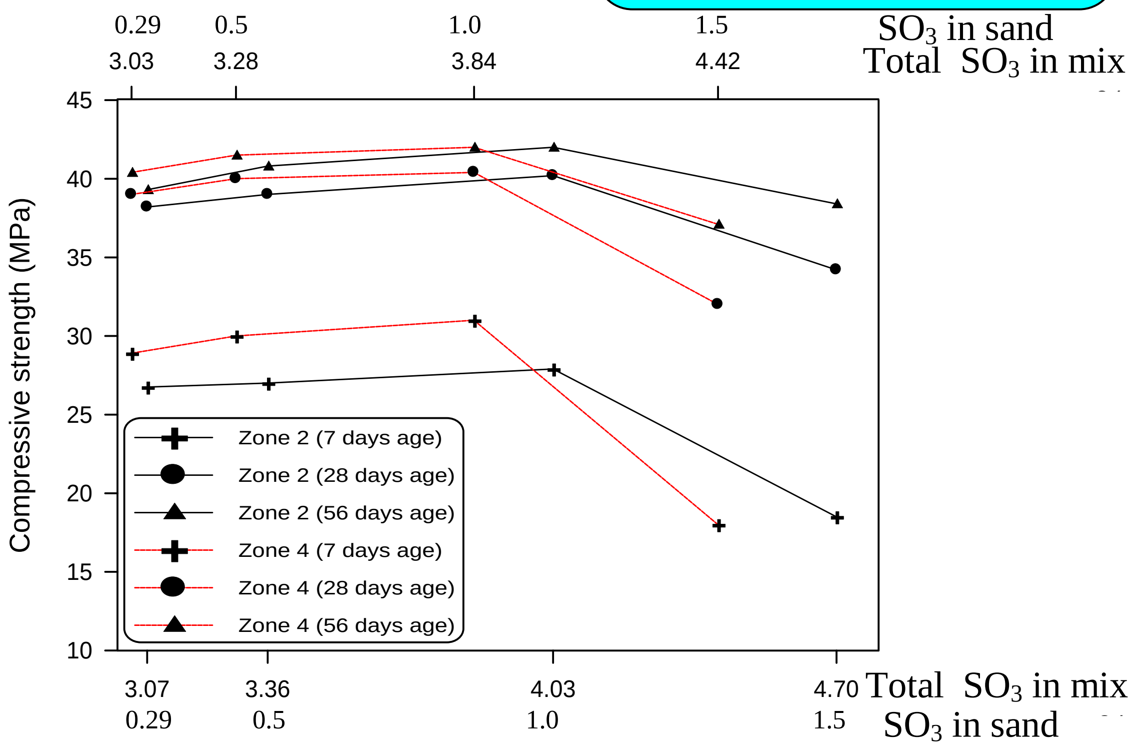
4.6 Compressive Strength

Results of the 7, 28, and 56 days compressive strength of concrete with various percentages gypsum content in sand are shown in Table (4-8) and Figures (4-30) to (4-33) for different mixes, different types of cement and different gradation of sand. It can be seen that for all mixes, there is an optimum gypsum content at which the compressive strength is maximum, beyond which content the compressive strength has decreased. The present data indicates that the optimum gypsum content for these mixes is about (1.0) percent (by weight of sand) and it is equal to 4.03% for concrete with OPC and sand from zone 2 and 3.84% for concrete with OPC and sand from zone 4 and 3.73% when SRPC and sand from zone 2 is used while it equals to 3.55% when SRPC and sand from zone 4 is used.

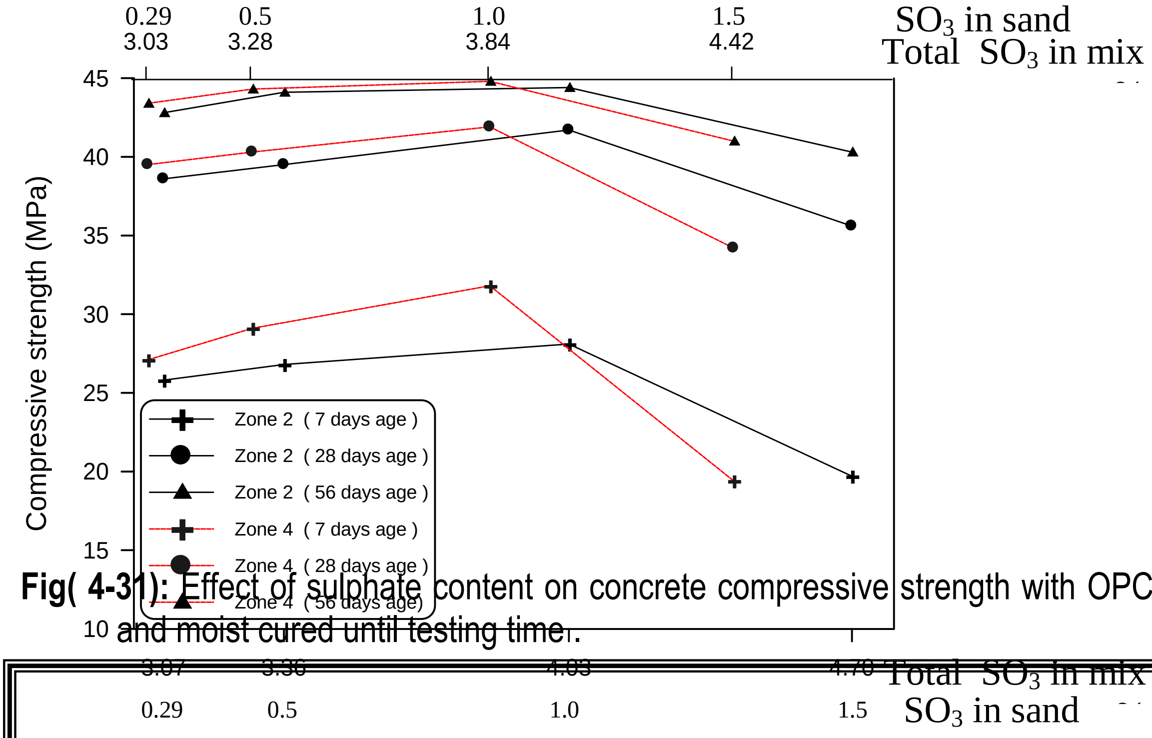
Table (4-8): Results of the compressive strength (MPa) of the concrete mixes with different SO_3 content .

Specimen designation	SO_3 content % by weight of sand	Total SO_3 content % by weight of cement	Compressive strength (MPa) at age of : Air curing			Water curing		
			7 days	28 days	56 days	7 days	28 days	56 days
OC_0	0.29	3.07	26.7	38.2	39.3	25.8	38.6	42.8
OC_1	0.5	3.355	27.0	39.0	40.8	26.8	39.5	44.1
OC_2	1.0	4.03	27.9	40.2	42.0	28.1	41.7	44.4
OC_3	1.5	4.70	18.5	34.2	38.4	19.7	35.6	40.3
SC_0	0.29	2.77	27.6	38.8	40.3	26.8	39.2	43.4
SC_1	0.5	3.055	30.0	40.0	41.5	30.9	42.4	44.9
SC_2	1.0	3.73	30.8	41.7	43.1	31.9	42.8	46.4
SC_3	1.5	4.41	23.7	37.5	40.2	24.7	38.0	43.1
OF_0	0.29	3.033	28.9	39.0	40.4	27.1	39.5	43.4
OF_1	0.5	3.28	30.0	40.0	41.5	29.1	40.3	44.3
OF_2	1.0	3.843	31.0	40.4	42.0	31.8	41.9	44.8
OF_3	1.5	4.42	18.0	32.0	37.1	19.4	34.2	41
SF_0	0.29	2.733	29.5	39.6	41.2	28.4	40.4	44.2
SF_1	0.5	2.973	32.3	41.3	43.2	32.7	42.9	45.3
SF_2	1.0	3.55	33.0	42.0	43.8	33.8	43.3	47.0
SF_3	1.5	4.12	23.3	37.1	40.0	24.4	37.4	43.5

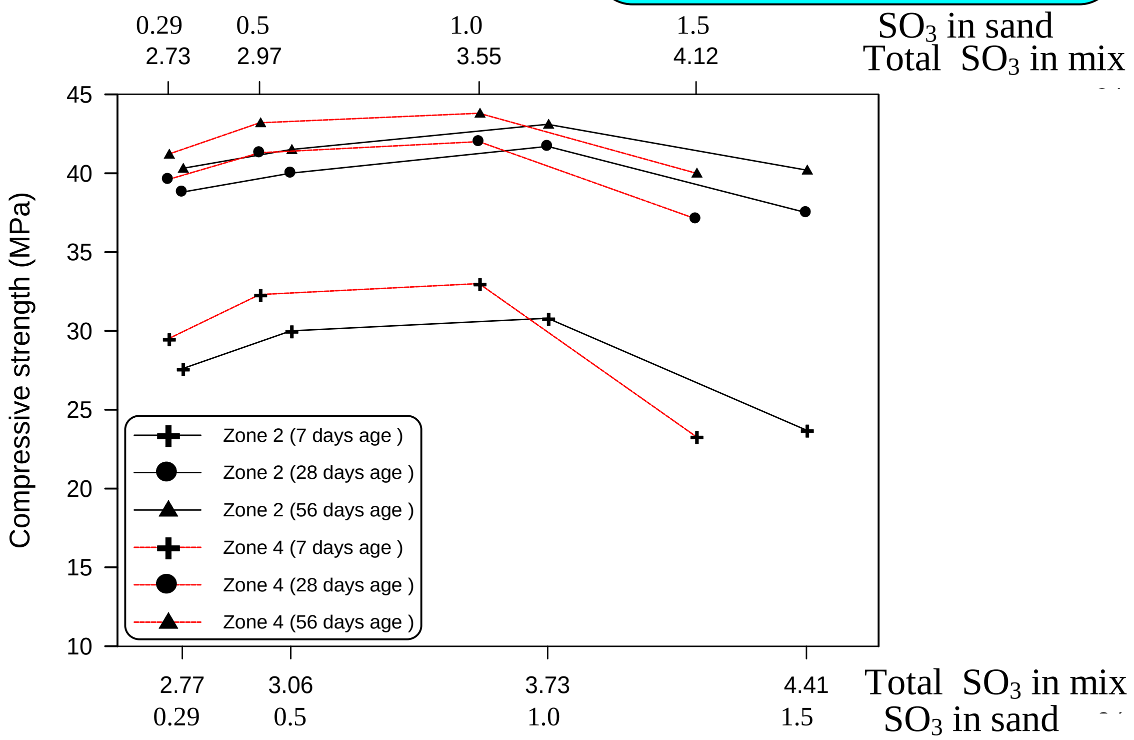
Note : Air curing means keeping the specimens out of water to the time of testing after three days of water curing .



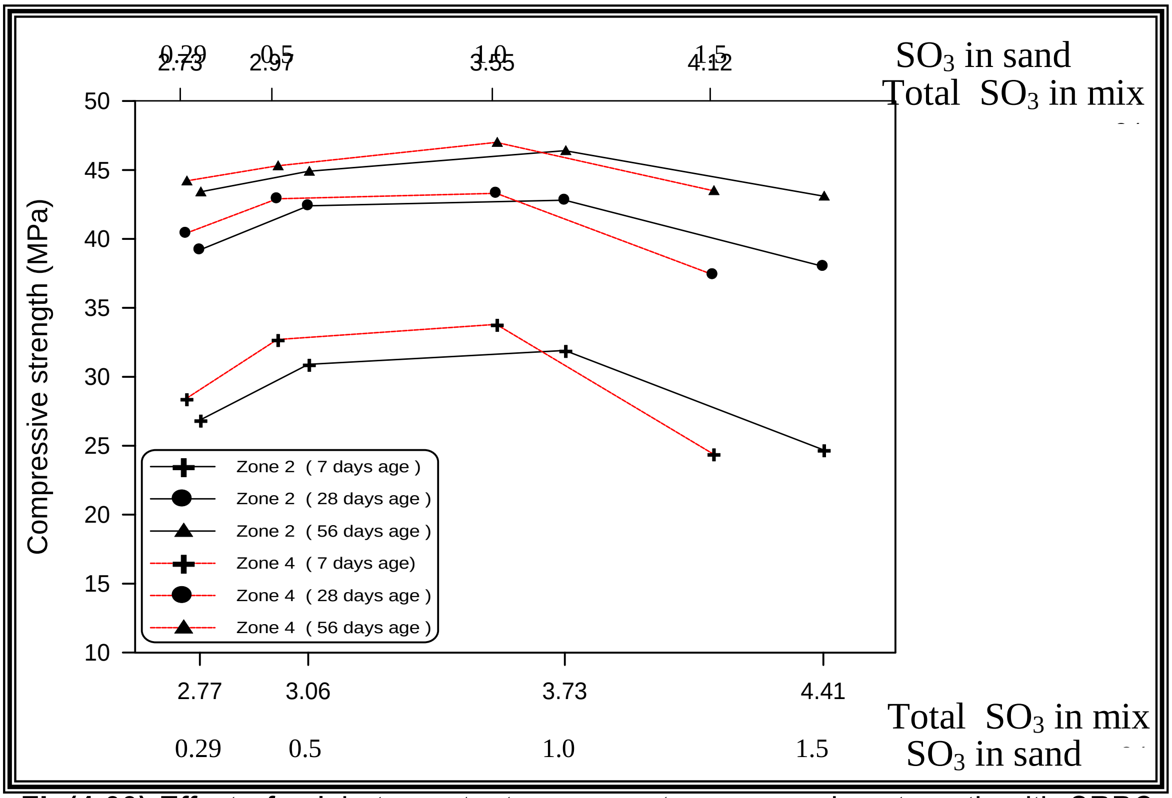
Fig(4-30): Effect of sulphate content on concrete compressive strength with OPC and moist cured for 3 days .



Fig(4-31): Effect of sulphate content on concrete compressive strength with OPC and moist cured until testing time.



Fig(4-32): Effect of sulphate content on concrete compressive strength with SRPC and moist cured for 3 days .



Fig(4-33): Effect of sulphate content on concrete compressive strength with SRPC and moist cured until testing time .

This was expected since several researchers [42,43,45,47] had referred to the presence of an optimum gypsum content. For example lerch

[43] reported that there is an optimum (SO_3) content for highest strength and lowest drying shrinkage. This conclusion is supported by Al-Rawi [42,45,47] who studied several factors that influence the value of optimum gypsum content. The increase in compressive strength of the concrete can be attributed to the ettringite formation which is produced by a chemical reaction between SO_3, C_3A and water. It fills some of the voids inside the cement past and increases the strength. But more ettringite formation induces internal stresses and decreases the compressive strength.

It can be noticed from the same Table and Figures that when using sand of zone 4 in concrete with OPC or SRPC, compressive strength increases with increasing the percentage of sulphate content up to the optimum value rather than when using sand of zone 2. This can be attributed to that the finer gypsum has a higher activity and thus faster formation of ettringite which yields denser impermeable and higher strength concrete. Beyond the optimum value of sulphate content, the compressive strength values become lower than that of concrete with sand of zone 2, this results agree with Al-Qaisi (54), but increasing the water curing period to 56 days may increases the compressive strength rather than that of mixes with sand of zone 2.

It is expected that the compressive strength will be improved when the concrete specimens are tested at later ages because of the subsequent autogenous healing.

The optimum SO_3 in this investigation is some what high because the tested concrete mixes were rich, consequently the amount of cement is large, and less sand is used. Hence, the amount of total sulphates, calculated as a ratio by cement weight, is less than that of lean and medium richness mixes, and this opinion agrees with references [4,81].

4.7 Splitting Tensile Strength

Results of the 28 and 56 days splitting tensile strength of concrete with various percentages of gypsum content in sand are shown in Table (4-5) for different mixes. It is clear that the effect of sulphate on the splitting tensile strength is some what similar to that on compressive strength. For all mixes, there is an optimum gypsum content at which the splitting tensile strength is maximum, beyond this content the splitting tensile strength has decreased.

4.8 Modulus of Elasticity

Table (4-6) presents the average modulus of elasticity for different mixes used in this study after 28 days moist curing. It is clear that the variation in modulus of elasticity with the variation of SO_3% content has the same trend as that for compressive strength. The presence of sulphates up to the optimum value of compressive strength means that more densification of material occurs. Therefore, the modulus of elasticity of concrete also increases. Further increase in SO_3 content above the optimum, resulted in internal cracks formation which decreases the strength and hence decreases the modulus of elasticity. This behavior is in line with Abood [50].

4.9 The Mathematical Regression Model

4-9-1 Introduction:

In order to obtain a mathematical model that can accurately predicts the shrinkage strain of concrete, the analysis of experimental data includes the regression analysis and the choosing of the best mathematical model that can be used to predict the shrinkage strain at the age of 3 up to 65 days.

The analysis has been carried out by the aid of a computer program package called "STATISTICA 5.0", this program includes extensive statistical operations and regression and analysis capabilities.

Several combinations of groups of variables were used in order to obtain the best regression model that can predict shrinkage strain with high accuracy.

The results obtained from the experimental work for 32 different concrete specimens are listed in Tables (A-1) to (A-8) in Appendix (A).

4-9-2 Choosing of Mathematical Regression Model

The regression methods were designed to fit function that minimize the sum of the residual squares between the data and the fitted function. Such methods are termed least-squares regression. Linear least-squares regression is used where dependent and independent variables are related to each other in a linear fashion [82].

The general form of such relationship is:

$$y = a_o + a_1 x_1 \tag{4-1}$$

When a depended variable is a linear function of two or more independent variable, multiple linear regression is utilized [83]

$$y = a_o + a_1 x_1 + a_2 x_2 + a_3 x_3 + \dots + a_m x_m \tag{4-2}$$

Equation (4-2) can be transformed to multivariable non-linear equation of the type:

$$y = a_o + a_1 x_1^{b1} + a_2 x_2^{b2} + a_3 x_3^{b3} + \dots + a_m x_m^{bm} \tag{4-3}$$

In this study, the multivariable non-linear equation was found to be very suitable for predicting shrinkage strain as the relationship between the dependent and independent variables is a non-linear one.

To consider the effect of the drying period on the shrinkage strain of concrete, the variables in equation (4-3) are multiplied by the drying period (t)

$$y(t) = a_o + \left(a_1 x_1^{b1} + a_2 x_2^{b2} + a_3 x_3^{b3} + \ldots + a_m x_m^{bm}\right) t \qquad (4\text{-}4)$$

Table (4-9) shows the relation between the shrinkage strain at different ages and selected variables that are going to be used in the proposed model. This relation is presented by the correlation coefficient between each variable and the shrinkage strain. From this table also, it can be seen that the highest significant correlation are with the fineness of cement followed by the gravel content, this significant correlations were for the drying period from 3 up 65 days

Table (4-9): Correlation coefficient between shrinkage strain and the variables used in the proposed model .

Variable used	Symbol	Correlation coefficient (R)
Curing time	**CT**	0.439
Sulphate content	**SO_3**	0.596
Tricalcium aluminate	**C_3A**	0.545
Fineness modulus	**FM**	0.564
Cement / sand ratio	**C/S**	0.794
Water /sand ratio	**W/S**	0.519
Sand content	**S**	0.845
Gravel content	**G**	0.860
Specific surface for cement	**SS**	0.874

Many attempts have been made to introduce other variables such as:

1- SO_3 / C_3A, W/C , S/G

2- Initial setting time and final setting time.

3- C_4AF, MgO

After analyzing these variable by using the model that comprises them, it was found that there is no significant improve in correlation of the proposed model, moreover, the existing variables in the proposed model, yielded good and reasonable results. Also, it is not preferred to load the mathematical model with a large number of variables, because the favorite model is with a lesser number of variables and higher possible accuracy to assure the rapid and easy use of the model.

The final form of the proposed model with the variables used was:

$$S_H = \lfloor a_o + \left(a_1 CT^{(a_1 - a_2 \times t)} + a_3 SO_3^{(a_3 - a_4 \times t)} + a_5 C_3 A^{(a_5 - a_6 \times t)} + a_7 FM^{(a_7 - a_8 \times t)} + a_9 (C/S)^{(a_9 - a_{10} \times t)} + a_{11} (W/S)^{(a_{11} - a_{12} \times t)} + a_{13} S^{(a_{13} - a_{14} \times t)} + a_{15} G^{(a_{15} - a_{16} \times t)} + a_{17} SS^{(a_{17} - a_{18} \times t)}\right).t \rfloor 10^{-6}$$

where;

FM = Fineness modulus of sand,
C/S = Cement to sand ratio,
W/S = Water to sand ratio,
S = Sand content (kg/m^3),
G = Gravel content (kg/m^3), and
SS = Specific surface area of cement (m^2/kg).

The range of the difference (df) between the actual and predicted shrinkage was calculated for each model within confidence interval of 0.95. This means that there is a probability of 95% of the difference between the actual and the predicted shrinkage falls within a range of $\pm dfx10^{-6}$,thus Actual shrinkage = predicted shrinkage $\pm dfx10^{-6}$.

Table (4-10) gives the regression coefficient for the prediction models and the value of correlation coefficients ®, as well as the range of the difference (df) between the actual and predicted shrinkage. In this Table several notes have to be pointed out:

1- S and G were taken together.
2- SO_3 and C_3A where taken as one group.

Table (4-10): Regression coefficients for the free shrinkage prediction models .
.

Variable	Coefficient	Model 1	Model 2	Model 3	Model 4
	a_o	-87.3515	27.8538	25.5544	22.8188
CT	a_1	0.1119	0.0179	0.462	0.0013
	a_2	0.0271	0.0226	0.0437	-0.0182
SO_3	a_3		0.0197	0.0252	0.0297
	a_4		-0.0347	-0.0328	-0.0306
C_3A	a_5		0.8613	0.8716	0.8386
	a_6		0.0057	0.006	0.0056
FM	a_7				1.0055
	a_8				0.0026
C/S	a_9	0.5757		-0.4144	2.4602
	a_{10}	0.0639		-0.0716	-0.1622
W/S	a_{11}	0.7345	0.4227	0.6368	-0.0014
	a_{12}	-0.0045	0.0219	0.018	0.0902
S	a_{13}	0.6722			0.4927
	a_{14}	0.0282			0.002
G	a_{15}	0.5602			0.4728
	a_{16}	0.0024			0.0068
SS	a_{17}	0.4497	0.6283	0.6276	-0.0771
	a_{18}	0.0068	0.0036	0.0036	0.0098
R		**0.921**	**0.942**	**0.958**	**0.987**
df $*10^{-6}$		**± 97.2**	**± 85.4**	**± 76.15**	**± 60.13**

From this Table, it can be seen that the correlation coefficient increases slightly with increasing the number of variables used in the proposed model. In the fourth model the chemical effect of SO_3 and C_3A taken in to account with the physical effect of the mix proportion which is presented by C/S, W/S, S and G and the properties of the material used which are presented by Fm and SS, as well as the effect of curing time (CT) and drying period (t) taken in account too.

Table (4-11) gives the difference ranges for the proposed models for different confidence intervals.

Table (4-11): Confidence intervals and difference ranges for the proposed models.

Confidence interval %	Difference interval $*10^{-6}$			
	Model 1	Model 2	Model 3	Model 4
50	±37.43	±32.59	±26.08	±20.10
75	±60.06	±56.52	±50.99	±35.00
90	±81.61	±72.24	±67.71	±50.37
95	±97.20	±85.40	±76.15	±60.13

4-9-3 Checking the Proposed Model

To check the validity of the proposed model to predict the shrinkage strain of concrete dried for periods of 3 up to 65 days, 16 specimens of concrete were tested. The concrete beam specimens contain sand with different levels of sulphates, and they were kept at a moist curing condition for different periods. OPC and SRPC with sand of Zone 2 and Zone 4 were used. Table (4-12) gives the properties of the mixes used for checking.

Table (4-12): Properties of mixes used for checking the proposed model

No.	Type of cement	Cement content	Sand content	Gravel content	Curing period (days)	Sand gradation (zone)	SO_3 in sand % (by	total SO_3 in mix %

							weight)	(by weight)
1	OPC	475	644	968	3	2	0.25	2.437
2	OPC	475	542	1068	28	4	0.5	2.69
3	OPC	475	542	1068	3	4	0.75	2.975
4	OPC	475	644	968	28	2	1.0	3.45
5	OPC	475	644	968	3	2	1.25	3.787
6	OPC	475	542	1068	28	4	1.5	3.83
7	OPC	475	542	1068	3	4	1.75	4.115
8	OPC	475	644	968	28	2	2.0	4.8
9	SRPC	475	644	968	3	2	0.25	2.397
10	SRPC	475	542	1068	28	4	0.5	2.65
11	SRPC	475	542	1068	3	4	0.75	2.935
12	SRPC	475	644	968	28	2	1.0	3.41
13	SRPC	475	644	968	3	2	1.25	3.747
14	SRPC	475	542	1068	28	4	1.5	3.79
15	SRPC	475	542	1068	3	4	1.75	4.075
16	SRPC	475	644	968	28	2	2.0	4.76

Note : W/C ratio for all mixes was 0.48

The details of the properties of the material used are given in Table (B-1) to (B-7) in Appendix (B).

The fourth model was used to predict the shrinkage strain after drying periods of 30, 45 and 60 days for the concrete specimens in question.

Table (4-13) gives the observed and predicted shrinkage strain at these three drying periods. The maximum difference between the observed and predicted shrinkage is about $\pm 56 \times 10^{-6}$. Thus, it may be concluded that the present model is appropriate to predict the shrinkage strain with a good accuracy.

Table (4-13) : Observed and predicted shrinkage strain at ages of 30,45 and 60 days using the fourth model

No.	observed shrinkage strain	predicted shrinkage strain

	*10^-6			*10^-6		
	30 days	45 days	60 days	30 days	45 days	60 days
1	582	684	710	543.96	646.86	702.56
2	560	658	677	525.63	617.72	671.86
3	558	653	674	525.70	617.80	671.54
4	522	625	681	544.94	650.55	713.79
5	526	630	690	545.04	650.88	714.55
6	478	575	640	526.54	621.18	682.39
7	492	595	650	526.60	621.38	682.87
8	560	686	715	546.00	655.06	729.09
9	495	580	610	458.94	543.47	592.44
10	460	550	591	440.62	514.32	561.71
11	446	530	570	440.68	514.40	561.35
12	443	525	565	459.92	547.14	603.57
13	450	535	570	460.02	547.46	604.28
14	430	510	545	441.52	517.76	572.13
15	480	567	614	441.58	517.96	572.57
16	506	600	650	460.98	551.63	618.73

4-9-4 Comparison with Other Models

1- ACI 209 R-92 Model [9]

$$\varepsilon_{sh}(t) = \frac{t}{t+35} \times \varepsilon_{sh}\alpha$$

$$\varepsilon_{sh}\alpha = 780 \times 10^{-6} \times k$$

where: k = correction factor.

More details about this model are presented in Appendix (C).

2-Sakata Model as cited by Ref [11]

$$\varepsilon_{sh}(t,to) = \varepsilon_{sh}\alpha\left[1 - \exp(-0.108)(t-to)^{0.56}\right]$$

$$\varepsilon_{sh}\alpha = \left[-50 + 78(1 - \exp(RH/100) + 38(\ln(w)) - 5(\ln(v/s))/10^{2})\right]10^{-5}$$

More details about this model were presented in appendix [D]

The data of the same 16 specimens of concrete that is used for checking the proposed model, has been used with ACI 209 R-92 model and sakata model to predict the shrinkage strain after drying periods of30, 45and 60 days. Table (4-14) gives the predicted values of shrinkage by using the above models. From this Table and Table (4-13), it can be seen that the equations of the type of the proposed model have a lower difference between the observed and predicted values than that of the other equations. This may be due to the appropriate selection of the variables considered in the proposed model and the right selection of the mathematical model.

Table (4-14) : Predicted shrinkage strain at ages of 30,45 and 60 days using ACI model and Sakata model.

No.	predicted shrinkage strain $*10^{-6}$ by using ACI model			predicted shrinkage strain $*10^{-6}$ by using Sakata model		
	30 days	45 days	60 days	30 days	45 days	60 days
1	483	588.7	661	569	659	725
2	340	413.8	464.6			
3	434.3	529.3	594.3			
4	372	452.5	508			
5	473.4	577	647			
6	340	413.8	464.6			
7	429.8	523.9	588.18			
8	370.1	451.1	507			
9	473.4	577	648			
10	344	418.7	470.1			
11	429.8	523.9	588.18			
12	372	452.5	508			
13	473.4	577	647			
14	340	413.8	464.6			
15	429.8	523.9	588.18			
16	370.1	451.1	507			

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 5

5.1 Conclusions

The present work is an attempt to study the influence of sulphate content, sulphate fineness and curing period on the shrinkage strain and other concrete properties. - Shaped molds have been used for the determination of shrinkage strain, tensile strain capacity, elastic tensile strain capacity, creep and cracking time of concrete. On the basis of the observations made in the present work, the following conclusions can be drawn:

1- The presence of sulphates in percentages up to 1.5% (by weight of sand) plays an important role in decreasing shrinkage strain at early ages. In the first 3 days drying the reduction was about 54.3% and 57.6% for 3 and 28 days moist curing respectively for concrete with OPC and sand of zone 2 and about 50% and 51.5% respectively when SRPC is used. The reduction of shrinkage strain was about 61.0% and 66.18% for 3 and 28 days moist curing respectively for concrete with OPC and sand of zone 4, and it was about 56.4% and 65.0% respectively when SRPC is used with this gradation of sand. But the shrinkage increases at later ages with increasing the sulphate content to 1.5 percent (by weight of sand).

2- The optimum sulphate content which gives maximum compressive strength and minimum shrinkage strain in mixes with OPC is higher than that of mixes with SRPC, where the total SO_3 in mixes by weight of cement are 4.03% and 3.73% respectively when sand of zone 2 is used, while the total SO_3 are 3.84% and 3.55% respectively when using sand of zone 4. This can be attributed to the low C_3A content in the SRPC.

3- The optimum sulphate content in mix with OPC and sand of zone 2 is higher than that of mix with OPC and sand of zone 4, where the total SO_3 in mix by weight of cement was 4.03% and 3.84% respectively.

4- Increasing the curing period from 3 to 28 days decreases the shrinkage strain of concrete which contains a percentage of sulphate lower than or equal to the optimum value and increases it at higher values.

5- The cracking time is delayed with increasing the percentage of sulphate content up to the optimum value of sulphates, and then it speeds up at the higher values of sulphate.

6- 28 days moist curing increases the cracking time of concrete. It is much better than 3 days moist curing as results in continuous cement reaction and provides on amount of expansion of restrained concrete which must be relieved by subsequent drying shrinkage. Therefore this leads to eliminate or minimize the occurrence of cracking.

7- The free shrinkage strain at cracking time increases with increasing the percentage of sulphate content in sand (by weight) and with increasing the curing period.

8- The tensile strain capacity of the concrete mixes increases with increasing the sulphate content. Also, when the curing period increases, the tensile strain capacity increases too.

9- Increasing the fineness of sulphates in concrete mixes containing OPC decreases the effect of curing period on the tensile strain capacity associated with increasing the sulphate, while increasing the fineness of sulphates in concrete mixes containing SRPC enhances the effect of curing period on the tensile strain capacity associated with increasing the sulphate content.

10- Increasing the curing period increases the elastic tensile strain capacity of concrete, but with different rates of increase from one mix to another. This is in line with Al-Rawi [25].

11- The creep strain of the concrete mixes (at cracking time) increases with increasing the sulphate content. Also, when the curing period increases, the creep strain (at cracking time) increases too and this increment is more pronounced when concrete with SRPC and sand from zone 2 is used.

12- Generally, the crack width development decreases with increasing the sulphate content in sand up to an optimum values, and beyond this value the crack width development speeds up.

13- For all mixes, there is an optimum gypsum content at which the compressive strength of concrete is maximum and shrinkage is minimum. This is in line with previous works [43, 50].

14- The percentage reduction in compressive strength of OC_3 (the mix with OPC and sand of zone 2 which contains sulphate of 1.5% by weight of it) compared with the reduction in strength of OF_3 (the mix with OPC and sand of zone 4 which contains sulphate of 1.5% by weight of it) at ages 7, 28 and 56 days was (30.86%-37.7%), (10.47%-17.9%) and (2.29%-8.16%) for air curing and (23.6%-28.4%), (7.7%-13.4%) and (5.8%-5.5%) for moist curing, while the percentage reduction in compressive strength of SC_3 (the mix with SRPC and sand of zone 2 which contains sulphate of 1.5% by weight of it) compared with the reduction in strength of SF_3 (the mix with SRPC and sand of zone 4 which contains sulphate of 1.5% by weight of it) at ages 7, 28 and 56 days was (14.13% - 21%), (3.3%-6.3%) and (0.25%-2.9%) for air curing and (8%-14%), (3.06%-7.4%) and (0.7-1.58%) for moist curing.

15- The influence of sulphates on the splitting tensile strength and static modulus of elasticity is found to be some what similar to that of compressive strength.

16- An accurate mathematical model to predict shrinkage strain can be proposed by using the curing period, sulphate content, C_3A content, fineness modulus, cement / sand ratio, water /sand ratio, sand content, gravel content , specific surface for cement and drying period. The correlation coefficient (R=0.987) and minimum value of the difference (df = ± 60.13 x 10^{-6}) which was obtained when the model included all these variables.

5.2 Recommendations for Further Work

1- Studying the effect of other types of sulphates which can be present in the aggregates such as sodium sulphate and magnesium sulphate rather than gypsum on the shrinkage strain and concrete strength.

2- Monitoring the rate of reaction of internal sulphates in concrete by the measurement of the amount of ettringite formation.

3- Increasing the curing period more than 28 days (60 days) or using the accelerated process to ensure depletion of the sulphate content by the chemical reaction.

4- Studying the effect of changing the compound composition of OPC (C_3S, C_2S, C_3A and C_4AF) on the relationship between the internal sulphate attack and the drying shrinkage.

5- The effects of sulphate with superplasticizer on drying shrinkage cracking are needed to be investigated.

6- Improving the proposed model by introducing other variables that influence the shrinkage strain such as relative humidity and the degree of temperature as they have an important effect on shrinkage strain.

7- Improving the accuracy of the present model .i.e improving the correlation coefficient value to decrease the difference between the observed and predicted shrinkage strain.

FREE SHRINKAGE FROM THE EXPERIMENTAL WORK

APPENXID A

Table (A-1): Experimental free shrinkage strain of concrete containing OPC and sand from zone 2 with different sulphate contents, (3 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	162	115	85	74
7	296	255	222	216
15	412	371	343	354
25	539	496	459	488
35	610	578	538	567
45	655	634	608	624
55	681	665	640	667
65	692	680	654	684

Table (A-2): Experimental free shrinkage strain of concrete containing OPC and sand from zone 2 with different sulphate contents, (28 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	151	110	79	64
7	272	218	196	195
15	401	363	327	357
25	539	488	451	504
35	600	572	535	586
45	648	626	604	640
55	676	658	634	677
65	685	666	644	700

Table (A-3): Experimental free shrinkage strain of concrete containing SRPC and sand from zone 2 with different sulphate contents, (3 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	140	100	75	70
7	267	230	203	200
15	361	323	304	328
25	464	429	417	441
35	529	496	475	505
45	579	534	522	541
55	605	570	552	574
65	618	588	565	593

Table (A-4): Experimental free shrinkage strain of concrete containing SRPC and sand from zone 2 with different sulphate contents, (28 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	130	91	68	63
7	264	217	194	192
15	354	313	294	330
25	460	421	397	463
35	525	490	466	550
45	576	549	516	600
55	599	575	547	628
65	615	582	556	648

Table (A-5): Experimental free shrinkage strain of concrete containing OPC and sand from zone 4 with different sulphate contents, (3 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	154	105	72	60
7	290	244	208	210
15	399	364	332	356
25	508	480	443	498
35	596	563	512	591
45	630	623	570	635
55	660	654	615	665
65	670	664	628	682

Table (A-6): Experimental free shrinkage strain of concrete containing OPC and sand from zone 4 with different sulphate contents, (28 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	139	95	63	47
7	257	203	179	182
15	384	347	310	359
25	505	473	432	507
35	591	557	505	600
45	635	615	575	645
55	660	636	612	670
65	669	645	621	684

Table (A-7): Experimental free shrinkage strain of concrete containing SRPC and sand from zone 4 with different sulphate contents, (3 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	133	90	65	58
7	259	219	193	198
15	345	307	292	334
25	429	412	400	451
35	510	483	462	520
45	550	534	507	560
55	575	565	536	585
65	595	582	550	605

Table (A-8): Experimental free shrinkage strain of concrete containing SRPC and sand from zone 4 with different sulphate contents, (28 days moist curing).

Drying period (days)	Free shrinkage strain (10^{-6})			
	SO_3 = 0.29%	SO_3 = 0.50%	SO_3 = 1.00%	SO_3 = 1.50%
3	120	77	52	42
7	246	207	181	195
15	336	297	280	345
25	422	402	390	460
35	507	477	454	540
45	555	530	500	598
55	587	561	530	632
65	605	572	540	657

APPENXID B

EXPERIMENTAL DATA

Table (B-1): Physical properties of the OPC used.

Physical Properties	Test Results	1.Q.S.5 : 1984 [69]Limits
Fineness, Blaine, m^2/kg	305	≥ 230
Setting, time, Vicat's method Initial hrs: min Final hrs: min	 3:0 5:0	 ≥0:45 ≤10:0
Compressive strength of 70.0 mm Cube, MPa 3 days 7 days	 20.7 29.6	 ≥15 ≥23

Table (B-2): Chemical composition of the OPC used.

Oxide	(%)	1.Q.S.5 : 1984 [69]Limits
CaO	62.2	-
SiO_2	21.62	-
Fe_2O_3	3.6	-
Al_2O_3	5.1	-
MgO	2.8	≤5.0
SO_3	1.94	≤2.8
Free Lime	0.72	-
L.O.I	2.57	≤4.0
I.R (Insoluble Residue)	0.4	≤1.5
Compound composition	(%)	1.Q.S.5: 1984 [69] Limits
C_3S	41.03	-
C_2S	31.03	-
C_3A	7.42	-
C_4AF	10.95	-
L.S.F	0.88	0.66-1.02

Table (B-3): Physical properties of the SRPC used.

Physical Properties	Test Results	1.Q.S.5: 1984 [69] Limits
Fineness, Blaine, m^2/kg	328	≥250
Setting time, vicat's method Initial hrs: min Final hrs: min	 2:10 3:40	 ≥0:45 ≤10:0
Comprf 70.0 mm cube, MPaessive strength o 3 days 7 days	 22 29.2	 ≥15 ≥23

Table (B-4): Chemical composition of the SRPC used.

Oxide	(%)	1.Q.S.5 : 1984 [69] Limits
CaO	63.4	-
SiO_2	21.72	-
Fe_2O_3	5.2	-
Al_2O_3	3.44	-
MgO	1.68	≤5.0
SO_3	1.9	≤2.5
Free Lime	0.74	-
L.O.I	2.2	≤4.0
I.R (Insoluble Residue)	0.36	≤1.5
Compound composition	(%)	1.Q.S.5: 1984 [69] Limits
C_3S	54.05	-
C_2S	21.5	-
C_3A	0.31	≤3.5
C_4AF	15.82	-
L.S.F	0.9	0.66-1.02

Table (B-5): Properties of the sand from zone (2).

Sieve size (mm)	Percent passing	I.Q.S.45: 1984 [70] Limits Zone (2)
9.5	100	100
4.75	98	90-100
2.36	84	75-100
1.18	75	55-90
0.6	56	35-59
0.3	27	8-30
0.15	6	0-10
0.075	1	5
Properties	Test Results	I.Q.S.45: 1984 [(70)] Limits
Sulphate content (SO_3) %	0.25	$\leq$0.5
Fineness modulus	2.54	
Specific Gravity	2.58	
Absorption %	0.70	

Table (B-6): Properties of the sand from zone (4).

Sieve size (mm)	Percent passing	I.Q.S.45: 1984 [70] Limits Zone (4)
9.5	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	86	80-100
0.3	25	15-50
0.15	2.4	0-15
0.075	1.6	5
Properties	Test Results	I.Q.S.45: 1984 [70] Limits
Sulphate content (SO_3) %	0.25	$\leq$0.5
Fineness modulus	1.87	
Specific Gravity	2.58	

Table (B-7): Properties of the gravel.

Sieve size (mm)	Percent passing	I.Q.S.45: 1984 [70] Limits
37.5	100	-
20	100	100
12.5	100	90-100
9.5	70.5	50-85
4.75	7.5	0-10
Properties	**Test Results**	**I.Q.S.45: 1984 [70] Limits**
Sulphate content (SO_3) %	0.08	$\leq$0.1
Density kg/m^3	1690	-
Specific gravity	2.61	-
Absorption (%)	0.5	-

THE MATHEMATICAL REGRESSION MODELS

APPENXID C

1- ACI 209R-92 Model

For normal curing

$$ACI_t = \frac{t}{t+35} 780 \times 10^{-6} k$$

where

$k = k_1\ k_2\ k_3\ k_4\ k_5\ k_6\ k_7$

k_1=Table (C1)

Table (C1) K1 and curing time

Curing time	K_1
1	1.2
3	1.1
7	1
14	0.93
28	0.86
90	0.75

K_2=(1.4-0.01 H) if 40%≤H≤80%

=(3.0-0.01 H) if 80%≤H≤100%

K_3=Table (C2) if v/s ≤ 37.5 mm

Table (C2) K3 and v/s ratio

v/s	K_3
12.5	1.35
19	1.25
25	1.17
31	1.08
37.5	1.00

K_4=0.89+0.00264 S

$K_5=0.3+0.014\dfrac{Af}{Atotal}100 \;\text{ if }\; \dfrac{Af}{Atotal}\leq 50\%$

$=0.9+0.002\dfrac{Af}{Atotal}100 \;\; if \;\; \dfrac{Af}{Atotal}\geq 50\%$

K_6=0.75+0.00061 Cc

K7=0.95+0.008Ac

Where

t=Drying time in (days)

k=The product of all the correction factors $k_1 x k_2 x k_3 x k_4 x k_5 x k_6 x k_7$.

H=Ambient relative humidity

v/s=volume to surface ratio

S=slump of fresh concrete

Af=fine aggregate content.

Atotal=Total aggregate content.

Cc=Cement content kg/m^3

Ac=Air content%

2- Sakata Model.

$$\varepsilon_{sh}(t,t_o)=\varepsilon_{sh}\left[1-\exp\left\{(-0.108)(t-t_o)^{0.56}\right\}\right]$$

$$\varepsilon_{sh}\alpha=\left[-50+78\left(1-\exp\left(\frac{RH}{100}\right)\right)+38\left(\ln(w)-5\left(\frac{\ln(v/s)}{10}\right)^2\right)\right]\times10^{-5}$$

where;

$\varepsilon sh(t,t_o)$=predicted shrinkage strain.

$\varepsilon_{sh}\alpha$=ultimate shrinkage strain.

W=water content of concrete (kg/m^3).

RH = relative humidify (%)

v/s = Volume – to – surface area ratio.

t = time (days)

t_o=time drying started (days).

REFERENCES

1- Troxell, G.E., Davis, H.E. and Kelly , J.W., “***Composition and Properties of Concrete***”, Mc Graw – Hill , 2nd Edition , 1968.

2- Buchanan, P.M., “***Shrinkage of Latex- Modified and Microsilica Concrete Overlay Mixtures***”, M.Sc. Thesis, Blacksburg , Virginia , May. 2002 . بواسطة شبكة الانترنيت

3- Neville, A.M., “***Properties of Concrete***”, Fourth and Final Edition , Wiley , New York and Longman , London, 1995.

4- Lea , F.M., “***The Chemistry of Cement and Concrete*** ”, 3rd .Edition Edward Arnold Ltd. ,1976.

5- السامرائي . مفيد "***مقترح تحديد نسبة الأملاح في الرمل***"، المركز القومي للمختبرات الإنشائية ،، منشور في مجلة البناء الحضاري العدد(1) السنة الأولى .

6- رؤوف ،زين العابدين "***الرمال العراقية***" ، مركز بحوث البناء ,تشرين أول 1970 .

7- Lerch, William, “***Plastic Shrinkage***”, ACI Journal Proceeding V.53, N0.8, 1957.

8- ACI Committee 305, "***Hot Weather Concreting***", American Concrete Institute, 1991.

9- ACI Committee 209R-92, “ ***Prediction of Creep , Shrinkage and Temperature Effect in Concrete Structures***", ACI Manual of concrete Practice, Part 1, 1996.

10- Powers , T.C. and Brownyard , T.L, “ ***Studies of the Physical Properties of Hardened Portland Cement Past***", Proceeding of the ACI, V.43, October – December . 1946 .

11- Mokarem ,D.W., “***Development of Concrete Shrinkage Performance Specifications***", Ph.D Dissertation , civil and Environmental Engineering , Blacksburg , Virginia , May,2002. . بواسطة شبكة الانترنيت

12- Davis , H.E., “ ***Autogenous Volume Change of Concrete***", proc. of ASTM , 40 , (1940) , pp.1103.

13- Houk , I.E., Borge, O.E. and Houghton , D.L. "***Studies of Autogenous Volume Change in Concrete for Dworshak Dam***", J.Amer . Concr . Inst, 66 , July. 1969 , pp .560 .

14- Han ,N., Walraven ,J.C., "***Creep and Shrinkage of High – Strength Concrete at Early and Normal Ages***", (Citet by Ref. 11).

15- Pickett , G., " ***Effect of Aggregate on Shrinkage of Concrete and a Hypothesis Concerning Shrinkage***", ACI Journal , V.52 , No.1 , Dec. 1956 , pp.581-590 .

16- Neville, A.M. and Brooks, J.J., "***Concrete Technology***", First Edition , Longman Scientific and Technical , 1987, London .

17- Almudaheem, Jamal A., and Hansen , will , "***Effect of Specimen Size and Shape on Drying Shrinkage of Concrete***", ACI Materials Journal , V.84 , No.2 . 1987 .

18- ACI Committee 224, "***Control of Cracking in Concrete Structure*** ", concrete international , V.2 , No.10 , Oct . 1980 .

19- Carlson , R.W., ***" Drying Shrinkage of Concrete as Affected by Many Factors***", proceedings ASTM , V. 35 , part 11 , 1935 , pp. 350.

20- Carlson , R.W., Houghton , D.L. and polivka , M., ***" Causes and Control of Cracking in Unreinforced Mass Concrete***", ACI Journal , V. 76 ,No.7 , July .1979.

21- Alsayed , S.H., "***Effect of Curing Condition on Strength , Porosity , Absorptivity , and Shrinkage of Concrete in Hot and Dry Climate***", Cement and Concrete Research , V.24 , No.7 , 1994 , (Citet by Ref.11).

22- Tremper , B. and Spellman, D.L., "***Shrinkage of Concrete – Comparison of Laboratory and Field Performance***" ,Highway Research Record No.3, Highway Research Board , 1963 . pp 30-61.

23- Al-Nassar , W.A.A., " ***Effect of Some Admixtures on The Shrinkage of Concrete***", M.Sc. Thesis , University of Baghdad , College of Engineering , November. 2002.

24- Shah, S.P., Karaguler , M.E., and Sarigaphuti , M., "***Effects of Shrinkage Reducing Admixtures on Restrained Shrinkage Cracking of Concrete***" , ACI materials Journal , V.89 , No.3 , 1992 , pp. 291-295. (Cited by Ref. 11).

25- Al- Rawi , R.S, "***New Method of Determination of Tensile Strain Capacity and Related Properties of Concrete Subjected to Restrained Shrinkage***", ACI symp . singapore , Aug . 1985.

26- Samman, T.A., Mirza, W.H., and Wafa,F.F. "***Plastic Shrinkage Cracking of Normal and High – Strength : A Comparative Study***" ,ACI materials Journal ,V.93 , No.1 , January-February. 1996.

27- ACI Committee 207, "***Effect of Restraint, Volume Change and Reinforcement on Cracking of Massive Concrete***" ,ACI manual part (1).1980.

28- Hughes, B.P. and Ghunaim, F., " ***An Experimental Study of Early Thermal Cracking in Concrete***", Magazine of Concrete Research , V.34 , No.118 , England, March 1982 , pp.18-24 .

29- Al- Rawi , R.S " ***Laboratory Tests on Small Beams to Study Shrinkage Cracking in Continuously Reinforced Concrete Pavement***" , Transportation Research Board , Annual Meeting , Washington , D.C., U.S.A. January 1986, pp.24 .

30- Al-Rawi, R.S. and Kheder ,G.F., " ***Control of Cracking due to Volume Change in Base – Restrained Concrete Members***" , ACI – structural Journal , July – August 1990 , pp. 397-405 .

31- Kadhum, M.M., "***Drying Shrinkage of Concrete Slabs Subjected to Fire***", M.Sc .Thesis, University of Babylon , College of Engineering , July 2003 .

32- Alexander ,K.M., Wardlaw , J. and Ivanusec , I., " ***The Influence of SO_3 Content of Portland Cement on The Creep and Other Physical Properties of Concrete***", Cement and Concrete Research , V.9 , 1979 , pp. 451-459.

33- Houk , I.E., paxton , J.A. and Houghton , D.L., "***Prediction of Thermal Stress and Strain Capacity of Concrete by Tests on Small Beams***", ACI Journal, V.67 , March 1970, pp.253-261 .

34- Lee, C.R., and Lamb, W. "***Effect of Various Factor on The Extensibility of Concrete***", Building Research Establishment (London) , Jan. 1976 , pp. 11 .

35- B.S. code 5337. 1982 (Amendment 2)

36- الحربي , موفق و آخرون , "***نسبة الأملاح الكبريتية في الخرسانة وتعديل المواصفة العراقية 45***" , وزارة الإسكان و التعمير , المركز القومي للمختبرات الإنشائية , بغداد , تشرين الثاني , 1993 .

37- Tian , B., and Cohen , M., 2000, "***Does Gypsum Formation During Sulfate Attack on Concrete Lead to Expansion ?***", Cement and concrete Research , No. 30 .

38- Rasheeduzzafar, "***Influence of Cement Composition on Concrete Durability***", ACI Material Journal, Nov- Dec. 1992, pp. 574 – 585.

39- Mansour, M. H., "***The Effect of Sulphates on The Physical Properties and Geometrical Changes of Concrete***", M.Sc Thesis, University of Baghdad, College of Engineering, 1976.

40- Ali, N.H , "***Effect of Sulphates Content on Concrete with Different Gypsum Content Cements***" , M.Sc Thesis, University of Baghdad , College of Engineering , 1981 .

41- Shallal, A.S., "***A Study of Cement Retarders Related to Internal Sulphate Attack***", M.Sc Thesis, University of Baghdad, College of Engineering, 1989.

42- Al- Rawi R.S., "***Gypsum Content of Cements Used in Concrete Cured by Accelerated Methods***", Journal of Testing and Evaluation V.5, No.3, May 1977, pp. 231-236.

43- Lerch, W., "***The Influence of Gypsum on the Hydration and Properties of Portland Cement Pastes***", ASTM proc, V. 46, 1946.

44- Salman , M.M., " ***The Effect of Addition of Some Local Materials on the Dimensional Changes and Cracking of Concrete***", M.Sc Thesis , University of Baghdad , College of Engineering , 1987.

45- Al- Rawi, R.S and Abdul - Latif A. M., ***" Compatibility of Sulphate Contents in Concrete Ingredients***", Fourth Scientific Conference , College of Engineering of Baghdad University , 1998 .

46- Mater , S.G., " ***Resistance of Steel Fiber Reinforced Concrete to Internal Sulfates Attack***", M.Sc Thesis , University of Baghdad , College of Engineering , 2000.

47- Al- Rawi , R.S., Ali , N.H.M ., shalal , A.R., Al . Salihi , R.A., " ***Effective Sulphate Content in Concrete Ingredients***" , Fourth Scientific Conference , College of Engineering , University of Baghdad , 1998.

48- Abdule Latif A .M ., "***Compatibility of Sulphate Content in Concrete Ingredients***", M.Sc Thesis , University of Baghdad , College of Engineering , 1997.

49- Yousfani , N.A., ***" The Effect of Sulphates on Concrete Under Sustained Load***" , M.Sc Thesis , University of Baghdad , College of Engineering , 1977.

50- Abood , S.H., ***" Creep Behavior of Concrete With Sulphate Contaminated Fine Aggregate*** ,, , M.Sc Thesis University of Baghdad , College of Engineering , 1988.

113

51- مقداد عبد الكريم الزيوري "***تأثير المواد الناعمة واملاح الكبريتات المتواجدة في الرمل على خواص الخرسانة***" ، اطروحة ماجستير . الجامعة التكنولوجية . بغداد 1988 .

52- Woods,H., "***Durability of Concrete Construction***" , Published Jointly by ACI, Detroit.1968.

53- Hobbs , D.W., "***Expansion and Shrinkage of Over Sulphated Portland Cement***" , Cement and Concrete Research ,V.8 ,No.2, 1978 .

54- Al–Qaisi, W.A., " ***The Activity of Sulphate Contaminating Fine Aggregate in Concrete***" , M.Sc., Thesis , University of Baghdad , College of Engineering , 1989 .

55- Al- Kadhimi , T.K., "***Internal Sulphate Attak . It's Reaction and Effect on Concrete Durability***" , Journal of Building Research , Building Research center , V.3, No.1 , Baghdad , pp. 1- 15 , May 1984.

56- Zari , A.S., "***Role of Aggregate in Sulphate Effect on Cement Mixes***" , M.Sc Thesis , University of Baghdad , College of Engineering , 1981.

57- Taylor, H.F.W., Famy C., Scrivener K.L., "***Delayed Ettringite Formation***", Cement and Concrete Research , 31 (2001) , pp. 683 – 693 .

58- Yosif , S.H., " ***Effect of Sulphates on Lean and Medium Richness Concrete***" , M.Sc Thesis , University of Baghdad , College of Engineering , 1980 .

59- B. MATHER, A Discussion of the paper "***Theories of Expansion in Sulfoaluminate. Type Expansive Cements. School of Thought***", by Mocohes. Cement and Concrete Research , 14 , 1984 ,(According to Nevill).

60- Renhe et – al , "***Delayed Ettringite Formation in Heat – Cured Portland Cement Mortars***" , Journal Cement and Concrete Research , V.29 , 1999 , pp.17-25 .

61- V. Johansen, et. al, " ***Delayed Ettringite Formation***" , Advanced Cement Research , V.5 , No . 17 , 1993, pp. 23, (Cited by Ref.60)

62- H.F.W. Taylor , H.F.W. Taylor, "***Symosium on Materials Science of cement and Concrete***", High Tatra , Slovakia , June 1993 , (Cited by Ref. 60)

63- S. Diamond , "***Cement and Concrete Composition***" , V. 18 , No.3, 1996 , pp.205 , (Cited byRef.60)

64- P.K MEHTA , " ***Sulfate Attack on Concrete – Acritical Review***", Materials Science of Concrete ((Ed .3.Skalny American Ceramic Society , 1993 , {According to Nevill }

65- H.F.W. Taylor , C. Famy , K.L. Serivener , " ***Delayed Ettringite Formation_***" , Cement and Concrete Research , V.31, 2001 , pp.683-693 .

66- C.D. Lawrence , "***Long Term Expansion of Mortar and Concrete***" , in : B. Erlin (Ed) , Ettringite – The Some times Host of Destruction , SP 177 , American Concrete Institute International , Farmington Hills , MI, USA, 1999 , pp. 105 – 123 , (Cited by Ref.65)

67- C.D. Lawrence , "***Delayed Ettringite Formation***" : An Issue ? , In : j . Skalny , S. Mindess (Eds) , Materials Science of Concrete IV , American Ceramic Society , Wester Ville , OH , USA , 1995 , pp.113 – 154 , (Cited by Ref. 65)

68- Collepardi.M, "***Ettringite Formation and Sulfate Attack on Concrete***" ,Politecnico. Dimilano. Milan. Italy. بواسطة شبكة الانترنيت

69- "Iraqi Organization of Standards ,***IQS" , 5: 1984 , for Portland Cement .***

70- "Iraqi Organization of Standards", ***IQS, 45: 1984 , for Aggregate.***

71- Al- Kadhimi , T.K. and Abdul Kadir , F., " ***Separation of Gypsum Particles From Sand .Used in Concrete***" , BRC Journal , V.4 , No.2 , Nov . 1985 , pp.1-17 , Baghdad, Iraq.

72- American Society for Testing and Materials , C143-89 a , "***Standard Test Method for Slump to Hydraulic Cement Concrete***" , Annual Book of ASTM Standards , V.04.02 , 1989, pp.85-86 .

73- British Standard Institution, "***Method for Determination of Compressive Strength of Concrete Cubes***", B.S.1881 : part 116: 1983 , pp.3 .

74- American Society for Testing and Material, (496-86), "***Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens***" , Annual Book of ASTM Standards , V.04.02 , 1989 , pp.32-34.

75- ASTM Designation (469 – 87 a ; "***Static Modulus of Elasticity and Poison's Ratio of Concrete in Compression***" , 1984 Annual Book of ASTM , Standard American Society for Testing and Material , Philadelphia , Pennsylvania , Section 4 , V. 04.02 .

76- المشهدي سامر واخرون ، "***تأثير املاح الكبريتات في الرمل على تشققات الانكماش في مونة السمنت***"، مجلة جامعة بابل ، العلوم الهندسية ، المجلد 7 ، عدد 5 ، 2002.

77- Hansen, T. C. and Mattock, A. H., "***Influence of Size and Shape of Member on The Shrinkage and Creep of Concrete***" , ACI, Feb. 1966, pp.97- 111. .

78- Famy,C. , "***Expansion of Heat-Cured Mortars***" , PhD Thesis, Imperial College of Science,. Technology and Medicine, University of London, 1999.

79- Evans, E.P and Hughes, B.P., "***Shrinkage and Thermal Cracking in a Reinforced Concrete Retaining Wall***", Proceedings The Institution of Civil Engineers (London), V.39, Jan., 1968, PP.111-125.

80- Salih, S.M., “***Shrinkage and Thermal Cracking of Internally Restrained Reinforced Concrete Members***”, M.Sc. Thesis, University of Baghdad, College of Engineering, May. 2001.

81- مؤيد الخلف ، ***"تأثير الاملاح المتواجدة في الرمل على بعض خواص الخرسانة"***، الدورة العربية لتكنولوجيا الخرسانة ، 1983.

82- Steven, C. Chapra, Raymond, P. Canale, “***Numerical Methods for Engineers with Personal Computer Applications***” ,1989.

83- Al Ta'ii, S.M., “***Mathematical Model for the Prediction of Cement Compressive Strength at the Ages of 7 and 28 Days Within 24 Hours***” , M.Sc Thesis, Department of Civil Engineering, Al- Mustansiriyah University, 2001.

الخلاصـــة

يتناول هذا البحث دراسة تأثير الكبريتات الموجودة في الرمل على تشققات انكماش الجفاف في الخرسانة. في هذه الدراسة استخدم نموذج يعتقد انه يشابه إلى حد ما الظروف الطبيعية والموقعية. تم صب عدد من العتبات الخرسانية المقيدة النهاية ونماذج غير مقيدة لحساب الانكماش الحر ومن ثم تعريضها لظروف المختبر. وتم أيضا صب نماذج لغرض تعين مقاومة الانضغاط، مقاومة الشد (الانشطار) ومعامل المرونة. جرى تصميم خلطة خرسانية بمقاومة انضغاط (35 ميغا باسكال) وتثبيتها على جميع العمل. محتوى الكبريتات في الرمل كان 0%، 0.29%، 0.5%، 1%، 1.5% التي قابلت نسبة كبريتات كلية في الخلطة من وزن السمنت تساوي [3.07%، 3.355%، 4.03%، 4,7%] في الخلطات التي استخدمت سمنت بورتلاندي اعتيادي ورمل من منطقة 2و[3,033%، 3,28%، 3,84%، 4,42%] في الخلطات التي استخدمت سمنت بورتلاندي اعتيادي ورمل من منطقة 4و [2.77%، 3.055%، 3.73، 4.41%] في الخلطات التي استخدمت سمنت مقاوم للأملاح ورمل من منطقة 2 و [2.733%، 2.973%، 3.55%، 4.12%] في الخلطات التي استخدمت سمنت مقاوم للأملاح ورمل من منطقة 4.

بينت النتائج العملية بأن زيادة نسبة الكبريتات الموجودة في الرمل تؤدي إلى انخفاض مقدار انكماش الجفاف الطليق في الأعمار المبكرة في حين إن النسب العالية من الكبريتات والتي كانت (1.5% من وزن الرمل) والتي قابلت نسبة كبريتات كلية في الخلطة من وزن السمنت تساوي [4.7% عند إستخدام سمنت بورتلاندي اعتيادي ورمل من منطقة 2 ، 4.42% عند استخدام سمنت بورتلاندي اعتيادي ورمل من منطقة 4، 4.41% عند استخدام سمنت مقاوم للأملاح ورمل من منطقة 2 و 4.12% عند استخدام سمنت مقاوم للأملاح ورمل من منطقة 4] تسبب زيادة مقدار انكماش الجفاف في الأعمار المتأخرة.

اعتمادا على نتائج هذا البحث يمكن الاستنتاج بأن زيادة محتوى الكبريتات تسبب زيادة في انفعال الشد الأقصى (tensile strain capacity) والزحف (creep) للخرسانة, إن الزيادة في انفعال الشد الأقصى كانت حوالي 24.38%والزيادة في الزحف حوالي 24.9% عند استخدام رمل من المنطقة 4 في الخلطة التي تحتوي على سمنت بورتلاندي اعتيادي ونسبة كبريتات 1.5%وتم إنضاجها لمدة 3 أيام. إن إضافة الكبريتات تؤخر من حدوث تشققات الانكماش وان تطور عرض الشق يصبح أبطأ مع زيادة الكبريتات إلى حد معين يمثل النسبة المثلى للكبريتات وفي الخرسانة ذات النسبة العالية من الكبريتات (1.5% من وزن الرمل) فان عرض الشق يتطور أكثر من الخرسانة ذات نسبة الكبريتات القليلة.

إن زيادة فترة الإنضاج من 3 إلى 28 يوم سبب ابتعاد وقت حدوث الشق وزيادة انفعال الشد الأقصى ،انفعال الشد الأقصى المرن وانفعال الزحف في الخرسانة. علاوة على ذلك إن مقاومة انضغاط الخرسانة تزداد بزيادة الكبريتات إلى حد معين يمثل النسبة المثلى للكبريتات والذي كان (1% من وزن الرمل) ثم تبدأ بعد ذلك بالانخفاض عند تجاوز هذه النسبة وان مقاومة الشد (الانشطار) ومعامل المرونة يبديان اتجاها مشابها للذي لوحظ في مقاومة الانضغاط.

وأخيرا تم اقتراح وتطوير نموذج رياضي يعتمد على معادلات غير خطية متعددة المتغيرات للحصول على قيم تخمينية لانفعال الانكماش وكانت قيمة معامل الارتباط (0.987) فيما كان الاختلاف بين القيم الحقيقية للانكماش والقيم المخمنة بحدود ($\pm60.13\times10^{-6}$).

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة
قسم الهندسة المدنية

تأثير أملاح الكبريتات الموجودة في الركام الناعم على تشققات انكماش الجفاف في الأعضاء الخرسانية المقيدة من النهايات

رسالة

مقدمة إلى كلية الهندسة في جامعة بابل

كجزء من متطلبات نيل درجة الماجستير

في علوم الهندسة المدنية

جنان جواد حسن علوش

إشراف

أ.م.د. مهدي صالح عيسى
أ.م. سامر عبد الامير المشهدي

ذو القعدة 1426 كانون الأول 2005