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وزارة التعليم العالي والبحث العلمي  
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كلية الهندسة  
قسم الهندسة المدنية

# تأثير أملاح الكبريتات الموجودة في الركام الناعم على بعض الخواص الميكانيكية للخرسانة ذاتية الرص

رسالة

مقدمة إلى كلية الهندسة في جامعة بابل  
كجزء من متطلبات نيل درجة الماجستير  
في علوم الهندسة المدنية

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# **EFFECT OF SULFATES IN FINE AGGREGATE ON SOME MECHANICAL PROPERTIES OF SELF COMPACTING CONCRETE**

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

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بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ

﴿يُؤْتِي الْحِكْمَةَ مَنْ يَشَاءُ وَمَنْ يُؤْتَ الْحِكْمَةَ فَقَدْ أُوتِيَ خَيْرًا كَثِيرًا وَمَا يَذَّكَّرُ إِلَّا أُولُو الْأَلْبَابِ﴾

صدق الله العظيم  
سورة البقرة (الآية 269)

# الإهداء

إلى.....

إلى النحلة الباسقة... أبي... رحمه الله

إلى الأرض الحنون... والصابغ..

إلى الأزهار النضرة... أحواتي وأحوالتي

فاو الفقار حبيب حسيه

## الخلاصة

الخرسانة ذاتية الرص توصف بأنها خرسانة لها القابلية أن ترص لوحدها تحت تأثير وزنها الذاتي دون الحاجة إلى استخدام الهزاز. أنها تملأ الفجوات والمسافات بين قضبان حديد التسليح والفراغات حتى خلال الأعضاء الإنشائية الكثيفة التسليح.

تعتبر مهاجمة أملاح الكبريتات الداخلية من المشاكل الخطيرة التي تواجه صناعة الخرسانة في العراق وأفطار الشرق الأوسط. هذه المشكلة أصبحت أكثر جدية مع الزمن فمن الصعوبة إيجاد ركام ناعم مطابق للمواصفات مع حدود المواصفات الحالية لحدود أملاح الكبريتات .

أهدف من هذا العمل هو دراسة تأثير أملاح الكبريتات في الركام الناعم على بعض الخواص الميكانيكية للخرسانة ذاتية الرص بإضافة الجبس الطبيعي إلى الركام الناعم كإحلال جزئي من وزنه. تم دراسة أربع نسب لمحتوى الكبريتات (0.16, 0.5, 1.0, and 1.5) % في الركام الناعم والذي يساوي (3.22,3.79,4.62,5.45)% من وزن الإسمنت للخلطات التي تحوي على مادة ألغبرة كمادة مألئة ومساوي إلى(3.07,3.63,4.47,5.31) % من وزن السمنت للخلطات التي تحوي على مادة ( pigment) كمادة مألئة ومساوي إلى(3.02,3.58,4.42,5.25) % من وزن الإسمنت للخلطات التي تحوي على مادة النورة ألمطفأة.

برنامج العمل يقسم إلى جزئين ; الجزء الأول هو أنتاج خرسانة ذاتية الرص باستعمال الملدنات و المادة المألئة ثم إيجاد قابلية التشغيل . تم استخدام طرق فحص مختلفة مثل فحص جريان الهطول, القمع على شكل حرف V, القمع على شكل حرف V بعد مرور 5 دقائق , الصندوق على شكل حرف L والصندوق على شكل حرف U.

أجزاء الثاني هو دراسة الخواص الميكانيكية مثل مقاومة الانضغاط , مقاومة الانشطار, مقاومة الانثناء, معامل المرونة والفحوصات اللاتلافية مثل سرعة الذبذبات فوق الصوتية ومطرقة الارتداد. هناك محتوى امثل للجبس الذي عنده ألمقاومة أعلى ما يمكن ,أي زيادة أضافية في محتوى الكبريتات بعد أالنسبة المثلى يسبب تناقص في المقاومة والفحوصات اللاتلافية. تم إيجاد محتوى الجبس الأمثل في الخرسانة ذاتية الرص عند نسبة 0.5 % من وزن ألكام الناعم.

محتوى الجبس الأمثل لكل الخلطات يعطي زيادة في الخواص الميكانيكية والفحوصات اللاتلافية بمقدار (1.8-16.2)% لمقاومة الانضغاط, (2.3-8.8) % لمقاومة الانشطار, (3.5-7.3) %

لمقاومة الانثناء, (2.6-3.8)% لمعامل المرونة, (0.9-3.8)% لسرعة الذبذبات فوق الصوتية و(2.9-

8.1)% لمطرقة الارتداد عندما نسبة الكبريتات في الركام الناعم تزداد من (0.16 إلى 0.5)% بينما بعد

النسبة المثلى يعطي تناقص بمقدار (1.8-10.4)% لمقاومة الانضغاط, (0.8-7.6) % لمقاومة  
الانشطار, (0.7-7.1) % لمقاومة الانثناء, (1.4-1.9) %  
لمعامل المرونة, (0.2-5.0) % لسرعة الذبذبات فوق الصوتية و (0.7-2.1) % لمطرقة الارتداد  
عندما نسبة الكبريتات في الركام الناعم تزداد من (0.16 الى 1) % , (0.16 الى 1.5) %

## **ACKNOWLEDGEMENTS**

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*THULFEKAR*



*ABSTRACT*

Self compacting concrete is described as concrete with ability to compact itself by means of its own weight without the requirement of vibration. It fills all recesses, reinforcing spaces and voids even in highly reinforced concrete members.

Internal sulfate attack is considered as very important problem of concrete manufacture in Iraq and Middle East countries . This problem becomes more serious with time as it is difficult to find aggregate complying with the current specifications for sulfate limits.

The objective of this work is to study the effect of sulfates in fine aggregate on some mechanical properties of self compacting concrete by adding natural gypsum to fine aggregate as a partial replacement by weight. Four sulfate contents (0.16, 0.5, 1.0, and 1.5) % in fine aggregate which it is equal to (3.22,3.79,4.62,5.45)% by weight of cement for mixes contained limestone powder filler and it is equal to (3.07,3.63,4.47,5.31) % by weight of cement for mixes contains pigment filler and it is equal to (3.02,3.58,4.42,5.25) % by weight of cement for mixes contains hydrated lime filler . The experimental program is divided into two parts; The first part is devoted to produce self compacting concrete by using superplasticizers and fillers then determine the workability. Different test methods are adopted such as slump flow and T50 cm, V-funnel, V-Funnel at T5 minutes, L-box and U-box.

The second part is devoted to study the mechanical properties such as the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity , the ultrasonic pulse velocity and schmidt rebound hammer tests .There is an optimum gypsum content at which the strength is maximum . Further increase in  $SO_3$  content beyond the optimum causes a decrease in strength and non

destructive tests. This optimum gypsum content was found in SCC at the percentage of 0.5% by wt. of fine aggregate .The optimum gypsum content for all mixes gives increases in the mechanical properties and non-destructive tests by a range(1.8-16.2)% for compressive strength , (2.3-9.2)% for splitting tensile strength,(3.5-7.3)% for flexural strength,(2.6-3.8)% for modulus of elasticity, (0.9-3.8)% for ultrasonic pulse velocity and (2.9-8.1)% for schmidt rebound hammer when SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5) % while beyond the optimum give decreases by a range(1.8-10.4)% for compressive strength, (0.5-7.6)% for splitting tensile strength,(0.7-7.1)% for flexural strength,(1.4-1.9)% for modulus of elasticity,(0.2-2.8)% for ultrasonic pulse velocity and (0.7-1.7)% for schmidt rebound hammer when SO<sub>3</sub> in fine aggregate increases from (0.16 to 1) %, (0.16 to 1.5)% respectively .

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# ***NOTATIONS***

C <sub>3</sub> S	Tricalcium Silicate (3CaO.SiO <sub>2</sub> )
C <sub>2</sub> S	Dicalcium Silicate (2CaO.SiO <sub>2</sub> )
C <sub>3</sub> A	Tricalcium aluminate (3CaO.Al <sub>2</sub> O <sub>3</sub> )
C <sub>4</sub> AF	Ferrite phase (4CaO.Al <sub>2</sub> O <sub>3</sub> .Fe <sub>2</sub> O <sub>3</sub> )
CH	Calcium Hydroxide
C-A-H	Calcium Aluminate Hydrates
C-S-H	Calcium Silicate Hydrate
D	Final diameter
DEF	Delayed Ettringite Formation
E <sub>c</sub>	Static modulus of elasticity
ESA	External Sulfate Attack
HRM	High reactive metakaolin
HRWRA	High range water reducing agent
ISA	Internal Sulfate Attack
ITZ	Interfacial Transition Zone
LSP	Limestone Powder
MH	Mixes with hydrated lime filler
ML	Mixes with limestone powder filler
MP	Mixes with pigment filler
NMS	Nominal Maximum Size
PC	Portland Cement
SCC	Self Compacting Concrete
SP	Superplasticizer
SP/P	Superplasticizer/ powder ratio
SRA	Shrinkage Reducing Admixture
U.P.V	Ultrasonic Pulse Velocity

VMA	Viscosity Modifying admixture
w/b	water-to-binder ratio
W/C	water /cement ratio
W/P	water /powder ratio

# CERTIFICATION

We certify that we have read this thesis, titled (**Effect of Sulfates in Fine Aggregate on Some Mechanical Properties of Self Compacting Concrete**), and as examining committee examined the student **Thulfekar Habeeb Hussain** in its contents and in what is connected with it, and that in our opinion it meets the standard of thesis for the Degree of Master of Science in Civil Engineering (Construction Materials).

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# Chapter 1 Introduction

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## 1.1 General:-

Self- Compacting Concrete (SCC) is a concrete with a high viscosity that can flow freely with minimal segregation. SCC is able to flow under its own self-weight into corners of formwork and through closely spaced reinforcement with little or no vibration or compaction <sup>(1)</sup>. It is used to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members.

SCC was developed in Japan at the late 1980's to be mainly used for highly congested reinforced concrete structures in seismic regions.

Recently, this concrete has gained a wide use in many countries for different applications and structural configurations <sup>(2)</sup>.

Fresh concrete can easily attain high flowability by simply increasing the water-to-binder (w/b) ratio. However, increasing the w/b ratio alone could lead to concrete segregation and less durability. Thus, in order to successfully develop SCC, mineral and chemical admixtures, e.g., pozzolans, limestone powder, superplasticizer, and viscosity-modifying admixture (VMA), need to be added to the mix to prevent segregation and enhance the workability of SCC <sup>(1)</sup>.

Concrete durability is one of the most important considerations in the design of new structures and when assessing the condition of existing structures. Concrete construction is becoming increasingly complex and the importance of producing structures that are both cost effective and durable has never been higher <sup>(3)</sup>.

The American Concrete Institute has defined the durability of concrete as its resistance to weathering action, chemical attack, abrasion and other degradation processes. Among the important degradation mechanisms in concrete structures are the following <sup>(4)</sup>:

1. Freeze-thaw damage (physical effects, weathering).
2. Alkali-aggregate reactions (chemical effects).
3. Sulfate attack (chemical effects).

Sulfates cause concrete or mortar deterioration when it exists in excessive amount. This phenomenon is called sulfate attack.

The sulfate reacting with  $\text{Ca(OH)}_2$  and with calcium aluminate hydrate (C-A-H). The products of reactions, gypsum and calcium sulphoaluminate have a considerably greater volume than the compounds they replace, so that the reactions with the sulfates lead to expansion and disruption of the concrete.

Sulfate in fine aggregate is a major problem encountered in the Middle and Southern part of Iraq. Most of the sulfate salts in fine aggregate are composed of calcium, magnesium, potassium and sodium sulfates. Calcium sulfate is the most predominant salt present in Iraqi fine aggregate. It is usually found in fine aggregate as gypsum. About 95% of sulfates in fine aggregate are in the form of calcium sulfates because of the low solubility of this type of sulfate <sup>(5)</sup>.

## **1.2 Objective of The Work:-**

The main objective of the research is to investigate the effect of internal sulfates in fine aggregate on compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, ultrasonic pulse velocity and schmidt rebound hammer tests of SCC..

In this study, the percentages of sulfate in concrete ingredients are obtained by adding natural gypsum to the fine aggregate as a partial replacement by weight of fine aggregate.

For the purpose of this research the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity and non-destructive methods are tested.

All specimens were cured in water until the time of testing except the specimens which contain 1.5% SO<sub>3</sub> in fine aggregate which were cured according to the method which is described in the experimental work.

The main variables used in the study:

1. Percentage of sulfates in fine aggregate ;( 0.16%, 0.5%, 1.0%, 1.5% by weight of fine aggregate).
2. Fillers type ;( limestone powder, pigments and hydrated lime).
3. Curing type ;( moist curing and wetting and drying curing).
4. Curing time; (28, 90 and 180 days for moist curing) and (90,180 days for wet and dry curing).

### **1.3 Research layout:-**

The thesis consists of four chapters in addition to this chapter.

Chapter two presents a review of the literature, Introduction, Development, Characterization, Rheology, Materials, Mix Design methods, hardened properties, external and internal sulfate attack of SCC .

Chapter three deals with materials and experimental work.

Chapter four introduces the experimental results and discussion.

Chapter five presents the conclusions and recommendations for future work.

# **Chapter 2 Literatures Review**

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## **2.1 Introduction :-**

**Self-compacting concrete (SCC)** represents one of the most outstanding advances in concrete technology during the last two decade. Due to its specific properties, SCC may contribute a significant improvement to the quality of concrete structures and open up new fields for the application of concrete. SCC is described as a concrete with the ability to compact itself only by means of its own weight without the requirement of vibration. It fills all recesses, reinforcement spaces and voids, even in highly reinforced concrete members, and flows free of segregation nearly to level balance. <sup>(6)</sup>.

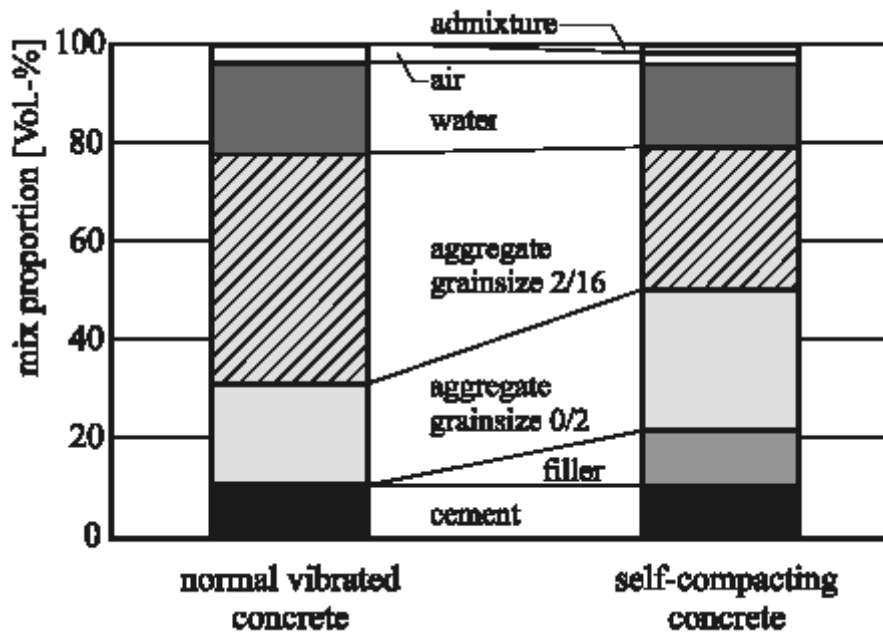
## **2.2 Development of Self-Compacting Concrete :-**

For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan. The creation of durable concrete structures requires adequate compaction by skilled workers. However, the gradual reduction in the number of the skilled workers in Japan's construction industry has led to a similar reduction in the quality of construction work <sup>(7)</sup>. One solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of Self-compacting concrete, which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction. The necessity of this type of concrete was proposed by Okamura in 1986. Studies to develop Self-compacting concrete, including a fundamental study on the

workability of concrete, have been carried out by Okamura and Ozawa at the University of Tokyo <sup>(7)</sup>.

The basic components for the mix composition of SCC are the same as those used in normal concrete. However, to obtain the requested properties of fresh concrete in SCC, a higher proportion of ultrafine materials and the incorporation of chemical admixtures, particularly an effective superplasticizer, are necessary. Ordinary and approved filler materials are fly ash, limestone powder, blast furnace slag, silica fume and quartzite powder <sup>(6)</sup>.

A comparison of a typical mix design of SCC and normal concrete is shown in Fig. (2-1) <sup>(6)</sup>.



**Fig. (2-1): Mix Composition of SCC in Comparison with Normal Vibrated Concrete <sup>(6)</sup>**

## **2.3 Characterization of Self Compacting Concrete :-**

### **2.3.1 Filling Ability :-**

Without vibrating the concrete, SCC has to fill any space within the formwork; it has to flow in horizontal or vertical directions without keeping air entrapped inside the concrete or at the surface. The driving forces of this process are the weight of the concrete and the casting energy<sup>(8)</sup>.

### **2.3.2 Passing Ability :-**

Passing ability is required to guarantee a homogeneous distribution of the components of SCC in the vicinity of obstacles.

The minimum bar distance to avoid blocking depends on the flowability of SCC, maximum aggregate size, the paste content and the shape of the aggregates<sup>(8)</sup>.

### **2.3.3 Segregation Resistance :-**

Segregation resistance is the resistance of the components of SCC for migration or separation. Particles having a relatively high density or a low surface volume ratio are more prone to segregation. The segregation resistance of SCC can be different under static (at rest) and dynamic (during the flow) conditions<sup>(8)</sup>.

Resistance to segregation can be improved by minimizing the free water to avoid bleeding and by making the liquid phase more viscous to enhance suspension of particles. Viscosity agent has been used to accomplish higher viscosity<sup>(9)</sup>.

For initial mix design of SCC, all three workability parameters need to be assessed to ensure that all aspects are fulfilled<sup>(10)</sup>. Table (2-1) indicates the test methods of workability and acceptance criteria for SCC.

**Table (2-1) Test methods for workability properties & Acceptance criteria of SCC <sup>(10)</sup>**

	Method	Property	Range
1	Slump flow	Filling ability	650-800 mm
2	T50 cm slump flow	Filling ability	2-5 sec
3	V-funnel	Filling ability	6- 12 sec
3	Increase in V-funnel at $T_{5 \text{ min}}$	Segregation resistance	+3 sec, max
4	L-box $(H_2/H_1)^*$	Passing ability	0.8- 1.0
5	U-box $(H_1- H_2)^{**}$	Passing ability	0- 30 mm

\* $H_2/H_1$  the height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the vertical section of L-box.

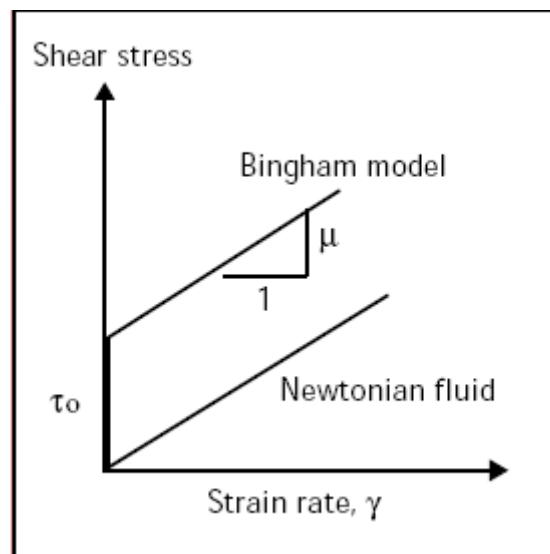
\*\*  $H_1-H_2$  the difference between the height of concrete in the right chamber and that in the left chamber of U-box.

## **2.4 Rheology of SCC :-**

In general, rheology is the science of deformation and flow of the matter and it is concerned with the relationships between stress, strain, rate of strain and time <sup>(11)</sup>. SCC has been applied in a wide range of composition. The most common rheological parameters, used to quantify workability, are the yield stress and plastic viscosity. For SCC a low shear yield stress and a maximum limiting value of the plastic viscosity are needed. The yield stress and viscosity depend on the flocculated microstructure in the concentrated suspensions, including cementitious suspensions <sup>(12,13)</sup>. Therefore, the flocculation between the cement particles should be limited with appropriate dispersion and stabilization

of the cement particles. Consequently, the shear viscosity and yield stress of fresh cement paste would be reduced, leading to high deformability of fresh cementitious mix.

The rheology of fresh concrete is described by the Bingham model. According to this model Fig. (2-2). Fresh concrete must overcome a limiting stress (yield stress,  $\tau_0$ ) before it can flow.



**Fig. (2-2): Bingham Rheology model** <sup>(14)</sup>

Once the concrete starts to flow, shear stress increases linearly with increases in strain rate as defined by plastic viscosity,  $\mu$ . Thus, one target of rheological property of SCC is to reduce the yield stress to as low as possible so as to behave like a Newtonian fluid with zero yield stress. The other target property is 'adequate' viscosity <sup>(14)</sup>.

The Bingham equation is a linear-relationship between the shear strain rate ( $\gamma$ ) and yield stress ( $\tau_0$ ). The viscosity ( $\mu$ ) is the slope, and the intercept is the yield stress, as shown in the equation below <sup>(15)</sup> :-

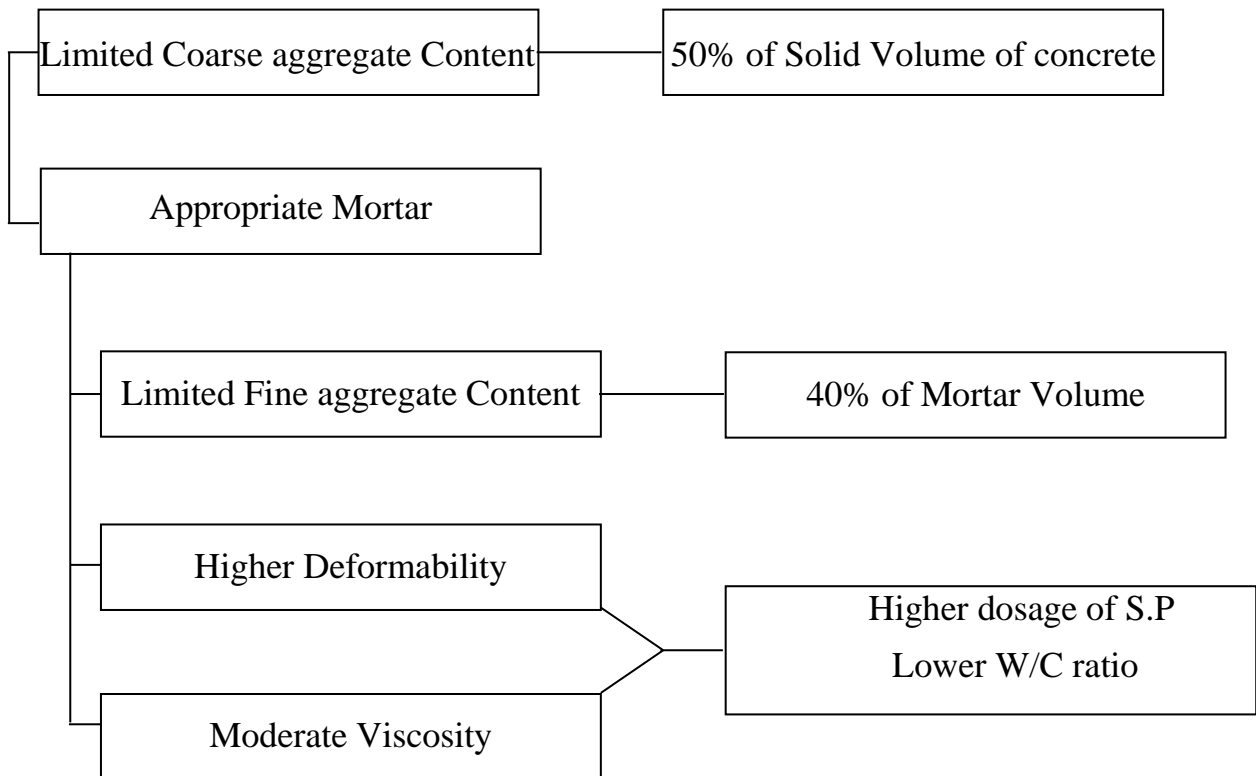
$$\tau = \tau_0 + \eta \gamma \dots \dots \dots (2-1)$$

## **2.5 Mechanism for Achieving Self-compactability :-**

The method for achieving Self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars<sup>(16)</sup>.

**Okamura and Ouchi** <sup>(16)</sup> employed the following methods to achieve Self-compactability:

- 1- Limited aggregate content.
- 2- Low water /powder ratio.
- 3- The use of superplasticizer.



**Fig. (2-3): Methods for Achieving Self-compactability**<sup>(16)</sup>

**Newman and Choo** <sup>(17)</sup> , reported that the development of SCC has mainly been focused on congested civil engineering structures, and its acceptance within the market place has primarily grown in solving technically difficult casting conditions. It is a niche product and problem solver.

## **2.6 Economy of SCC :-**

With all the benefits of Self compacting concrete, it can be used in every construction project. However, this is not the case. According to **Okamura** <sup>(18)</sup>, in First International Conference on self-compacting Concrete, only 0.5% of the premixed concrete market was SCC. The main reason for this low usage is its high supply cost, so there is an urgent need to reduce this cost if the full potential of SCC is to be realized.

The increasing costs in SCC are due to <sup>(19)</sup>:

- More demanding of mix design to admixtures & fines.
- Slightly extended mixing time.

Although the cost of self-compacting concrete is high, there are some advantages which may reduce the cost of SCC, as follows <sup>(10)</sup>:

1. High speed of placing.
2. Reduced machine and equipment cost.
3. Higher concrete quality and durability.
4. Homogeneous surfaces.
5. Reduced manpower.
6. Reduced finishing and repair work.
7. More flexibility for design (i.e. thinner elements if possible).

## **2.7 Materials Used in SCC Mix :-**

Before designing a mix for SCC, an understanding is needed of the properties required for self compaction and how this can be optimized by utilizing materials currently available. The two main requirements are a highly material which has significant resistance to segregation. To achieve a highly mobile concrete, a low yield stress is required and for a high resistance to segregation, a highly viscous material is important. Water can be added to decrease the yield stress but this addition also

lowers the viscosity. Addition of a superplasticizer will not only lower the yield stress but will lower the viscosity slightly <sup>(17)</sup>.

Each material, cement, fine aggregate, coarse aggregate, concrete admixture, fillers and pozzolans must be evaluated according to type, strength characteristics, gradation, fineness and interaction in combination with each other <sup>(19)</sup>.

To achieve high workability and avoid obstruction by closely spaced reinforcing bars, SCC is designed with limits on the nominal maximum size (NMS) of the aggregate, the amount of aggregate. However, when the workability is high, the potential for segregation and loss of entrained air voids increases. These problems can be alleviated by designing a concrete with a high fine-to-coarse-aggregate ratio, a low water-cementitious material ratio (w/cm), good aggregate grading, and a high-range water-reducing admixture <sup>(20)</sup>.

### **2.7.1 Cement :-**

The first choice to be made when making SCC is definitely that of the cement, even when one or two supplementary cementitious materials are used, because the performance of cement in terms of rheology and strength becomes crucial issue as the target workability and compressive strength increase.

**EFNARC** <sup>(10)</sup> reported that: all types of cement conforming EN 197 are suitable and the selection of the type of cement depends on the overall requirements for the concrete, such as strength, durability, etc.

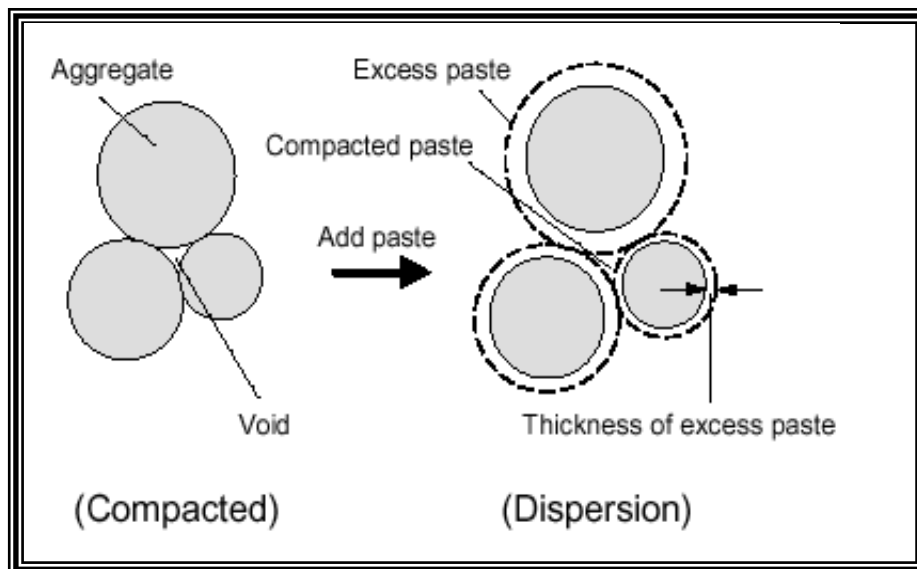
**Okamura, Ouchi and Ozawa** <sup>(21)</sup>, focused primarily on the use of Portland cement (PC) for SCC, the total fines content of the mix is balanced against aggregate size and grading.

In general, the fines content is much higher than in normal concrete for reasons of stability. The requirement for a high fines content leads to high cement contents, often in the range (450-500) kg/m<sup>3</sup>.

**Kennedy** <sup>(22)</sup> proposed the "*Excess Paste Theory*" which explains the fact that for attaining workability it is necessary to have not only enough cement paste to cover the surface area of the aggregates, so as to minimize the friction between them, but also more of it to give better flowability.

In Fig. (2-4), the left side model shows that the aggregates are closely contacted to each other, with voids in between them. If this model is mixed with cement paste, this closely packed aggregates are then separated by this thin film of cement paste around them, as shown in the model on the right side of the figure.

Adding cement paste will change the interaction between aggregates. This is a sort of a dispersion effect, so aggregates are pushed away from each other. Without a film of cement paste around them, the movement between aggregates would generate much friction and make workability impossible.



**Fig. (2-4): Excess Paste Theory** <sup>(22)</sup>

The direct effect of cement on concrete could be simplified by the fact that the cement paste is the effective part, and the strength of mortar or

concrete depends on the cohesion of the paste, and its adhesion to the aggregate particles <sup>(23)</sup>.

## **2.7.2 Aggregate :-**

### **2.7.2.1 Fine Aggregate :-**

The fine aggregate in SCC plays a major role in the workability and stability of the mix. The total fine in the mix is a function of filler and the fine aggregate content. The grading of fine aggregate is particularly important. The grading of fine aggregate in the mortar should be such that both workability and stability are simultaneously maintained <sup>(17)</sup>. Few researches have been done to optimize the fine aggregate characteristics for SCC applications in spite of the fact that fine aggregate characteristics can vary across a wide range <sup>(24)</sup>. The grading, particle shape and fineness modulus of the fine aggregate are significant factors in the production of SCC. Generally, there is no particular advantage of using one type of fine aggregate rather than another as long as it is clean and free from clay and silt <sup>(24)</sup>.

### **2.7.2.2 Coarse Aggregate :-**

The coarse aggregate chosen for SCC is typically round in shape, well graded and smaller in maximum size than that used for normal concrete; typical normal concrete could have a maximum aggregate size of 37.5mm or more. In general, a rounded aggregate and smaller aggregate particles aid in the flowability and deformability of concrete as well as in the prevention of segregation.

**Petersson** <sup>(25)</sup> stated that both natural and crushed aggregates can be successfully used in SCC as long as attention is given to the amount of paste necessary to avoid blocking of the aggregates (crushed coarse and

fine aggregates require more paste, while uncrushed aggregates and smaller maximum size require less paste).

Gradation is an important factor in choosing a coarse aggregate, especially in typical uses of SCC where reinforcement may be highly congested or the formwork has small dimensions. Gap-graded coarse aggregate promotes segregation to a greater degree than does well-graded coarse aggregate.

As with normal concrete construction, the maximum size of the coarse aggregate for SCC depends upon the type of construction. Typically, the maximum size of coarse aggregate used in SCC ranges from approximately 10 mm to 20 mm.

Coarse aggregate properties affect aggregate- cement bond characteristics and mixing water requirements. Generally, good quality aggregate must be used, to ensure good bond between the coarse aggregate particles and the matrix.

### **2.7.3 Filler Material :-**

Fillers ,supplementary cementitious materials or mineral admixtures have long provided the means to improve the fresh and hardened properties of concrete .

**EFNARC** <sup>(10)</sup> and **The British Cement Association** <sup>(26)</sup> defined additions as “Finely-divided inorganic materials used in concrete in order to improve certain properties or to achieve special properties”, and classified them into two categories:

1. Type I (semi-inert) additions like finely crushed (limestone, dolomite or granite), filler aggregate, pigments ...etc.

2. Type II (pozzolanic or latent hydraulic) like silica fume, metakaolin, rice husk ash, fly ash, ground granulated blast-furnace slag ...etc.

### **2.7.3.1 Limestone Powder :-**

BS 7979, **Specification for limestone fines for use with Portland cement** <sup>(27)</sup> defined limestone fines as a fine powder obtained from the processing of limestone. It is less reactive than Type II addition, but research shows that it may have slight reactivity as well as any physical effects conferred by virtue of its fine particle size. It can be concluded from the results of many researches that limestone powder has a good performance in both fresh and hardened SCC. The fraction less than 0.125 mm will be of most benefit. The usage of limestone filler in the mix increases the 24 hours compressive strength of concrete <sup>(28)</sup>.

### **2.7.3.2 Pigments :-**

BS EN 12878, **Pigments for the colouration of building materials** <sup>(29)</sup> **based on cement and lime – Specifications and methods of test** is a substance, generally in the form of fine particles, whose sole purpose is to color cement- and lime-based building materials. The pigment used in this work as a filling material is to improve the properties of concrete <sup>(26)</sup>.

### **2.7.3.3 Hydrated Lime :-**

Ca (OH)<sub>2</sub> or Ca (OH)<sub>2</sub> • MgO; produced by slaking, or adding water to, calcium quicklime (CaO) or dolomitic quicklime (CaO • MgO).

## **2.7.4 Chemical Admixtures :-**

Two types of chemical admixtures are commonly used in the production of SCC: superplasticizers and viscosity modifying agents VMA. Recently, shrinkage reducing admixture (SRA) has been used as new type <sup>(30)</sup>.

Superplasticizer is added during mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete.

The most common reasons for using admixtures in concrete are <sup>(31)</sup>:

1. To increase workability without changing water content.
2. To reduce water content without changing workability.
3. To effect a combination of the above.
4. To reduce segregation.
5. To reduce bleeding.
6. To increase strength.
7. To improve potential durability and reduce permeability.
8. To reduce the total cost of the materials used in the concrete.

The most important admixture is superplasticizer (high range water reducers), used with a water reduction greater than 20%. Admixture helps to provide very good homogeneity and reduces the tendency to segregation. There is more field for improvement for admixtures such as superplasticizer suitable for SCC <sup>(10)</sup>. Table (2-1) shows the development of the admixture with time.

**Table (2-2): The development of the admixture with time** <sup>(32)</sup>

Type of Super plasticizers	Year	% water reduce
plasticizers	1960	10-15
Poly-Super plasticizers	1970	20-33
Polymer modified Superplasticizer	1980	30-35
Poly Carboxylic ethers	1999	UP to 40

### **2.7.5 Mixing Water :-**

EFNARC <sup>(10)</sup> stated that the suitability of mixing water is the same as in normal concrete.

It is well known that the amount of water in normal concrete is of particular importance for the properties at the fresh stage. For SCC, the amount of water is even more important and in mix design methods of this family of concrete, water is addressed in several relations such as: water/total fines (powder + fine aggregate) and water to powder ratio.

### **2.8 Mix Design :-**

The first model for proportioning SCC mixes was developed in 1988 using constituent materials readily used in normal concrete <sup>(33)</sup>. The model performed satisfactorily with regard to fresh properties and also long-term hardened properties such as shrinkage. The cementitious component of the model is much larger than that in normal concrete with a subsequent reduction in the volume fraction of coarse aggregate.

There are three fundamental factors govern the fresh properties of SCC <sup>(17)</sup>:

- (i) The fresh properties of the mortar.
- (ii) The volume of coarse aggregate in the mix.
- (iii) The use of superplasticizing admixture to enhance workability.

#### **2.8.1 Mix Design Methods :-**

There are many different mix design theories, but they all mainly separate SCC into two phase design namely, "continuous" which covers the water, admixture, cement and fillers with particle size less than 0.1 mm and "particle" which considers the coarse and fine aggregate<sup>(17)</sup>. Some of these theories are summarized below:

### **2.8.1.1 Rational Mix Design Method :-**

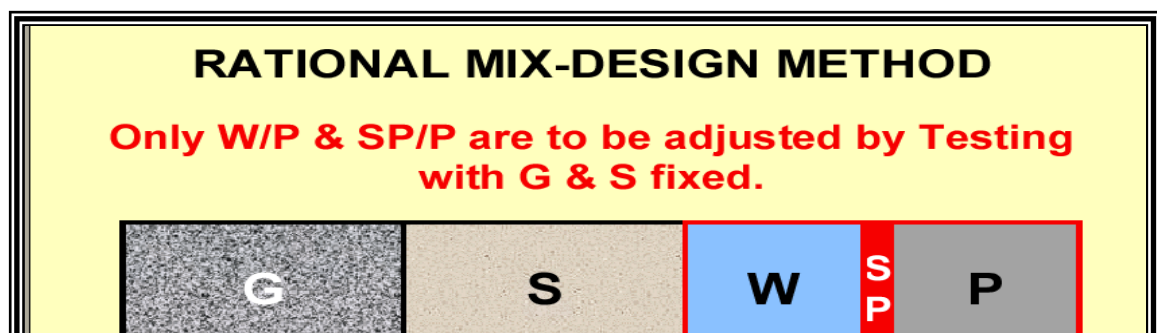
A relatively simple mix design method was developed in Japan in 1995. The method was based on the fact that self-compactability of concrete can be affected by the mix proportions<sup>(17)</sup>.

The principle of the mix design method is that the coarse and fine aggregate content is fixed so that the self-compactability of the fresh concrete can be achieved by adjusting only the water/powder ratio and superplasticizer<sup>(34)</sup>.

The fundamental steps in the procedure are as follows:

- (i) The coarse aggregate content is fixed at 50% of the solid volume of the concrete.
- (ii) The fine aggregate content is fixed at 40% of the mortar volume.
- (iii) The water/powder ratio is assumed to be 0.9-1.0 % by volume depending on the properties of the powder.
- (iv) The superplasticizer dosage and final water/powder ratio are determined so as to ensure self-compactability.

**Ouchi**<sup>(35)</sup>, summarized a rational mix-design method shown in Fig.(2- 5) only water/powder ratio and superplasticizer are to be adjusted by testing with coarse aggregate and fine aggregate fixed.



**Fig. (2-5): Rational Mix-Design Method** <sup>(35)</sup>**2.8.1.2 Linear optimization mix proportioning- Domone** <sup>(36)</sup>

The optimization mix design method is based on the rational mix design method, but modifies this by using the mathematical approach of linear optimization to produce an optimum mixture of water, powder and aggregate. The mix design procedure is as follows:

**Step 1** : A typical air content is chosen (1-1.5% for non-air-entrained mixes)

**Step 2** : The coarse aggregate content is fixed ( $0.5 \times$  dry rodded unit weight).

**Step 3** : A binder composition is chosen.

**Step 4** : The maximum water /binder ratio is chosen to ensure that the following three experience:

1. The paste has sufficient plastic viscosity (before addition of super-plasticizer) to provide adequate segregation resistance.
2. The concrete has sufficient compressive strength.
3. The durability requirements are met.

The minimum value of water /binder ratio from 1, 2 and 3 chosen.

**Step 5** : The volume of the fine aggregate in the mortar is chosen.

**Step 6**: The paste content is calculated and adjusted if outside the limits.

**Step 7**: The water and binder contents are calculated with the water being a limiting factor and set before Step 5 if greater than  $200 \text{ kg/m}^3$ .

**Step 8**: The superplasticizer dosage is then estimated from tests on the mortar component of the mix using the V-funnel test.

**Step 9**: The concrete mix is then made and tested for fresh concrete.

## **2.9 Mechanical Properties :-**

### **2.9.1 Compressive Strength :-**

The compressive strength, as one of the most important properties of hardened concrete in general, is the characteristic material value for the classification of concrete in national and international codes. For this reason, it is of interest whether the differences in the mixture composition and positive dissimilarities in the microstructure, as mentioned before, affect the short and long term load-bearing behavior <sup>(6)</sup>.

When normal concrete is vibrated, water tends to migrate to the surface of the coarser particles where there porous and weak interfacial zones develop. If SCC has been well designed and produced, it will be homogeneous, mobile, resist the segregation and has the ability to be placed into the form without the need for compaction. This will encourage minimal interfacial zones to develop between the coarse aggregate and the mortar phase. Thus, the microstructure of SCC is expected to be improved promoting strength, permeability, durability and ultimately a longer service life of the concrete <sup>(17)</sup>.

**Tviksta** <sup>(37)</sup>, reported that if limestone powder is used, higher compressive strengths are noticeable at the beginning of hardening process.

**Holschemacher and Klug** <sup>(6)</sup>, reported that an increase of the cement content and a reduction of filler content at the same time increases the initial and ultimate concrete strength.

For normal concrete, the proportion between cube and cylinder compressive strength ( $f_{cu}$ , cube (150mm)/ $f_c$ , cylinder (150/300mm)) is about (1.2). This relation is essentially lower for SCC; the ratio ( $f_{cu}$ , cube (150mm)/ $f_c$ , cylinder (150/300mm)) is in the range of (1.0 to 1.1). Consequently, the compressive strength is less related to the slenderness of the specimens <sup>(38)</sup>.

### **2.9.2 Splitting Tensile Strength :-**

The direct measurement of the tensile strength of normal concrete is not easy because of the complicated set-up that must be used. Therefore, tensile strength is usually calculated using indirect measurement, such as the measurement of the modulus of rupture (ASTM C78-84) <sup>(39)</sup> and / or the splitting tensile strength (ASTM C496-86) <sup>(40)</sup>.

The splitting tensile strength is determined on the standard cylinders size 100 x 200 mm and moist cured until the date of the test according to ASTM C496-86 <sup>(40)</sup>.

**Holschemacher** <sup>(6)</sup>, concluded from using a self-compacting concrete with different types of filler such as fly ash, silica fume, limestone powder, quartzite filler and blast furnace slag, that all parameters which influence the characteristics of the microstructure of the cement matrix and of the interfacial transition zone (ITZ) are of decisive importance in respect of the tensile load capacity behavior. He reported that most results of the measured splitting tensile strength values are in the range of valid

regulations for normal vibrated concrete with the same compressive strength. However, in about 30% of all measured data points a higher splitting tensile strength is recorded. The reason for this fact is given by the best microstructure, especially the smaller total porosity and more even pore size distribution within the interfacial transition zone of SCC.

**Ouchi** <sup>(41)</sup>, reported that the (28) days splitting tensile strength of self-compacting concrete ranges from (2.4-4.8) MPa when compressive strength is (40-80) MPa. Splitting tensile strength is about (6%) of the compressive strength at 28 days of age.

### **2.9.3 Flexural Strength :-**

The other way of estimating the tensile strength of concrete is by the flexural test (ASTM C78-84) <sup>(39)</sup>. The specimen is a beam 100x100x400 mm. The beams are cured in the standard manner and are then tested in flexure in two-point loading.

The maximum tensile strength, or modulus of rupture,  $R$ , is calculated from the simple beam bending formula for two point loading <sup>(42)</sup>:

$$MR = P L / bd^2 \quad \dots\dots\dots (2-2)$$

where:

$P$ = the maximum applied load ,N

$L$ =span length, mm

$b$ =specimen width, mm

$d$ =specimen depth, mm

Equation (2-2) is valid only if failure line is within the middle third span. If failure line is outside middle span by not more than 5% of the span length, Equation (2-3) is replaced by <sup>(42)</sup>:

$$MR = 3 Pa / bd^2 \quad \dots\dots\dots (2-3)$$

where:

a=the average distance between the point of fracture and the nearest support.

**Sonebi et al.** <sup>(43)</sup>, reported that performing the modulus of rupture measurement does not present any special difficulties in the case of self-compacting concrete, so that the same set-ups and procedures used for normal concrete can also be used for SCC.

The flexural test method is most widely used for quality control of highways and airport runways, where it gives more useful information than do compression tests <sup>(42)</sup>.

#### **2.9.4 Modulus of Elasticity :-**

The modulus of elasticity of concrete is one of the most important mechanical properties of concrete. The measurement of the elastic modulus of SCC can be done in the similar way as for normal concrete <sup>(6)</sup>.

The most common way for concrete is to measure the chord modulus of elasticity,  $E_c$ , following the method outlined in (ASTM C469-87a) <sup>(44)</sup>. The cord modulus of elasticity is calculated using the expression :

$$E = \frac{S_2 - S_1}{\epsilon_2 - 50 \times 10^{-6}} \dots\dots\dots (2-4)$$

where:

$S_2$ : the stress corresponding to 40% of the ultimate load

$S_1$ : the stress corresponding to a longitudinal strain,  $\epsilon_1$ , of  $50 \times 10^{-6}$

$\epsilon_2$ : the longitudinal strain produced by stress  $S_2$ .

The modulus of elasticity is related to compressive strength and density. The factors that affect strength should similarly influence modulus. The dominant parameter is the porosity, and the modulus will decrease markedly as the w/c ratio is increased <sup>(45)</sup>.

The modulus of elasticity of concrete increases for high contents of aggregates of high rigidity, whereas it decreases by increasing hardened cement paste content and porosity <sup>(6)</sup>.

**Sonebi** <sup>(43)</sup>, reported that the SCC and normal concrete bear a similar relationship between modulus of elasticity and compressive strength expressed in the form  $E_c/(f_{cy})^{0.5}$ , where E= modulus of elasticity (GPa),  $f_c$ = compressive strength (MPa) . They also reported that this ratio is close to the value 4.73 recommended by ACI 318-89 (revised 1992) for structural calculation, applicable for normal concrete.

**Holschemacher** and **Klug** <sup>(6)</sup>, reported that for SCC, a relative smaller modulus of elasticity can be expected, because of the high content of ultrafines and additives as dominating factors and accordingly minor occurrence of coarse and stiff aggregates at SCC. They also reported that the modulus of elasticity of SCC can be up to 20% lower compared with normal vibrated concrete having the same compressive strength and made of the same aggregates.

**Ouchi** <sup>(41)</sup>, reported that the modulus of elasticity of self-compacting concrete ranges from (30-36)GPa at age of 28 days.

## **2.10 Sulfate Attack :-**

Perhaps the most widespread and common form of chemical attack is the action of sulfates on concrete <sup>(45)</sup>.

Sulfate attack is one of the most common aggressive actions that lead to the deterioration of concrete. Usually, sulfate ions from an external source penetrate into concrete, resulting later in the formation of expansive ettringite by their reaction with alumina from cement. The way by which ettringite formation causes expansion **is still a subject of controversy** that even with low C<sub>3</sub>A cements expansive ettringite can be

formed, the alumina being supplied by the aggregates. In some conditions, calcium silicates may be also attacked with formation of thaumasite <sup>(46)</sup>.

**Mattey** and **Lowry** <sup>(47)</sup> , stated that the degradation of Portland cements by sulfate attack is well known and involves replacement of calcium silicate hydrate (C-S-H) by **ettringite** ( $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 31\text{H}_2\text{O}$ ) or **gypsum** ( $\text{CaSO}_4\cdot 2\text{H}_2\text{O}$ ).

### **2.10.1 External Sulfate Attack [ESA] :-**

Though [ESA] is out of the scope of this study, it is discussed here to cover the problem of sulfate attack as much as possible.

The reaction occurs between the sulfates , which come from external source such as the soil , ground water , sea water and sewage water , with concrete or cement paste .

External sulfate attack can be defined as a chemical between external sulfates and concrete or mortar, primarily with calcium aluminate hydrates in the cement paste matrix, often causing deterioration.

Solid salts do not attack concrete , but when present in solution they can react with hardened cement paste . Some clays contain alkali , magnesium and calcium sulfates , and the groundwater in such a clay is in effect a sulfate solution .Attack of cement can thus take place , the sulfate reacting with  $\text{Ca}(\text{OH})_2$  and with calcium aluminate hydrate <sup>(42)</sup>.

The products of the reactions ,gypsum and calcium sulphoaluminate , have a considerably greater volume than the compounds they replace , so that the reactions with the sulfate lead to expansion and disruption of the concrete .

For external sulfate attack (ESA) to occur the following three conditions must be presented :

1. High permeability of concrete
2. Sulfate – rich environment
3. Presence of water

**Bensted** <sup>(48)</sup>, stated the conditions needed to be present in the environment for sulfate attack to take place on mortar and concrete are as follows :

- 1) Soluble sulfate
- 2) Water (moisture)
- 3) Tricalcium aluminate ( $C_3A$ ) in the cement
- 4) Permeability of the mortar or concrete

According to **Jackson and Dhir** <sup>(49)</sup> , the sulfates commonly exist in soil and ground water are sulfates of sodium, potassium, magnesium, calcium and ammonium sulfates also can somewhat exist. These types of sulfates can react with calcium hydroxide and tricalcium aluminate ( $C_3A$ ), to form calcium sulfate (gypsum) and calcium sulfoaluminate compounds, resulting in expansion due to these two products.

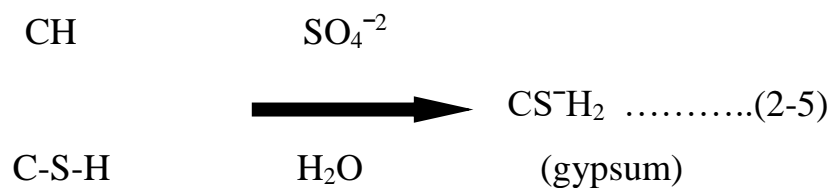
**Tian and Cohen** <sup>(50)</sup> , stated that the expansion due to gypsum formed is controversial.

The results obtained by **Wafa** <sup>(51)</sup> , showed that the use of a high w/c ratio with Portland cement produced weak concrete with a loss of compressive strength up to (50)% after (15) months of sulfate exposure. He also concluded that using a rich mixture with type V cement and low w/c ratio produced dense impermeable concrete that showed no loss of strength even after (15) months of sulfate exposure in a hot humid environment. The cement content is another factor affecting the sulfate attack resistance by its effect on permeability of concrete.

**Al-Khalaf and Yousif** <sup>(52)</sup>, reported that a fly ash that has a lime content exceeding (10%) resulted in an adverse effect on concrete resistance to sulfate attack.

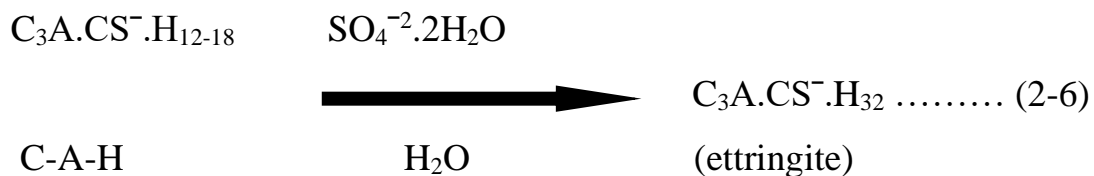
The ESA- related damage manifests itself in several forms including cracking and spalling. The specific manifestation of the ESA-related damage depends on which of the following three chemical processes is predominant:

1) Sulfate attack on CH and C-S-H to form gypsum



This process may cause expansion and spalling. However, its most important feature is the loss of strength and adhesion of the paste due to decalcification of C-S-H, which is responsible for the binding capacity of the cement paste <sup>(53)</sup>. This process may occur with sulfate salts (containing  $\text{Na}^+$ ,  $\text{K}^+$ ) but not calcium or magnesium sulfate.

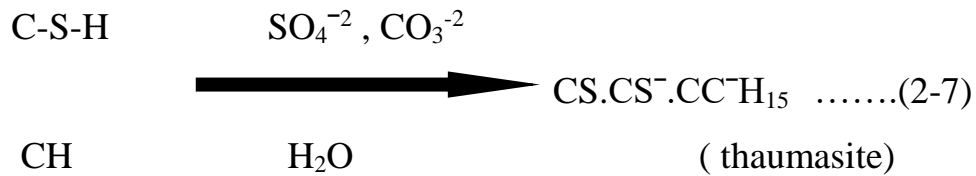
2) Sulfate attack on calcium aluminate hydrates (C-A-H) and monosulfate hydrate ( $\text{C}_3\text{A}.\text{CS}^-. \text{H}_{12-18}$ ) to form ettringite:



This process is mainly responsible for cracking and spalling as a result of expansion produced by delayed ettringite formation. This process may

occur with all the sulfate salts (except MgSO<sub>4</sub>) including calcium sulfate, which acts directly on C-A-H and/or monosulfate hydrate.

3) sulfate attack on C-S-H and CH in the presence of carbonate ions to form thaumasite :



Where

S : calcium sulfate

C<sup>·</sup>: calcium carbonates ( Arconite)

The thaumasite formation is accompanied by the most severe loss of strength and adhesion which is able to transform hardened concrete into a pulpy mass , since a significant part of C-S-H can be destroyed according to the reaction shown above .This process may occur with every type of sulfate salts and is favored by humid atmospheres and low temperature (< 10 °C) <sup>(54)</sup>.

### **2.10.2 Internal Sulfate Attack [ISA] :-**

Internal sulfate attack results from the reaction between sulfate in (cement , fine aggregate , coarse aggregate ) and cement paste or concrete which had calcium aluminates (C<sub>3</sub>A) and water to form calcium sulphoaluminate . The hazard is illustrated in the materials which cause high tensile stresses lead to expansion and disruption of concrete .

Sulfates may come either from raw materials and/or from gypsum added to cement at the grinding stage.

**Al-Qaisi** <sup>(55)</sup>, stated that the activity of gypsum is dependent on its fineness.

In their study on the effective sulfate content in concrete ingredients **Al-Rawi et al.** <sup>(56)</sup>, pointed out that the effect of SO<sub>3</sub> existing in cement on compressive strength of concrete is about two times more than in fine aggregate and effect of the latter is about two times more than in coarse aggregate. They attributed this to the fine particle size distribution of cement compared with fine aggregate and coarse aggregate.

In a later study by **Al-Rawi** <sup>(57)</sup>, to develop the concept of effective sulfate content, he found that the effectiveness of sulfates increased with increased fineness of fine aggregate. He suggested a formula to account for the effectiveness of sulfates in fine aggregate depending on its fineness modulus. He showed also that the same formula is applicable for the effectiveness of sulfates in coarse aggregates.

The sulfate content in fine aggregate contains sulfate higher than the acceptable limits in most of the fine aggregate in Middle East countries <sup>(58)</sup>.

**Collepari** <sup>(59)</sup>, stated that the ISA-related damage is relatively “new” with respect to the “traditional” external sulfate attack (ESA) since it was detected in the middle of 1980's in prestressed concrete railway ties.

### **2.10.2.1 Unsoundness Due to Presence of Gypsum :-**

The effect of sulfates on concrete durability is associated with ettringite formed by chemical reaction between sulfate ions contained in gypsum and certain constituents in concrete;



This reaction may generate deterioration in normal Portland cement concrete including expansion, loss of strength, and sometimes disintegration. Although, ettringite that causes expansion in some cases is apparently responsible for high strength in other cases as explained below:

The effect of the formation of sulfoaluminates on the strength and volume stability of hardened cement paste depends on the stage of hardening in which they are formed. **Troxell** <sup>(60)</sup>, who stated that the formation of sulfoaluminates in the early stages of hardening is useful structurally and leads to an increase in strength because the accompanying increase in volume can be accommodated without damage to the paste structure.

**Lerch** <sup>(61)</sup>, had done an interesting study about the effect of gypsum content on the hydration and properties of Portland cements mortar. He attributed the increase in strength with increase amount of gypsum content to its effect on accelerating the rate of hydration of Portland cement, particularly at early ages. He also found that a relationship between the strength and the degree of hydration at later ages does not exist. The heat of hydration decreases while the strength increases with increasing  $SO_3$  content. This result leads to the idea that the larger additions of gypsum, at least in part, affect the structure of the hardened paste.

**Al-Khalaf** <sup>(62)</sup>, stated that the increase in sulfate concentration increases the rate of sulfate attack. However, at low percent of sulfate, the strength increases with the increase in sulfate content up to an optimum value of sulfate content, after which the strength of concrete begins to decrease gradually. The strength decreases with the increase of sulfate and this decrease in strength is more at ages of 180 and 360 days than 7 and 28 days.

**Al-Rawi** <sup>(63)</sup>, pointed out that the formation of sulfoaluminates in hardened cement paste may lead to lower strength and undesirable expansion because the increase in volume within the structure of hardened cement paste causes large inner strains to develop. These strains may result in the disintegration of cement paste.

As reported by **Taylor** <sup>(64)</sup>, sulfate attack on concrete causes the concrete to weaken and this is normally accompanied by expansion.

**Hobbs** <sup>(65)</sup>, stated that if all the gypsum is not consumed when set occurs and the transformation of  $C_3A$  into ettringite continues after the concrete has hardened, then this may cause disruption in the hardened concrete.

**AL-Rawi** <sup>(66)</sup>,stated that the presence of sulfates in fine aggregate or in any concrete constituent will cause reaction with some cement compounds , mainly  $C_3A$  , such a reaction was associated with considerable increase in solid volume . This may be harmful to concrete structure because of the large stresses induced . This harmful effect was demonstrated by a larger reduction in compressive strength which was apparent at early ages ( as early as 3 days ) . This reduction will increase with time if the sulfate content was high , but it will be minimized by autogenous healing if the sulfate content was low , as in this case it depleted within a short period after casting concrete .

**AL-Rawi** <sup>(67)</sup> ,pointed out that a major causes of failure of concrete structures in the middle east was the contamination of fine aggregate with sulfates in the form of gypsum .The research pointed to the gypsum is normally added to cement to retard early hydration and prevent quick set .The total sulfate in concrete may , therefore ,be high enough to cause internal sulfate attack . This may lead to deterioration and possibly cracking and failure of concrete structures .

To avoid the adverse effects of sulfates, several specification put an upper limit on sulfate content in aggregates or on total sulfates in concrete . In some countries it is difficult to find aggregates with the required low sulfates content .

He also shows that it is possible to reduce the gypsum added to cement and consequently raise the upper limit of sulfate content in aggregate . This will allow the use of huge reserves of fine aggregate with no durability risk or undue loss in concrete strength . The reduction in gypsum will reduce the grinding efficiency. This may be overcome by addition of small percentage of pozzolan or lime . Reduction of gypsum will also cause a slight decrease in setting time of cement , but pozzolan addition will restore the original setting time <sup>(67)</sup>.

**Al-Salihi** <sup>(68)</sup>, observed that increasing the SO<sub>3</sub> content in fine aggregate affected the compressive and flexural strength and the dimensional changes of concrete. This effect is more significant than increasing SO<sub>3</sub> in coarse aggregate ; he concluded that the activity of sulfates in a concrete mix on its properties is dependent upon the sulfates bearing constituents.

### **2.10.2.2 Delayed Ettringite Formation :-**

Another reason for delayed expansion in cement paste, mortar and concrete which drew researchers attention in the last few years is the delayed formation of ettringite under heat-curing conditions. This leads to a deleterious expansion of concrete that may occur after curing at elevated temperature and subsequent exposure to moisture.

There are two different types DEF-related damage depending on the sulfate source, as shown in Table (2-3) <sup>(59)</sup> .

**Table (2-3): (DEF) caused by (ISA) and (ESA) <sup>(59)</sup>**

<b>Delayed Ettringite Formation (DEF)</b>
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<b>External sulfate Attack</b>	<b>Internal sulfate attack</b>
<p>1-It occurs when environmental sulfate (from water or soil) penetrates concrete structures in service.</p> <p>2-It occurs in a permeable concrete.</p> <p>3-It occurs in a moist environment.</p>	<p>1-It occurs in a sulfate- free environment for the late sulfate release from gypsum-contaminated aggregate or thermal decomposition of ettringite.</p> <p>2-It is favoured by preliminary microcracks where decomposition of ettringite crystals can occur.</p> <p>3-It occurs in a moist environment.</p>

There are several indications that the C-S-H gel phase may play a role in the expansion process. It was observed by **Odler** <sup>(69)</sup>, that calcium sulfate bound to the C-S-H phase formed from C<sub>3</sub>S hydration can serve as a source of SO<sub>4</sub><sup>-2</sup> ions needed for delayed ettringite formation.

**Taylor** <sup>(70)</sup> and **Lawrence** <sup>(71)</sup>, stated that the delayed ettringite formation (DEF) related to internal sulfate attack may also occur in large section and massive elements of non steam – treated concrete , where the heat of the hydration of the cement or an external heat source during service , may have caused 70°C or more temperature rise in concrete at early age .

**Divet and Randriambololona** <sup>(72)</sup>, demonstrated that the adsorption capacity of sulfate ions is high and is directly related to the basicity of the pore solution of concrete and to the temperature and they favor adsorption by C-S-H phases.

**Idorn** <sup>(73)</sup>, showed that ettringite becomes unstable at temperature exceed 60 to 70°C. Above these temperatures the result is decomposition of the ettringite already formed and no further formation of ettringite. During subsequent storage at ambient temperature, ettringite slowly reforms, results in cracking of the hardened concrete.

According to this mechanism for the internal sulfate attack related delayed ettringite formation <sup>(74)</sup> is based on the presence of three essential elements :

- 1- microcracking
- 2- late sulfate release
- 3- Exposure to water

### **2.10.2.3 Mechanism of Expansion Due to Ettringite Formation :-**

Several hypotheses have been introduced on the mechanism of expansion associated with ettringite formation.

**Hansen** <sup>(75)</sup>, showed that solid state conversion of  $C_3A$  to ettringite could cause eight – fold volumetric increase. He suggested that cement minerals could react as solid with water and with materials dissolved in water to be transformed directly into other solids.

An explanation introduced by **Mehta** <sup>(76)</sup>, interpreted the contradicting results of expansion with the rate of ettringite formed. He stated that there are two types of ettringite, the first one is a large lath – like crystals that are responsible for high strength but no expansion under conditions of low hydroxyl ions. The other type is a small rod – like crystals formed under conditions of high hydroxyl ions concentration. Large amount of these crystals was found in concrete deteriorated due to sulfate attack. So this type of ettringite can cause expansion depending on the environmental conditions such as restraint of the system, stiffness of the

cement paste, and the type and concentrations of ions in the contact solution.

**Kadhun** <sup>(77)</sup>, concluded in her work that increasing sulfate content in fine aggregate from 0.5 % to 2 % has a large effect on expansion of lean concrete mixes (w/c=0.86, 1:3:6 and w/c=0.67, 1: 2.6 : 3.6). The expansion increases from 300 micro-strain to about 1200 micro-strain at age of 180 days. The effect of increasing SO<sub>3</sub> in fine aggregate on expansion decreased with the increase in concrete mix richness .Table (2-4) represents the limitations of SO<sub>3</sub> % according to some standards.

**Table (2-4): Maximum allowable SO<sub>3</sub> limits in concrete and aggregate** <sup>(68)</sup>

Standards	Allowable SO <sub>3</sub> % (by wt. of agg.)	Allowable SO <sub>3</sub> % (by wt. of cement.)
BS 5328-1981	0.4	4.0
DIN 4226-1974	1.0	-
ISO 383-1976 (part 1)	0.5	-
JOST 4797-4798	1.0	-
IOS 45-1984	0.5 % in fine agg. <0.1%in coarse agg. 0.75 % in fine agg. <0.1 % in coarse agg.	4 Wet 4 = 4.5 dry 4.5 =

**Alwash** <sup>(78)</sup>, the percentage reduction in compressive strength of the mix with OPC and sand of zone 2 which contains sulfate of 1.5% by weight of it compared with the reduction in strength of the mix with OPC and sand of zone 4 which contains sulfate 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 and the influence of sulfates on the splitting tensile strength and static modulus of elasticity is found to be some what similar to that of compressive strength.



# Chapter **3** Experimental Work

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## **3.1 Introduction :-**

This chapter includes detailed information about the description of materials and mixes, mixing procedure, casting and curing .Various testing procedures adopted throughout this investigation were presented.

The tests are conducted in order to view the differences in behavior occurred during the fresh state as well as the hardened state. The Slump flow, L-box, U-box and V-funnel are performed during the fresh state. After the concrete has cured; compressive strength of (99) cubes, splitting tensile strength of (66) cylinders, flexural strength of (54) prisms, static modulus of elasticity for (18) cylinders are measured and non- destructive tests are performed.

## **3.2 Program of the work :-**

For each concrete mix four levels of  $SO_3$  contents in fine aggregate were investigated; these levels were 0.16%, 0.5%, 1.0%, , 1.5% by wt. of fine aggregate .Three types of fillers(limestone powder, pigment,hydrated lime)were used and curing time for (28,90,180 days) were conducted . Two types of curing (moist, wetting and drying)were followed . The identification of each concrete mix was summarized in Table (3-1).

**Table (3-1): Concrete mix designations**

Mixes designation	Types of filler	Curing time (days)	SO <sub>3</sub> content in sand (by weight of sand) %	Total SO <sub>3</sub> content (by weight of cement) %
ML <sub>0</sub>	Limestone Powder	28,90,180	0.16	3.22
ML <sub>1</sub>			0.5	3.79
ML <sub>2</sub>			1.0	4.62
ML <sub>3</sub>			1.5*	5.45
MP <sub>0</sub>	Pigments	28,90,180	0.16	3.07
MP <sub>1</sub>			0.5	3.63
MP <sub>2</sub>			1.0	4.47
MP <sub>3</sub>			1.5*	5.31
MH <sub>0</sub>	Hydrated Lime	28,90,180	0.16	3.02
MH <sub>1</sub>			0.5	3.58
MH <sub>2</sub>			1.0	4.42
MH <sub>3</sub>			1.5*	5.25

- \* Wetting and drying curing .

### **3.3 Materials :-**

#### **3.3.1 Cement :-**

Ordinary Portland cement produced at India (Lion) conformed to (Type I -IOS 5/1984) <sup>(79)</sup> was used through- out this investigation . The chemical composition and physical properties of this cement are presented in Tables (3-2) and (3-3) respectively .

**Table (3-2): Chemical composition of cement \***

Compound Composition	Chemical Composition	Percentage by weight	Limits of IOS 5:1984
Lime	CaO	61.40	–
Silica	SiO <sub>2</sub>	21.86	–
Alumina	Al <sub>2</sub> O <sub>3</sub>	4.66	–
Iron Oxide	Fe <sub>2</sub> O <sub>3</sub>	4	–
Magnesia	MgO	1.67	<5
Sulfate	SO <sub>3</sub>	2.56	<2.8
Loss on Ignition	L.O.I	3.16	<4
Insoluble residue	I.R	0.85	<1.5
Lime saturation factor	L.S.F	0.84	0.66-1.02
<b>Main Compounds (Bogue's equation) percentage by weight of cement</b>			
Tricalcium silicate (C <sub>3</sub> S)		39.43	
Dicalcium Silicate (C <sub>2</sub> S)		33.01	
Tricalcium Aluminate (C <sub>3</sub> A)		5.59	
Tetraclcium Aluminoferrite (C <sub>4</sub> AF)		12.16	

**Table (3-3): Physical properties of cement**

Physical Properties	Test result	Limits of IOS 5:1984
Fineness using Blain air permeability apparatus (m <sup>2</sup> /kg)	3100	>2300
Soundness using Autoclave method	0.19%	<0.8%
Setting time using Vicat's instruments		
Initial (hrs: min)	3:3	≥ 0:45
Final (hrs: min)	4:15	≤ 10:00
Compressive strength for cement paste mortar		
3 days (MPa)	16	>15
7 days (MPa)	24	>23

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

### **3.3.2 Fine Aggregate (sand) :-**

AL-Akhaider natural fine aggregate with fineness modulus =2.37 was used throughout this work. Table 3-4 illustrates the sieve analysis of fine aggregate. Results indicate that the fine aggregate grading and the sulfate content are within the requirements of the Iraqi specification No. 45/1984<sup>(80)</sup>. Table (3-5) illustrates the physical and chemical properties of fine aggregate.

**Table (3-4): Grading of fine aggregate**

No.	Sieve size(mm)	Passing %	Limits of Iraqi specification No. 45/1984 for zone 2
1	4.75	94	90-100
2	2.36	80	75-100
3	1.18	67	55-90
4	0.60	51	35-59
5	0.30	21	8-30
6	0.15	4	0-10

**Table (3-5): Physical and chemical properties of fine aggregate\***

No.	Properties	Test Results	Limits of Iraqi specification No.45/1984
1	Specific gravity	2.60	–
2	SO <sub>3</sub> content	0.16%	≤ 0.5%

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

### **3.3.3 Coarse Aggregate (gravel) :-**

Rounded coarse aggregate of passing sieve size 14 mm from AL-Nibae quarry is used. The coarse aggregate was washed, then stored in air to dry. Table (3-6) shows the grading of this aggregate, which conforms to the Iraqi Specification No.45/1984<sup>(80)</sup>. The specific gravity and sulfate content and absorption of coarse aggregate are illustrated in Table (3-7).

**Table (3-6): Grading of coarse aggregate**

No.	Sieve size(mm)	Passing %	Limits of Iraqi specification No. 45/1984 for zone 2
1	14	100	95-100
2	10	89	85-100
3	5	11	0-25
4	2.36	0	0-5

**Table (3-7): Physical and chemical properties of coarse aggregate \***

No.	Properties	Test Results	Limits of Iraqi specification No.45/1984
1	Specific gravity	2.65	–
2	SO <sub>3</sub> content	0.08%	≤ 0.1%

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University. \_

### **3.3.4 Water :-**

Tap water is used throughout this work for both mixing and curing of concrete.

### **3.3.5 Superplasticizer :-**

Superplasticizer (SP) is an essential component for SCC production. It is used to achieve high workability and stability for SCC <sup>(10)</sup>. According to ASTM C494, this SP is classified as type G.

The technical description of the Superplasticizer is given in the Table (3-8).

**Table (3-8): Technical description of the Superplasticizer (SP) \***

<b>Color</b>	Brown liquid
<b>Freezing point</b>	-2 °C approximately
<b>Specific gravity</b>	1.13 kg/l @ 25 °C
<b>Air entrainment</b>	Less than 2%
<b>Chloride content</b>	Nil

\* Technical description obtained from product catalogue.

### **3.3.6 Filler Materials :-**

Three types of filler materials are used for the purpose of this study. Limestone powder, pigment and hydrated lime.

#### **3.3.6.1 Limestone Powder (LSP) :-**

Limestone powder is a white ground material from limestone that found in different regions in Iraq, and usually used in the construction processes. Limestone powder which has been brought from local market is used to increase the amount of powder (cement + filler), the fraction less than 0.125mm will be of most benefit. This filler conforms to BS 7979 <sup>(27)</sup>. The chemical analysis of LSP is listed in Table (3-9).

**Table (3-9): Chemical analysis of the limestone powder \***

Oxide	Content %
SiO <sub>2</sub>	1.34
Fe <sub>2</sub> O <sub>3</sub>	0.12
Al <sub>2</sub> O <sub>3</sub>	0.69
CaO	55.13
MgO	0.13
SO <sub>3</sub>	1.70
L.O.I	40.56

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

### **3.3.6.2 Pigments :-**

The suitability of pigments used in SCC was established in EN 12878<sup>(29)</sup>. Pigments was used for the colouration of building, and filling material to improve the properties of fresh and hardened concrete. This material was brought from local market, then it was used in the concrete mixes after passing sieve number 0.075mm. The chemical analysis of the pigment is shown in Table (3-10).

**Table (3-10): Chemical analysis of the pigment \***

Oxide	Content %
SiO <sub>2</sub>	4.13
Fe <sub>2</sub> O <sub>3</sub>	0.10
Al <sub>2</sub> O <sub>3</sub>	0.50
CaO	63.21
MgO	0.14
SO <sub>3</sub>	0.70
L.O.I	31.15

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

### **3.3.6.3 Hydrated Lime :-**

This material was brought from karbalaa lime factory. The chemical and physical analysis of the hydrated lime is shown in Table (3-11).

**Table (3-11): Chemical and physical analysis of the hydrated lime \***

Oxide	Content %	Limits of Iraqi specification NO. 807 /1989
SiO <sub>2</sub>	2.8	<5%
Fe <sub>2</sub> O <sub>3</sub>	0.21	
Al <sub>2</sub> O <sub>3</sub>	-	
MgO	0.39	<5%
MgO+CaO	72.10	>=64%
SO <sub>3</sub>	0.32	-
L.O.I	23.41	-
CO <sub>2</sub>	1.75	<5%
Retained on sieve 90 μ	3.2	<=10

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

### **3.3.7 Gypsum :-**

Gypsum is added to the fine aggregate to obtain the required SO<sub>3</sub> content. The added gypsum is natural gypsum rock (brought from Kufa cement factory). Table (3-12) shows the chemical properties of gypsum.

**Table (3-12): The chemical properties of gypsum\***

Compound composition	Percent
SiO <sub>2</sub>	1.46
R <sub>2</sub> O <sub>3</sub>	0.36
CaO	32.72
MgO	0.97
SO <sub>3</sub>	42
I.R	0.68

Fe<sub>2</sub>O<sub>3</sub>Al<sub>2</sub>O<sub>3</sub>

\* Chemical tests were conducted in Construction Materials Laboratory of Babylon University.

It was crushed and ground to obtain nearly the same gradation set of fine aggregate used in the mix. This gypsum was used as a partial replacement by weight of fine aggregate with limited percentages.

The quantity of natural gypsum was calculated and added to the fine aggregate according to the following equation: <sup>(58)</sup>

$$W = (R - M) S / N \quad \dots\dots\dots (3-1)$$

Where:

W= the weight of natural gypsum needed to be added to fine aggregate.

R= the percentage of SO<sub>3</sub> % desired in fine aggregate.

S = the weight of fine aggregate in mix.

M = the actual SO<sub>3</sub> in fine aggregate (0.16 %).

N= the percentage of SO<sub>3</sub> % in the used natural gypsum (42).

### **3.4 Mix proportion :-**

The SCC mix Proportions are summarized in Table (3-13).

**Table (3-13): Mix proportions<sup>(14)</sup>**

Materials	Content	Limitation (Kg/m <sup>3</sup> )
Cement (kg/m <sup>3</sup> )	450	350-450
Fine aggregate (kg/m <sup>3</sup> )	750	710-900
Coarse aggregate (kg/m <sup>3</sup> )	790	750-920
Filler (kg/m <sup>3</sup> )	65	50-150
(Water / powder) ratio	0.45	0.33-0.62
SP (Liter/100kg cement)	3	-

### **3.5 Mixing procedure :-**

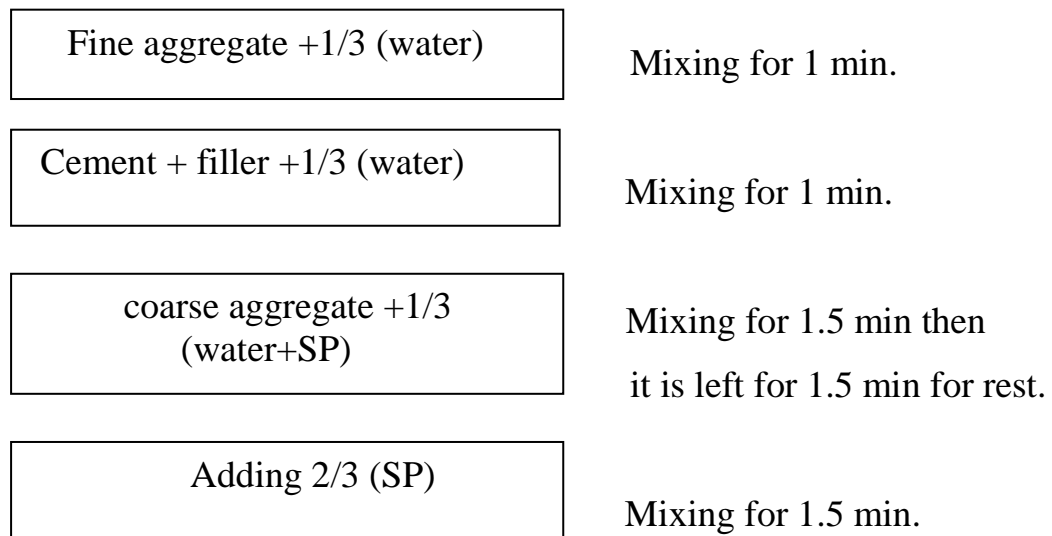
The required amount of gypsum was added to the fine aggregate, in order to obtain the desired level of SO<sub>3</sub> in the sample then fine aggregate and gypsum were mixed until a homogeneous mix is obtained.

Mixing procedure is important to obtain the required workability and homogeneity of the concrete mix. Concrete was mixed in drum laboratory mixer, with a capacity of 0.05m<sup>3</sup>. Before starting to mix, it is necessary to keep the mixer clean, moist and free from previous mixes.

The procedure used for mixing the batches was as follows: <sup>(81)</sup>

- 1- Adding the fine aggregate to the mixer with 1/3 water, and mixing for 1 minute.
- 2- Adding the powder (cement+filler) with another 1/3 mixing water, and mixing for 1 minute.
- 3- After that, the coarse aggregate is added with the last 1/3 mixing water and 1/3 of superplasticizer, and mixing for 1.5 minute then the mixture is left for 1.5 minute for rest.

4- Then, the remaining 2/3 of the superplasticizer is added and mixed for 1.5 minute as shown in Fig. (3-1).



**Fig. (3-1): Mixing procedure<sup>(81)</sup>**

### **3.6 Test methods for fresh SCC :-**

Fresh concrete tests are necessary in this study. SCC is defined by its behavior when it is in the fresh state, and it is determined whether concrete meets certain requirements, as stated in chapter 2, while flowability is an essential property in qualifying concrete as SCC or not. The slumpflow, L-box, U-box, V-funnel and V-Funnel at T5 minutes are all used for all mixes of this study.

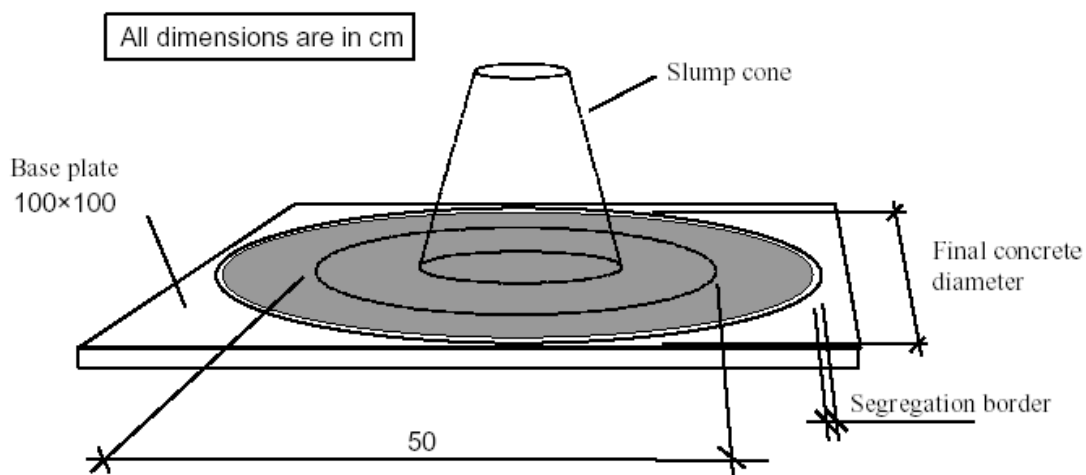
#### **3.6.1. Slump flow and T50cm tests :-**

The slump flow test is the most widely used method for evaluating concrete consistency and filling ability in the laboratory and at construction sites and can indicate segregation resistance of SCC to an experienced user.

The procedure described below has been followed in this respect :

1. The base plate is surely fixed horizontal and a circle with 50 cm diameter is marked on it.

2. The surfaces of the cone and the plate are cleaned with water then dried with a cloth so that they are moist, but without free water.
3. The slump cone is placed concentrically on the plate.
4. The slump cone is filled with concrete while pressing the slump cone to the table.
5. The slump cone is lifted vertically
6. The timing is started when lifting of the slump cone starts and the time taken for the concrete to reach the 50cm spread circle is recorded (This is the T50 cm time the value of T50 cm is to be (2-5) Sec).
7. When the concrete stopped flowing, the final diameter (D-final) of the concrete was measured by measuring two perpendicular diameters, the value (650-800) mm, is the best indicator of flow. The presence of mortar or cement paste without coarse aggregate at the edge of the pool of concrete can indicate segregation; The apparatus is shown in Fig. (3-2)



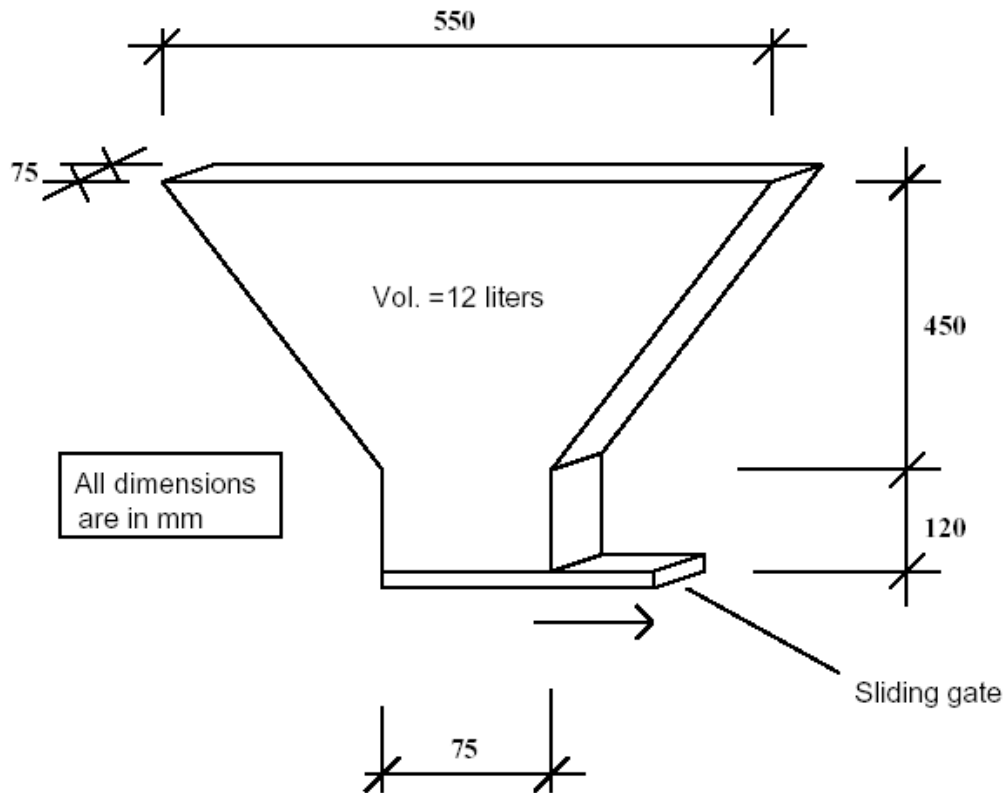
**Fig. (3-2): Apparatus for slump flow test** <sup>(37)</sup>

### **3.6.2 V-funnel test and V-Funnel at T5 minutes Tests :-**

The V-funnel is used to measure the filling ability (flowability) of SCC and can also be used to evaluate the material segregation resistance. The equipment consists of a V-shaped funnel, shown in Fig (3-3).

The procedure of the test is as follows:

1. About 12 liters of concrete are needed to perform the test.
2. The V-funnel is set on firm ground.
3. The inside surfaces of the V-funnel is moistened.
4. The bottom gate is kept open to allow any surplus water to drain.
5. The V -funnel is placed so that a container can be placed underneath the funnel opening.
6. The V-funnel is filled to its upper level with concrete.
7. The concrete is rested for 10 sec in the V-funnel.
8. The gate is opened then start timing exactly when opening the gate.
9. The time is recorded for the concrete to flow out of the V-funnel (Flow-time).The flow time (6-12) sec is the best indication of flowability and stability of SCC.
10. The concrete should be observed while it flows out. If any blocking occurs leading to total stop of flow or temporary stops (indicating instability).
11. Without cleaning or moistening the inside surfaces of the funnel, the bottom gate is closed and the V-funnel is immediately refilled.
12. The bottom gate is opened after 5 minutes from refilling the funnel and the concrete is allowed to flow out under gravity.
13. Simultaneously, the stopwatch is started when the bottom gate is opened, and the time for the complete discharge (the flow time at T5 minutes) is measured.



**Fig. (3-3): V-funnel test** <sup>(82)</sup>

### **3.6.3 L-box test :-**

The L-box test measures the passing ability of self-compacting concrete. Originally developed in Japan for underwater concrete <sup>(10)</sup>.

The procedure described below has been used:

1. The apparatus level is set on firm ground.
2. The inside surface of the apparatus is moistened then any surplus water is removed..
3. The vertical part of the box is filled with 12.7 liters of concrete.
4. The concrete is rested in the vertical part for one minute.
5. The sliding gate is lifted; Concrete will now flow out of the vertical part into the horizontal part of the L-box.
6. When concrete stops, the height of the concrete measurement at the beginning and end of the L-box.

7. Calculate  $H_2/H_1$ , the blocking ratio ( $H_2/H_1$ ) (0.8 to 1.0) is the best value which indicates the slope of concrete at rest and is an indication of the passing ability.

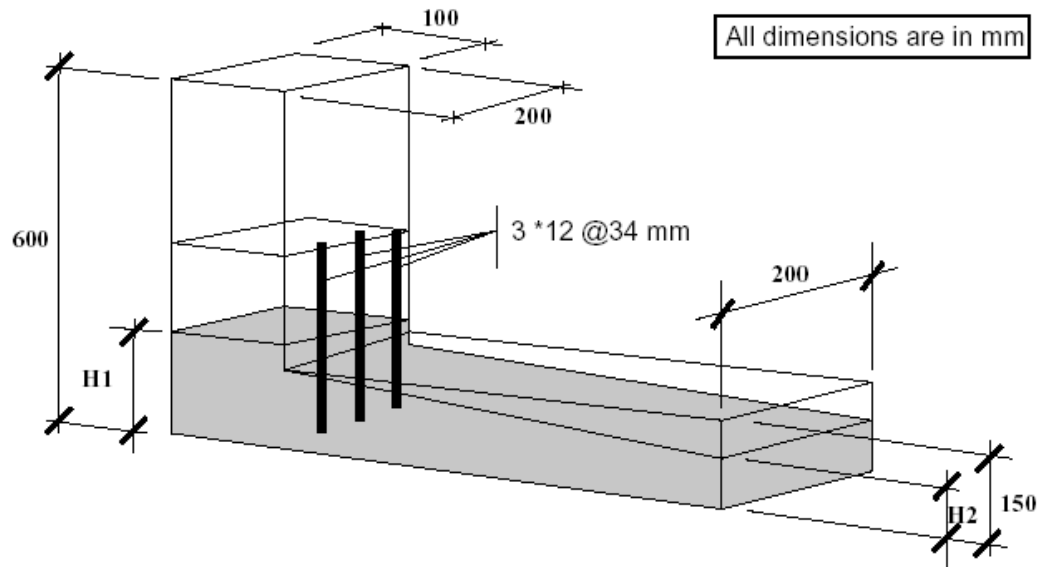


Fig. (3-4): L-box test <sup>(37)</sup>

### **3.6.4 U-box test :-**

U-box test is used to measure the filling ability of SCC. The procedure of the test is as follows : **All dimensions are in mm**

1. The apparatus is leveled on firm ground and the sliding gate is checked to make sure that it can be opened and closed freely.
2. The inside surfaces of U-box are moistened then any surplus water is removed.
3. The one compartment of the U-box is completely filled with concrete while the sliding gate between the two compartments is closed.
4. The concrete is left to stand for 1 minute.
5. The sliding gate is lifted and allows the concrete to flow out into the other compartment.
6. After the concrete has come to rest, the height of the concrete will be measured in the compartment that has been filled, in two places and the

mean ( $H_1$ ) is calculated. Measure also the height in the other compartment ( $H_2$ ).

7. The filling height ( $H_1 - H_2$ ) is calculated. The filling height is considered as an acceptable value for SCC when it ranges from 0 to 30 mm.

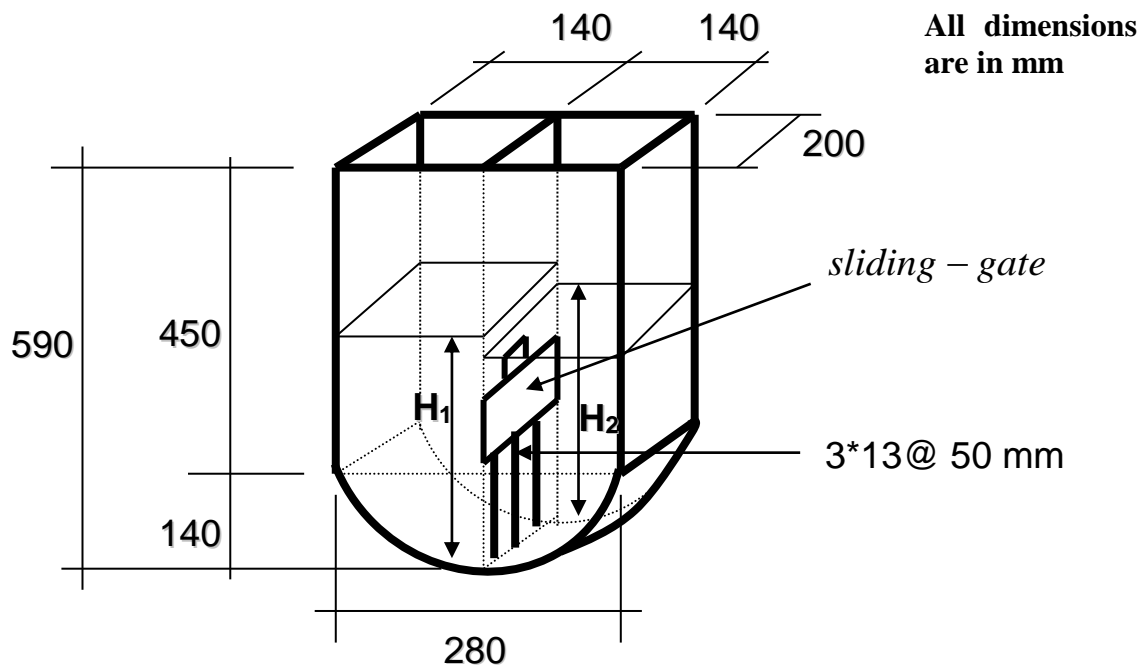


Fig. (3-5): U-box test <sup>(10)</sup>

### 3.7 Casting and Curing of Test Specimens :-

All test specimens were cast in tight steel moulds. These moulds are cleaned and their internal surfaces were oiled to prevent adhesion with concrete after hardening. The moulds were filled with concrete in one layer without compaction. Then the concrete surface is leveled and smoothed by means of trowel and the specimens left in the air for about 24 hr. After that, the specimens were demolded and immersed in tap water. Since, SCC was made with low water to powder ratios; water curing is very essential due to the high amount of fine materials (cement + fillers).

To adjust water temperature in  $25 \pm 3^\circ\text{C}$  that is used for curing a heater with a thermostat are used for this purpose .

Two types of curing are simulated:-

1. Moist curing in water until testing age at 28 , 90 and 180 days.
2. Wetting and drying curing for specimens contained 1.5%  $\text{SO}_3$  in fine aggregate were subjected to five alternate cycles of wetting and drying after they had been cured in tap water for 28 days in such manner that each cycle consisted of moist curing at  $(20 \pm 5^\circ\text{C})$  for four days and drying in the oven at  $(105 \pm 5^\circ\text{C})$  for one day then the specimens were in the water for remaining ( 28,118)days

### **3.8 Testing of hardened concrete :-**

#### **3.8.1 Destructive tests :-**

##### **3.8.1.1 Compressive strength :-**

The compressive strength test was accomplished according to B.S.1881<sup>(83)</sup>. This test was conducted on 150 mm cubes by using a hydraulic compression machine with a capacity of 2000 kN. The average of three cubes was adopted for each test. The test was done at ages of 28, 90 and 180 days for moist curing and at ages of 90,180 for wetting and drying curing.

##### **3.8.1.2 Splitting tensile strength :-**

The splitting tensile strength test was performed according to ASTM C 496-86<sup>(40)</sup>. Cylindrical concrete specimens (100x200 mm) were used. The test was conducted at ages of 28, 90 and 180 days for moist curing and at ages of 90,180 for wetting and drying curing.

The splitting tensile strength was calculated from equation (3-2)

$$F_t = 2P / \pi DL \dots\dots\dots(3-2)$$

Where:

$F_t$  = splitting tensile strength (N/mm<sup>2</sup>) .

P = maximum applied load (N) .

D = diameter of cylinder (mm).

L = length of cylinder (mm).

Splitting tensile strength (MPa) is obtained by the mean results of two specimens.

### **3.8.1.3 Flexural strength :-**

Concrete prisms (100x100x400 mm) which were prepared according to ASTM C78-84 <sup>(39)</sup>. The prisms were cast, demolded and cured in a similar manner as the cubes. Prisms were tested using the two points loading with clear span of 300 mm according to the ASTM specification <sup>(39)</sup>. The test was conducted at ages of 28, 90 and 180 days for moist curing and each value of the modulus of rupture was the average of the test results for two specimens.

Modulus of rupture was calculated from the simple beam bending formula:

1. If the fracture initiates in the tension surface within the middle third of the span length, then

$$MR = P L / bd^2 \dots\dots\dots (2-2)$$

where:

MR = modulus of rupture, MPa

P = maximum applied load, N

b = average width of specimen, mm

d = average depth of specimen, mm

L = span length ,mm

2. If the fracture occurred in the tension surface outside the middle third of the span length by not more than 5% of the span length, then:

$$MR = 3 Pa / bd^2 \dots\dots\dots (2-3)$$

where:

a = average distance between line of fracture and the nearest support measured on the tension surface of the prism, mm.

### **3.8.1.4 Static Modulus of Elasticity :-**

The static modulus of elasticity was determined according to ASTM C 469-87 a<sup>(44)</sup>. The cylinder specimens (150x300 mm) are cured in water and tested at 28 days. The top surface of cylinders was well-finished and grinded with a grinding machine to avoid any loss of strength.

1- The first cylinder of each pair was tested to compressive failure by a hydraulic compression machine of 2000 kN and the load at failure was recorded.

2- The second cylinder of each pair was fitted with a proving rings which were clamped to have a gauge length of 200 mm. The contraction was measured by using a dial gauge with an accuracy of 0.01 mm.

3- A load equal to approximately 40% of the load at failure of the first cylinder was applied to the second cylinder to “seat” the gage, then the load was released and adjustments were made if necessary to ensure the gauge was properly seated.

4- The load was increased to approximately 40% of the load at failure of the first cylinder and the corresponding load and gage reading were recorded.

5- The load was released then the load was re-applied to check the accuracy of the gage reading.

6- The load was released and the gauge was removed.

The modulus of elasticity is calculated as follows:

$$E = S_2 - S_1 / \epsilon_2 - 50 \times 10^{-6} \dots\dots\dots (3-3)$$

Where:-

E: static modulus of elasticity, GPa .

S<sub>2</sub>: stress corresponding to (40) % of ultimate load in, GPa.

S<sub>1</sub>: stress corresponding to longitudinal strain of (50 x 10<sup>-6</sup>), GPa.

ε<sub>2</sub> : longitudinal strain produced by stress S<sub>2</sub> .

### **3.8.2 Non-destructive tests :-**

#### **3.8.2.1 Ultrasonic Pulse Velocity test (U.P.V.) :-**

This test was carried out according to BS 4408:Part5<sup>(84)</sup> using the portable ultrasonic concrete tester known as (PUNDIT) 54 KHz was used for this purpose. Ultrasonic pulse velocity method consists of measuring the time of travel of an ultrasonic pulse, passing through the concrete to be tested. The pulse generator circuit consisted of an electronic circuit for generating pulses and transducer for transforming these electronic pulses into mechanical energy having vibration frequency. The transducers are smeared with grease to give good contact. The time of travel between initial onset and the reception of the pulse was measured electronically. The path length between transducers, divided by the time of travel, gave the average velocity of wave propagation:

$$V = L / T \dots\dots\dots (3-4)$$

Where:

V = Ultrasonic pulse velocity, km/sec

L = Path length, mm

T = transit time,  $\mu$ sec .

#### **3.8.2.2 Schmidt rebound hammer test :-**

Schmidt hammers were used to estimate the surface hardness of concrete specimens by recording the rebound number, which could be used as a measure of the concrete strength and surface hardness. The test method was described by BS 1881:202<sup>(85)</sup> specifications. The test results of rebound number were the average of 5 readings on each face of the concrete cube.

# Chapter 4 Results and Discussion

## 4.1 Introduction :-

The discussion is divided into two parts :

The first part presents the results of testing the fresh properties of self compacting concrete which are Slump flow and T50cm, U-box, V-funnel ,V-funnel at  $T_{5 \text{ min}}$  and L-box.

The second part presents the results of testing the mechanical properties of self compacting concrete which are, (compressive strength, splitting tensile strength& flexural strength as well as static modulus of elasticity in addition to two non-destructive tests, ultrasonic pulse velocity and schmidt rebound hammer) have been studied and discussed .

## 4.2 Fresh Concrete properties :-

### 4.2.1 Slump Flow and T50 cm Results: -

The flowing ability of fresh concrete is described by slump flow investigated with Abrams cone which is the simplest and most widely used test method for self-compacting concrete .

The values of Slump-flow represent the maximum spread (slump flow final diameter) obtained by calculating the average of two perpendicular measured diameters for determining the slump flow of SCC ,while the values of T50 represent the time required for the concrete flow to reach a circle with 50 cm diameter.

The results of the slump-flow range between (710-750) mm and the results of T<sub>50</sub> cm range between (3-4.5) sec .These results show that the SCC used is conformed with the requirements of EFNARC 2002<sup>(10)</sup> (i.e has a good consistency and workability at fresh state).

**Table (4-1): Results of workability tests of the SCC**

test	unit	Mix Notation			Typical range of values
		*ML	*MP	*MH	
<b>Slump-flow</b>	<b>mm</b>	750	740	710	600-800
<b>T 50cm</b>	<b>sec</b>	3	3.5	4.5	2-5
<b>V-funnel</b>	<b>sec</b>	6	7.5	9	6-12
<b>V-funnel at T<sub>5 min</sub></b>	<b>sec</b>	7	9	12	+3 sec, max
<b>L-Box</b>	<b>(H2/H1)</b>	1	0.93	0.88	0.8-1.0
<b>U-Box</b>	<b>(H1-H2)mm</b>	11	15	20	0-30

\* ML: Mixes of SCC with limestone powder filler.

\* MP: Mixes of SCC with pigment filler.

\* MH: Mixes of SCC with hydrated lime filler.

### **4.2.3 V-funnel and V-funnel at T5 minutes Results:-**

The values of V-funnel test (flow time) represent the ability of the concrete to flow out of the funnel and it refer to the filling ability of SCC. Although the T 50 test can be considered a “good” test to assess the flowing ability of the concrete, the funnel test can be used as another supporting test to evaluate the viscosity of the SCC mixes, while the flow time at (T5 minutes) value represents the segregation resistance but after refilling the funnel and allowing the concrete to flow 5 minutes after the first filling.

Table (4-1) shows the time of the concrete to pass through the V-funnel and shows that the time of flow through the V-funnel for all mixes is (6 to 9) sec which agrees with the acceptance criteria for SCC reported by EFNARC 2002 <sup>(10)</sup>, while the results of the V-funnel at (T5 minutes) range between (7-12) mm .These results show that the SCC used agrees with the requirements of EFNARC 2002<sup>(10)</sup> too.

### **4.2.3 L -box Results:-**

The L-box test results are listed in Table (4-1). The values of (H2/H1) represent the blocking ratio. The L-box results indicate good flowability and show that the blocking ratio values for all mixes are greater than 0.8 which is often considered in the EFNARC 2002 <sup>(10)</sup> as the critical low limit.

### **4.2.4 U-box Results:-**

The U- box test is used to assess the passing ability of concrete through reinforcing bars. In this test, the degree of compactability can be estimated by the height that the concrete reaches after flowing through an obstacle.

Results in Table (4-1) show the U-box results of the fresh SCC concrete. From these results it can be seen that the (H<sub>1</sub>-H<sub>2</sub>) values are between (11-20) mm which is within the acceptable range of EFNARC 2002 <sup>(10)</sup>. If concrete flows as freely as water at rest, it will be horizontal, so when [H<sub>1</sub>-H<sub>2</sub>=0] ,better flow and passing ability of the concrete will be achieved <sup>(43)</sup>,but this may contradict the segregation resistance.

## **4.3 Hardened Concrete Properties:-**

### **4.3.1 Compressive Strength:-**

The compressive strength, as one of the most important properties of hardened concrete, is in general the characteristic material value for the classification of concrete in national and international codes. Standard cubes size 150 mm were tested at ages of 28, 90, 180 days for moist curing condition and at ages of 90,180 days for wetting and drying curing condition .Three cubes are tested at each age for compressive strength determination of self compacting concrete with various percentages of gypsum content in fine aggregate are shown in Table (4-2) and Figs. (4-1)

(4-2)&(4-3), Natural gypsum was added as a partial replacement by weight of fine aggregate.

**Table (4-2): Effect of sulfate content in fine aggregate on compressive strength of SCC**

Mix Notation	SO <sub>3</sub> content % by weight of fine aggregate	Total SO <sub>3</sub> content % by weight of cement	Compressive strength (MPa)		
			28 (days)	90 (days)	180 (days)
ML0	0.16	3.22	34.5	42.4	44.8
ML1	0.5	3.79	36.8	46.7	51.0
ML2	1.0	4.62	32.7	39.2	44.0
ML3	1.5	5.45	-	38.7*	45.0*
MP0	0.16	3.07	33.6	38.9	41.3
MP1	0.5	3.63	34.2	41.7	48.0
MP2	1.0	4.47	30.1	37.3	46.0
MP3	1.5	5.31	-	37.4*	44.6*
MH0	0.16	3.02	33.1	38.8	39.4
MH1	0.5	3.58	35.9	42.0	44.8
MH2	1.0	4.42	31.6	36.7	42.7
MH3	1.5	5.25	-	36.2*	40.1*

\* Wetting and drying curing

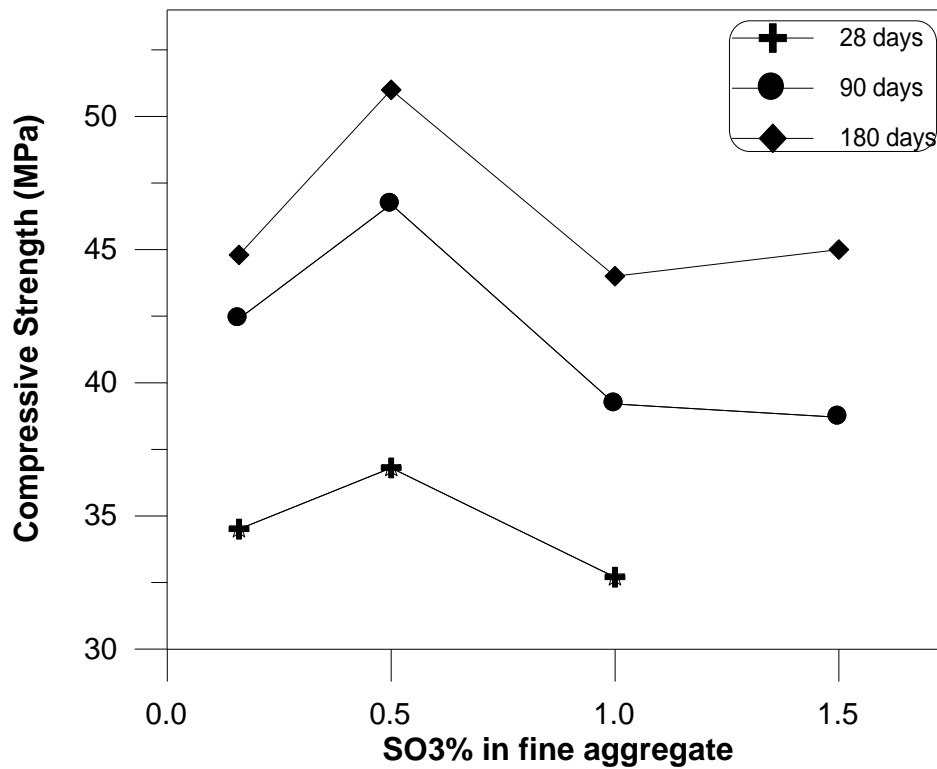


Fig. (4-1): Relationship between compressive strength and SO<sub>3</sub> content in fine aggregate at different age with limestone powder filler.

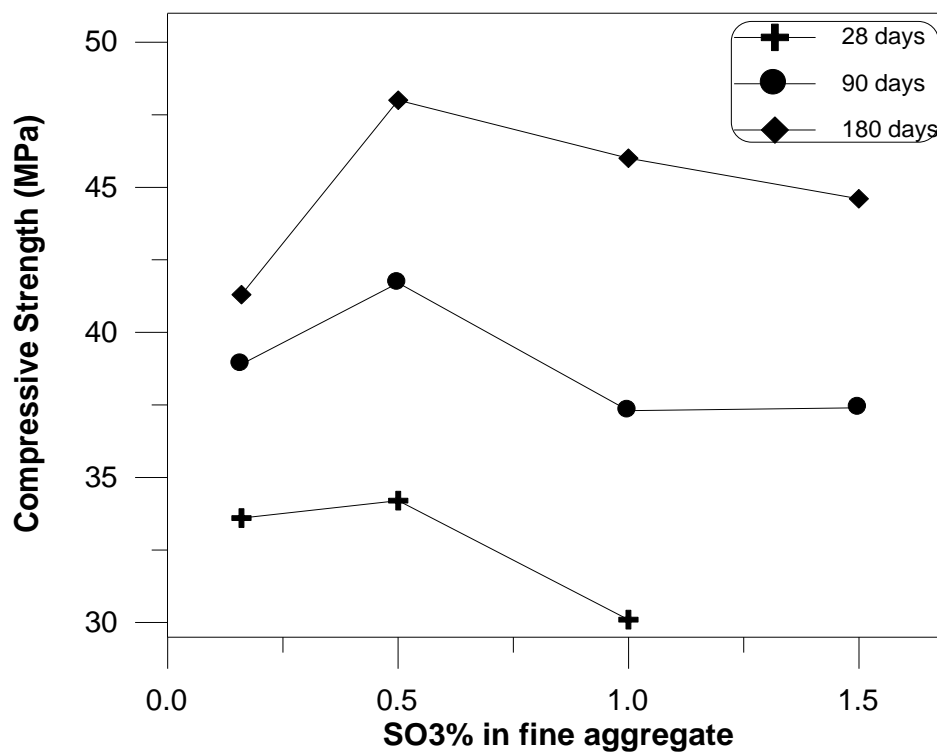


Fig. (4-2): Relationship between compressive strength and SO<sub>3</sub> content in fine aggregate at different age with pigment filler.

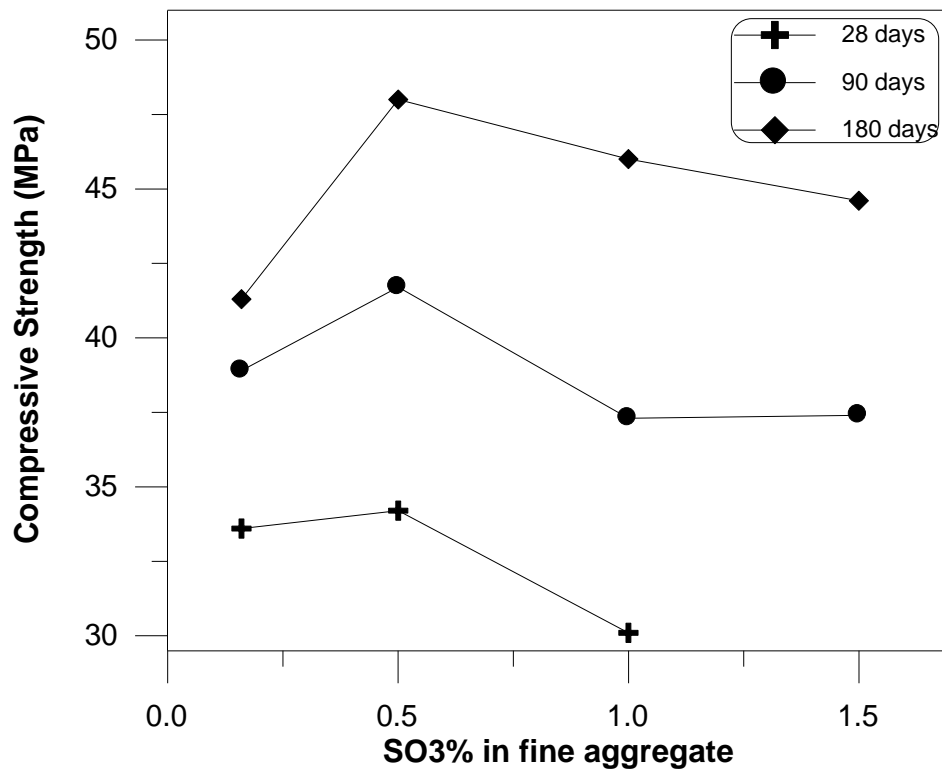


Fig. (4-3): Relationship between compressive strength and SO<sub>3</sub> content in fine aggregate at different age with hydrated lime filler.

It can be seen that for all mixes, there is an optimum gypsum content at which the compressive strength is maximum. Further increase in SO<sub>3</sub> content beyond the optimum causes a decrease in compressive strength. The optimum gypsum content for these mixes is about (0.5% by weight of fine aggregate) and it is equal to (3.79% by weight of cement) for mixes which contain limestone powder filler and about (0.5% by weight of fine aggregate) and it is equal to (3.63% by weight of cement) for mixes which contain pigment filler and about (0.5% by weight of fine aggregate) and it is equal to (3.58% by weight of cement) for mixes which contain hydrated lime filler.

From the results of compressive strength shown in Figs. (4-1), (4-2) & (4-3), it can be seen that:

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5) %, this leads to an increase in compressive strength of the concrete cubes in the range

(6.7 to 13.8)% , (1.8 to 16.2)% and (8.5 to 13.7) % at ages 28, 90&180 days for ML1, MP1 and MH1 respectively .

2. When  $\text{SO}_3$  in fine aggregate increases from (0.16 to 1)% , this leads to a decrease in compressive strength of the concrete cubes in the range (7.5 to 1.8)% , (10.4 to 11.4\*)% and (4.5 to 8.4\*)% at ages 28, 90&180 days for ML2, MP2 and MH2 respectively .

3. When  $\text{SO}_3$  in fine aggregate increases from (0.16 to 1.5)% , this leads to a decrease in compressive strength of the concrete cubes in the range (8.7 to 0.5\*)% , (3.9 to 8.0\*)% and (6.7 to 1.8\*)% at ages 90&180 days for ML3, MP3 and MH3 respectively .

\* Increasing in compressive strength.

The compressive strength of concrete cubes which contains pigment filler which gives improvement in the compressive strength with increasing curing time at sulfate content 1% ,1.5% by wt. of fine aggregate when compared with mixes that contain limestone powder and hydrated lime fillers. This may be due to the cementation materials that are present in pigment which give more cohesion between the ingredients in the concrete mix .

The wetting and drying curing may increase the acceleration of the hydration process of cement that causes depletion of  $\text{SO}_3$  in ages less than for moist curing and this cause improvement in the compressive strength.

4. These results are in line with that obtained by **Alwash**<sup>(78)</sup> and **Abdul – Latif**<sup>(86)</sup> for many types of cement but many researchers were contradicted with these results as explained below:

1. **Lerch**<sup>(61)</sup> , **Meissner**<sup>(87)</sup> , **Al-Rawi and Mattar**<sup>(88)</sup> and **Borhan**<sup>(89)</sup> stated that there are two optimum  $\text{SO}_3$  contents in cement instead of one optimum  $\text{SO}_3$  .

2. **Bajai** <sup>(90)</sup> stated that compressive strength decreases with the increase of sulfate content for high performance concrete at all ages of test.

**Abdul-Latif** <sup>(86)</sup> presented interpretation for the two optimum gypsum content phenomenon (for other types of cement) .This interpretation was based on the concept that the cement is assumed to be a mixture of two materials (namely aluminate and silicate ).The mechanical properties of both materials were affected by the addition of gypsum .He assumed that the effect of  $SO_3$  content on the strength was separated into two components; the first one was the effect of  $SO_3$  contents on the strength of the silicates phases and the other is the effect of  $SO_3$  on the strength of aluminates phases. The strength increased with increased  $SO_3$  content because the hydration of silicate phases is accelerated with addition of gypsum (i.e. more quantity of CSH gel are formed).The second case represented the effect of  $SO_3$  contents on the strength of cement due to the presence of alumina phases. The strength increased with increased  $SO_3$  because of the beneficial effect of sulphoaluminate formation when it occurs before the cement hardened .Above a certain limit of  $SO_3$  the addition of gypsum became harmful because there was a residual amount of gypsum which can react with the alumina phases after the cement has hardened causing internal stresses and disruption of cement paste.

**Al-Rawi** and **Abdul - Latif** <sup>(91)</sup>stated that the increase in compressive strength of the concrete can be attributed to the ettringite formation which was produced by a chemical reaction between  $SO_3, C_3A$  and water. It filled some of the voids inside the cement paste and increases the strength. More ettringite formation induces internal stresses and decreases the compressive strength.

There is an increase in strength with increased curing time; this attributed to the phenomenon called "Autogenous healing ".After longer

period of curing and for certain levels of  $\text{SO}_3$  ; the reaction of sulfate with cement will diminish due to the depletion of sulfate and the concrete will start to gain some strength because the damaging effect had stopped, while the hydration of cement continued<sup>(86)</sup> .

**Yousif** <sup>(92)</sup> reported that concrete could recover from moderate internal sulfate attack after a longer period of curing and the allowable levels of  $\text{SO}_3$  could be increased if longer curing periods are adopted .

### **4.3.2 Splitting Tensile Strength :-**

The splitting tensile strength (ft) is determined on cylinders size (100x200) mm and cured in a similar manner as that cubes.

The splitting tensile strength results of SCC with the percentages of  $\text{SO}_3$  content in fine aggregate at the ages of test are presented in Table (4-3) and Figs. (4-4), (4-5)& (4-6).

**Table (4-3): Effect of sulfate content in fine aggregate on splitting tensile strength of SCC**

Mix Notation	$\text{SO}_3$ content % by weight of fine aggregate	Total $\text{SO}_3$ content % by weight of cement	Splitting tensile strength (MPa)		
			28 (days)	90 (days)	180 (days)
<b>ML0</b>	<b>0.16</b>	<b>3.22</b>	<b>3.50</b>	<b>3.75</b>	<b>3.85</b>
<b>ML1</b>	<b>0.5</b>	<b>3.79</b>	<b>3.65</b>	<b>4.02</b>	<b>4.19</b>
<b>ML2</b>	<b>1.0</b>	<b>4.62</b>	<b>3.40</b>	<b>3.67</b>	<b>3.81</b>
<b>ML3</b>	<b>1.5</b>	<b>5.45</b>	-	<b>3.55*</b>	<b>3.73*</b>
<b>MP0</b>	<b>0.16</b>	<b>3.07</b>	<b>3.42</b>	<b>3.62</b>	<b>3.80</b>
<b>MP1</b>	<b>0.5</b>	<b>3.63</b>	<b>3.50</b>	<b>3.90</b>	<b>4.15</b>
<b>MP2</b>	<b>1.0</b>	<b>4.47</b>	<b>3.35</b>	<b>3.55</b>	<b>3.78</b>
<b>MP3</b>	<b>1.5</b>	<b>5.31</b>	-	<b>3.37*</b>	<b>3.61*</b>
<b>MH0</b>	<b>0.16</b>	<b>3.02</b>	<b>3.21</b>	<b>3.31</b>	<b>3.55</b>
<b>MH1</b>	<b>0.5</b>	<b>3.58</b>	<b>3.29</b>	<b>3.45</b>	<b>3.72</b>
<b>MH2</b>	<b>1.0</b>	<b>4.42</b>	<b>3.13</b>	<b>3.23</b>	<b>3.50</b>
<b>MH3</b>	<b>1.5</b>	<b>5.25</b>	-	<b>3.06*</b>	<b>3.30*</b>

\* Wetting and drying curing .

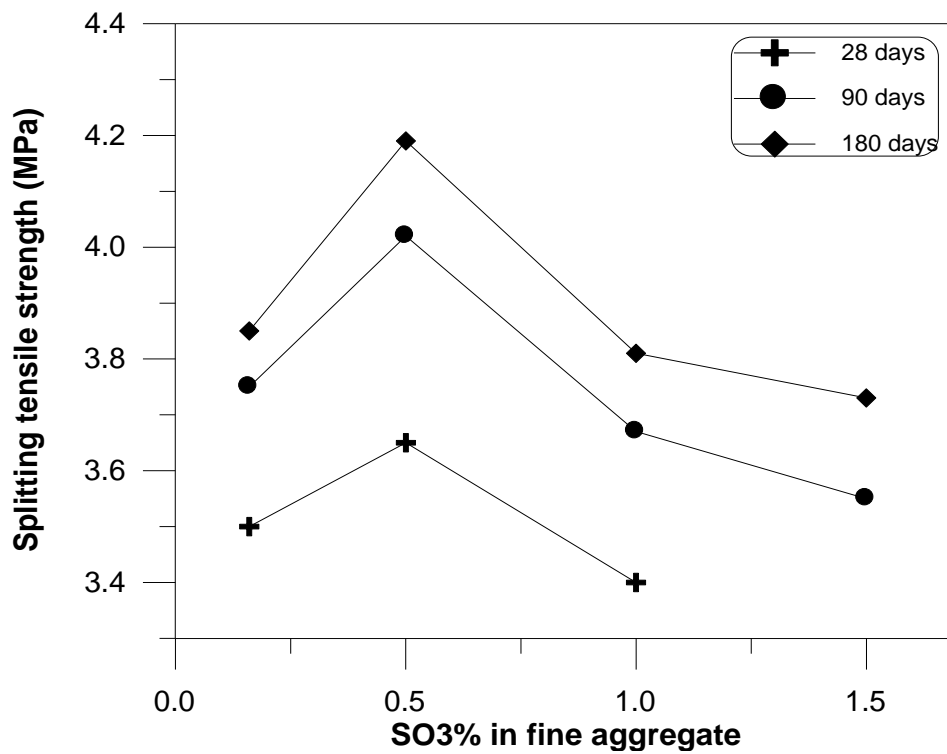


Fig. (4-4): Relationship between splitting tensile strength and SO<sub>3</sub> content in fine aggregate at different age with limestone powder filler.

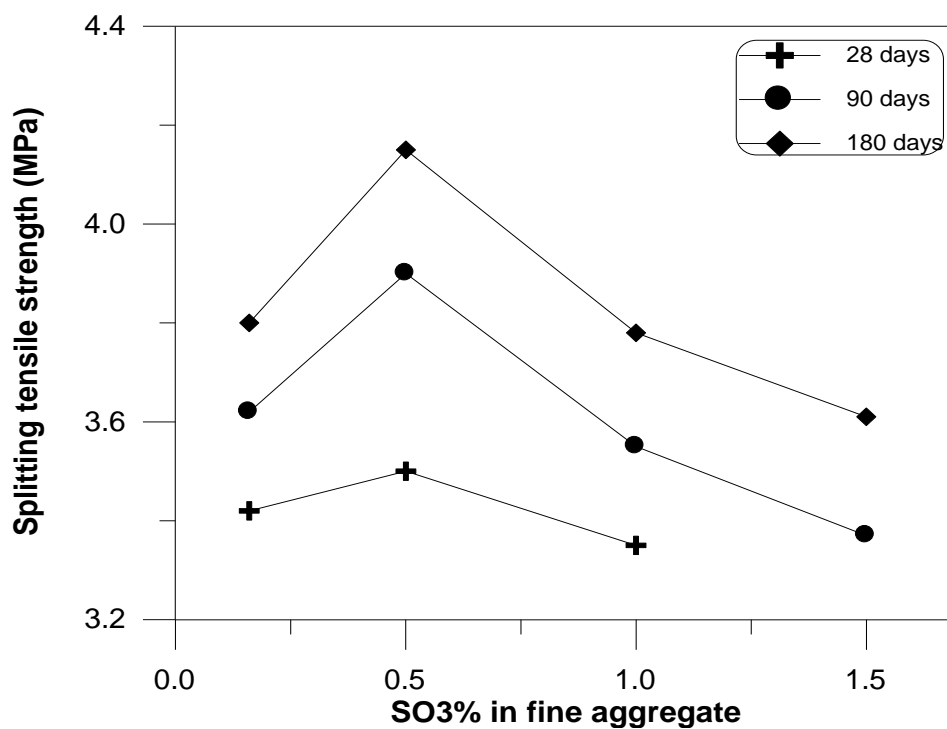


Fig. (4-5): Relationship between splitting tensile strength and SO<sub>3</sub> content in fine aggregate at different age with pigment filler.

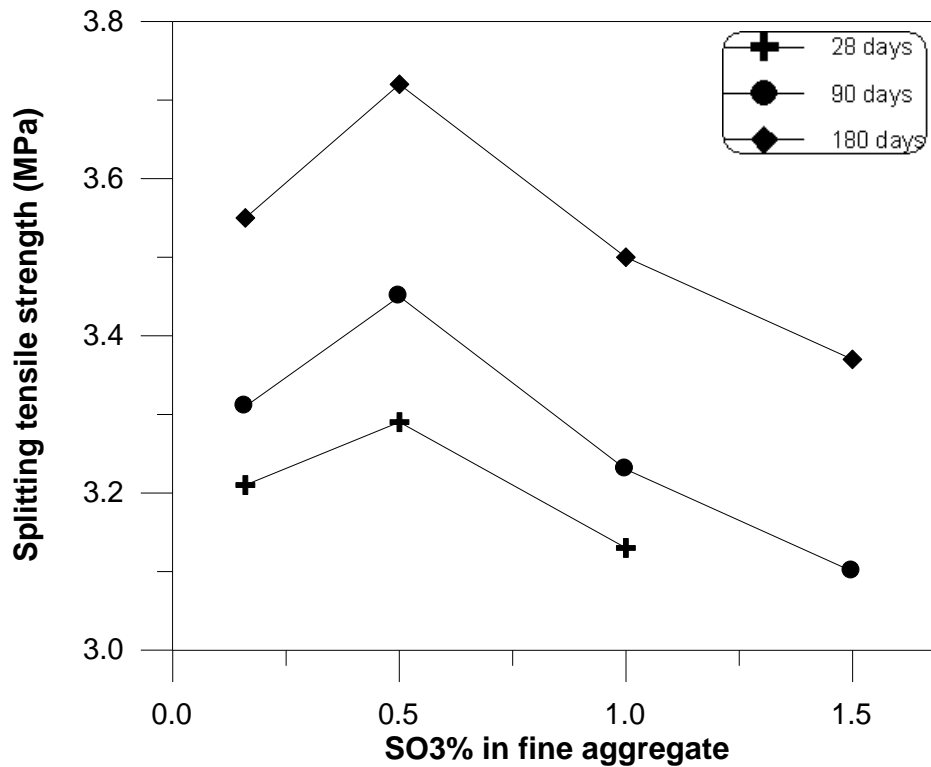


Fig. (4-6): Relationship between splitting tensile strength and SO<sub>3</sub> content in fine aggregate at different age with hydrated lime filler.

From the results of splitting tensile strength shown in Figs. (4-4), (4-5)& (4-6), it can be deduced that:

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5)%, this leads to an increase in splitting tensile strength of the concrete cylinders in the range (4.3 to 8.8)% , (2.3 to 9.2)% and (2.5 to 4.8)% at ages 28, 90&180 days for ML1, MP1 and MH1 respectively .
2. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1.0)%, this leads to a decrease in splitting tensile strength of the concrete cylinders in the range (2.9 to 1.0)% , (2.1 to 0.5)% and (2.5 to 1.4)% at ages 28, 90&180 days for ML2, MP2 and MH2 respectively .
3. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1.5)%, this leads to a decrease in splitting tensile strength of the concrete cylinders in the

range (5.3 to 3.1)% ,( 6.9 to 5)% and (7.6 to 7.1)% at ages 90&180 days for ML3, MP3and MH3 respectively .

4. The results show that the effect of sulfates on splitting tensile strength is similar to be some that on compressive strength .

5. These results agree with that obtained by Alwash <sup>(78)</sup>.

**Bajai** <sup>(90)</sup> stated that splitting tensile strength decreases with the increase of sulfate content for high performance concrete at all ages of test .

### **4.3.3 Flexural Strength :-**

The flexural strength was measured by (100\*100\*400) mm self compacting concrete prisms of different (sulfate in fine aggregate, filler type and curing condition).The results are shown in Table (4-4) and Figs. (4-7), (4-8)& (4-9).

**Table (4-4): Effect of sulfate content in fine aggregate on flexural strength of SCC**

Mix Notation	SO <sub>3</sub> content % by weight of fine aggregate	Total SO <sub>3</sub> content % by weight of cement	Flexural strength (MPa)		
			28 (days)	90 (days)	180 (days)
<b>ML0</b>	<b>0.16</b>	<b>3.22</b>	<b>3.69</b>	<b>4.08</b>	<b>4.13</b>
<b>ML1</b>	<b>0.5</b>	<b>3.79</b>	<b>3.82</b>	<b>4.24</b>	<b>4.43</b>
<b>ML2</b>	<b>1.0</b>	<b>4.62</b>	<b>3.62</b>	<b>3.95</b>	<b>4.10</b>
<b>ML3</b>	<b>1.5</b>	<b>5.45</b>	-	<b>3.79*</b>	<b>4.02*</b>
<b>MP0</b>	<b>0.16</b>	<b>3.07</b>	<b>3.53</b>	<b>3.88</b>	<b>4.05</b>
<b>MP1</b>	<b>0.5</b>	<b>3.63</b>	<b>3.66</b>	<b>4.03</b>	<b>4.25</b>
<b>MP2</b>	<b>1.0</b>	<b>4.47</b>	<b>3.48</b>	<b>3.84</b>	<b>4.10</b>
<b>MP3</b>	<b>1.5</b>	<b>5.31</b>	-	<b>3.70*</b>	<b>3.98*</b>
<b>MH0</b>	<b>0.16</b>	<b>3.02</b>	<b>3.30</b>	<b>3.49</b>	<b>3.66</b>
<b>MH1</b>	<b>0.5</b>	<b>3.58</b>	<b>3.45</b>	<b>3.67</b>	<b>3.85</b>
<b>MH2</b>	<b>1.0</b>	<b>4.42</b>	<b>3.25</b>	<b>3.40</b>	<b>3.70</b>
<b>MH3</b>	<b>1.5</b>	<b>5.25</b>	-	<b>3.30*</b>	<b>3.59*</b>

\* Wetting and drying curing .

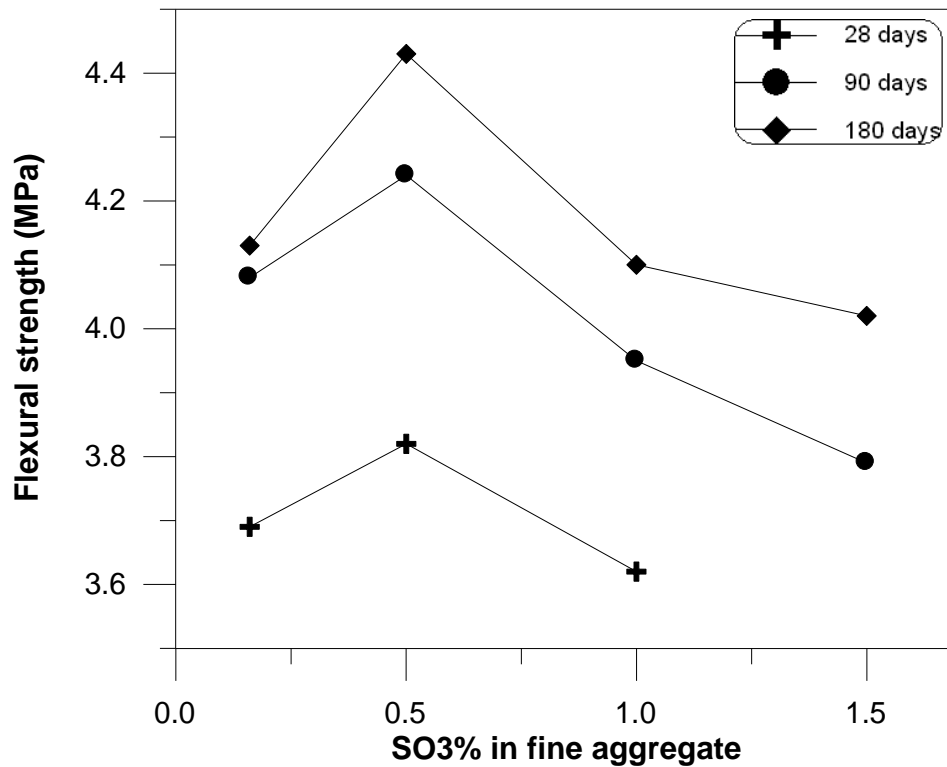


Fig. (4-7): Relationship between flexural strength and SO<sub>3</sub> content in fine aggregate at different age with limestone powder filler.

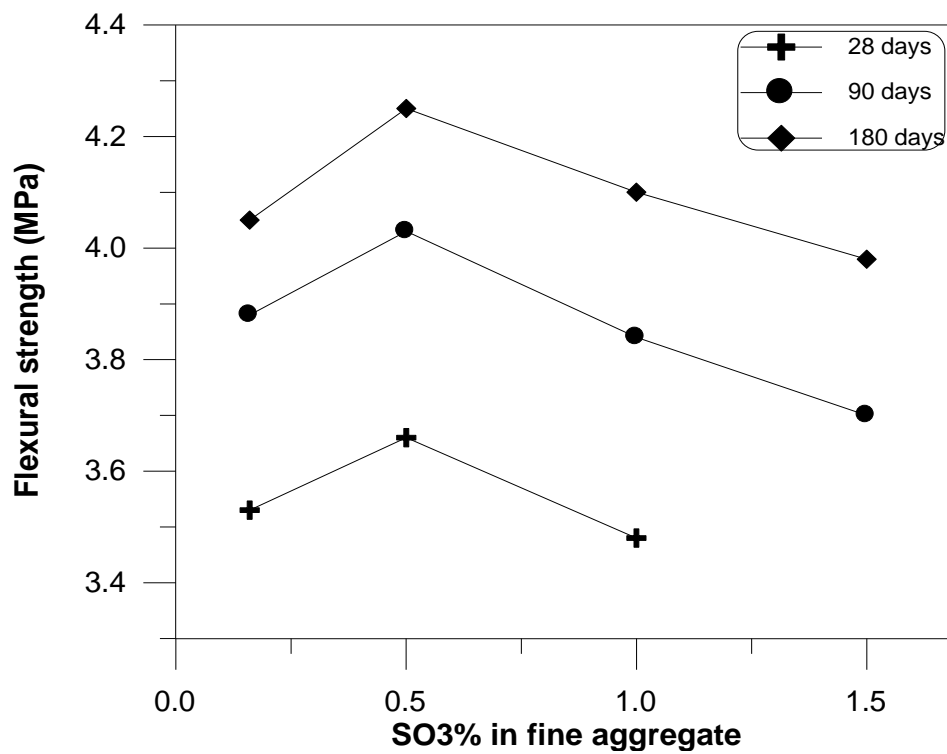


Fig. (4-8): Relationship between flexural strength and SO<sub>3</sub> content in fine aggregate at different age with pigment filler.

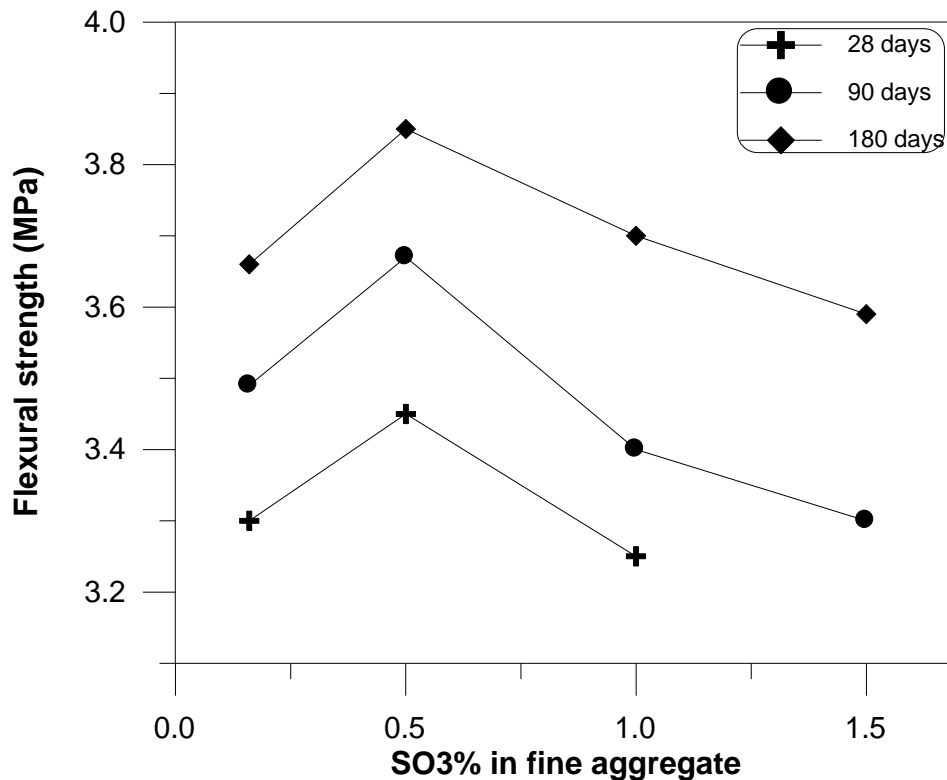


Fig. (4-9): Relationship between flexural strength and SO<sub>3</sub> content in fine aggregate at different age with hydrated lime filler.

From the results of flexural strength shown in Figs. (4-7),(4-8)& (4-9), it can be stated that:

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5)%, this leads to an increase in flexural strength of the concrete prisms in the range (3.5 to 7.3)% ,(3.7 to 4.9)% and (4.5 to 5.2)% at ages 28, 90&180 days for ML1, MP1 and MH1 respectively .
2. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1)% , this leads to a decrease in flexural strength of the concrete prisms in the range(3.2 to 0.7)% ,(1.4 to 1.2\*)% and (1.5 to 1.1\*)% at ages 28, 90&180 days for ML2, MP2 and MH2 respectively .
3. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1.5)% , this leads to a decrease in flexural strength of the concrete prisms in the range (7.1 to

2.7)%, (4.6 to 1.7)% and (5.4 to 1.9)% at ages 90&180 days for ML3,MP3 and MH3 respectively .

4. The results show that the effect of sulfates on flexural strength is similar to that on compressive strength .

\* Increasing in flexural strength.

#### **4.3.4 Static Modulus of Elasticity :-**

The secant modulus of elasticity is defined as the slope of the chord of the uniaxial stress-strain curve between the point corresponding to 40 percent of maximum stress and the point corresponding to a strain of 0.00005<sup>(93)</sup>. The modulus of elasticity of the SCC mixes is measured by (150\*300) mm cylinders at 28-days .

Table (4-5) shows the results of the static modulus of elasticity for SCC specimens, each result presents the average of two specimens.

**Table (4-5): Effect of sulfate content in fine aggregate on static modulus of elasticity of SCC**

Mix Notation	SO <sub>3</sub> content % by weight of fine aggregate	Total SO <sub>3</sub> content % by weight of cement	Ec (GPa)
			28 (days)
<b>ML0</b>	<b>0.16</b>	<b>3.22</b>	<b>28.8</b>
<b>ML1</b>	<b>0.5</b>	<b>3.79</b>	<b>29.9</b>
<b>ML2</b>	<b>1.0</b>	<b>4.62</b>	<b>28.4</b>
<b>MP0</b>	<b>0.16</b>	<b>3.07</b>	<b>27.6</b>
<b>MP1</b>	<b>0.5</b>	<b>3.63</b>	<b>28.5</b>
<b>MP2</b>	<b>1.0</b>	<b>4.47</b>	<b>27.2</b>
<b>MH0</b>	<b>0.16</b>	<b>3.02</b>	<b>26.8</b>
<b>MH1</b>	<b>0.5</b>	<b>3.58</b>	<b>27.5</b>
<b>MH2</b>	<b>1.0</b>	<b>4.42</b>	<b>26.3</b>

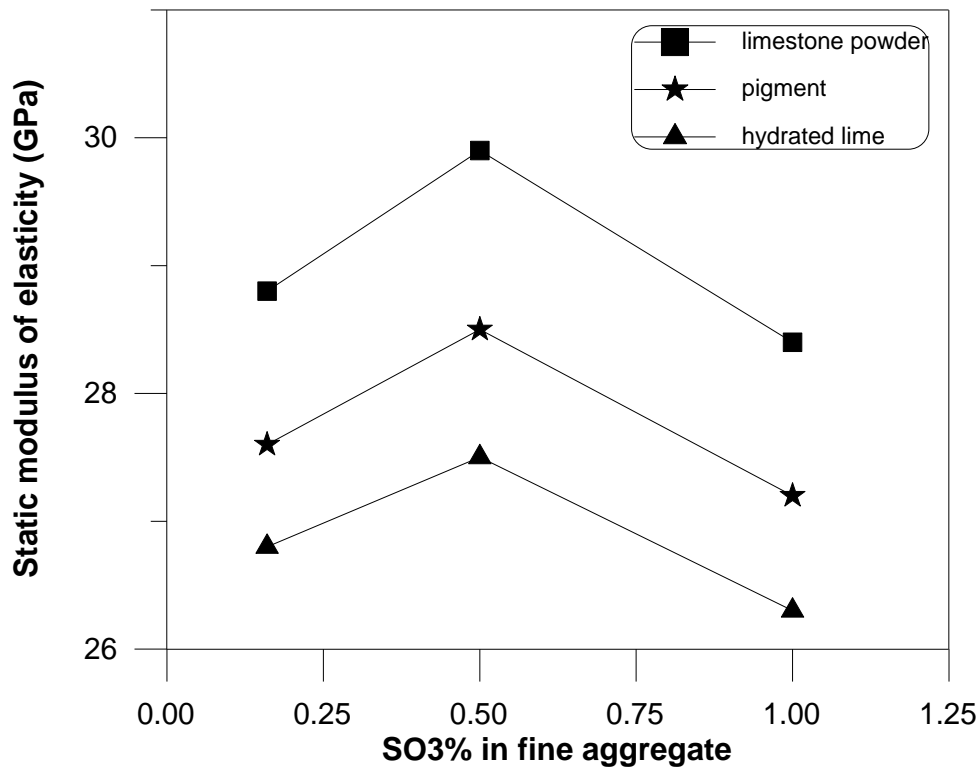


Fig. (4-10): Relationship between static modulus of elasticity and SO<sub>3</sub> content in fine aggregate at 28 days for different fillers

From the results of static modulus of elasticity shown in Fig. (4-10), it can be seen that:

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5)% , this leads to an increase in the modulus of elasticity by 3.8% , 3.3% and 2.6% at age of 28 days for ML1, MP1 and MH1 respectively.
2. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1)% , this leads to a decrease in the modulus of elasticity by 1.4% , 1.5% and 1.9 % at age of 28 days for ML2, MP2 and MH2 respectively.
3. These results are similar to that obtained from Alwash <sup>(78)</sup>. This means that there is no difference between SCC and normal concrete in this respect because of the higher amount of fine aggregate and the lower amount of coarse aggregate in SCC when compared with normal concrete.

## **4.4 Non-Destructive Testing Results :-**

### **4.4.1 Ultrasonic Pulse Velocity (U.P.V) :-**

The results of U.P.V test were measured on 150 mm cubes at ages of 28, 90 and 180 days. They are shown in Table (4-6) and plotted in Figs. (4-11) ,(4-12)& (4-13). Three cubes were tested at each age for U.P.V .

**Table (4-6): Effect of sulfate content in fine aggregate on Ultrasonic Pulse Velocity (U.P.V) of SCC**

Mix Notation	SO <sub>3</sub> content % by weight of fine aggregate	Total SO <sub>3</sub> content % by weight of cement	U.P.V (km/sec)		
			28 (days)	90 (days)	180 (days)
ML0	0.16	3.22	4.31	4.60	4.70
ML1	0.5	3.79	4.40	4.71	4.88
ML2	1.0	4.62	4.25	4.57	4.69
ML3	1.5	5.45	-	4.51*	4.64*
MP0	0.16	3.07	4.28	4.49	4.61
MP1	0.5	3.63	4.33	4.58	4.71
MP2	1.0	4.47	4.37	4.62	4.84
MP3	1.5	5.31	-	4.59*	4.74*
MH0	0.16	3.02	4.29	4.50	4.55
MH1	0.5	3.58	4.33	4.56	4.62
MH2	1.0	4.42	4.26	4.48	4.60
MH3	1.5	5.25	-	4.39*	4.50*

\* Wetting and drying curing .

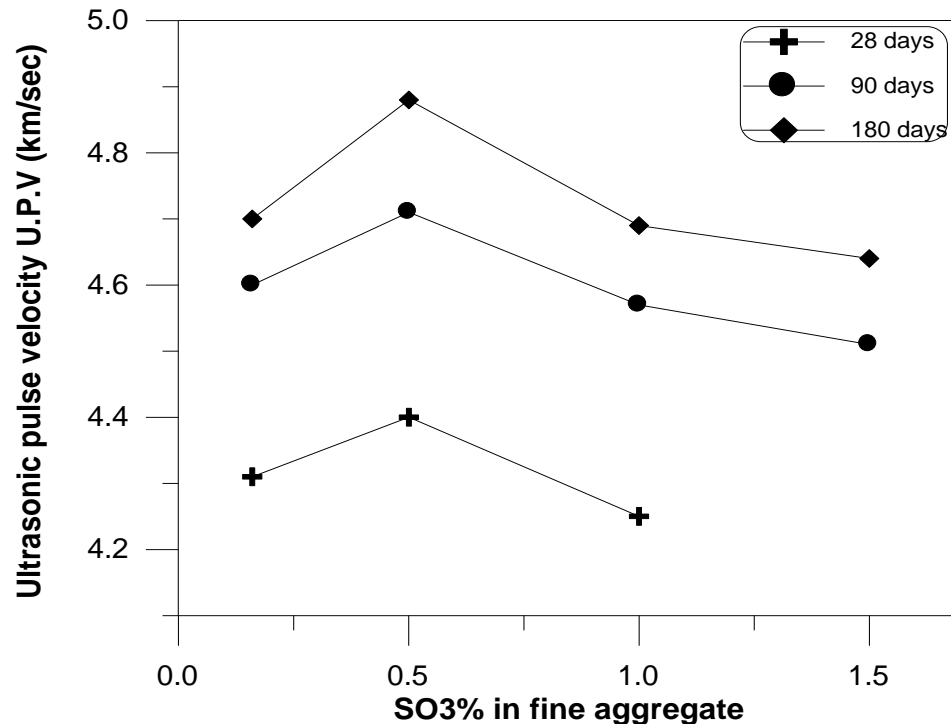


Fig. (4-11): Relationship between U.P.V and SO<sub>3</sub> content in fine aggregate at different age with limestone powder filler.

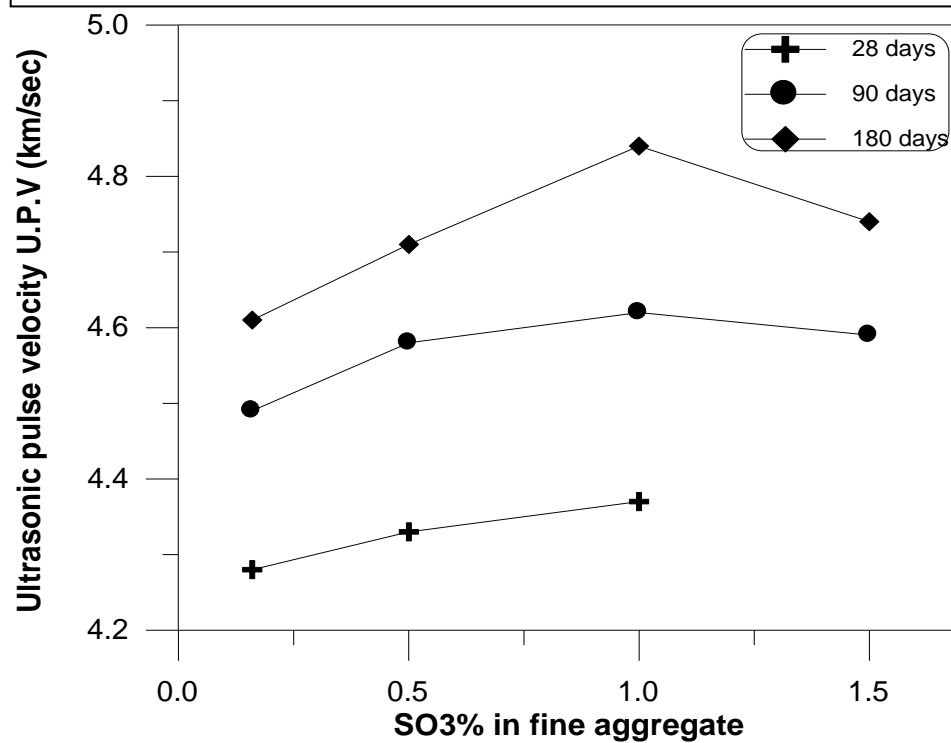


Fig. (4-12): Relationship between U.P.V and SO<sub>3</sub> content in fine aggregate at different age with pigment filler.

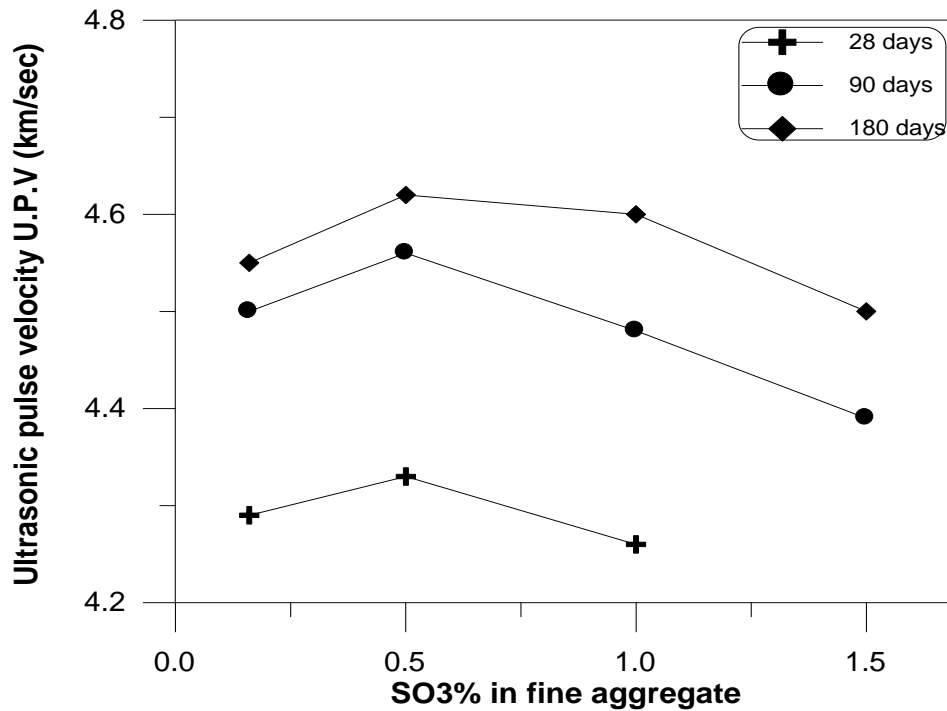


Fig. (4-13): Relationship between U.P.V and SO<sub>3</sub> content in fine aggregate at different age with hydrated lime filler.

From the results of ultrasonic pulse velocity (U.P.V) shown in Figs. (4-11), (4-12)&(4-13), it can be found that:

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5)%, this leads to an increase in the pulse velocity in the range (2.1 to 3.8)% , (1.2 to 2.2)% and (0.9 to 1.5)% at ages of 28, 90&180 days for ML1, MP1 and MH1 respectively .
2. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1)% , this leads to a decrease in the pulse velocity in the range (1.4 to 0.2)% and (0.7 to 1.1\*) % at ages of 28, 90&180 days for ML2, and MH2 and increase in the pulse velocity in the range (2.1 to 5.0)% at ages of 28, 90&180 days for MP2.
3. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1.5)% , this leads to a decrease in the pulse velocity in the range (2.0 to 1.3)% , (2.2 to 2.8)% and (2.4 to 1.1)% at ages of 90&180 days for ML3, MP3 and MH3 .

**Bajai** <sup>(90)</sup> stated that pulse velocity decreases with the increase of sulfate content for high performance concrete at all ages of test.

\* Increasing in pulse velocity.

#### **4.4.2 Rebound Hammer Results:-**

The surface hardness of the 150 mm SCC cubes was assessed by the, "Schmidt rebound hammer test". The test results of rebound number were the average of 5 readings on each of face of the concrete cube. The concrete cube was put on the ground and the procedure of the test was adopted. The rebound number results of SCC with the percentages of SO<sub>3</sub> content in fine aggregate at the ages of test are presented in Table (4-7) and Figs. (4-14), (4-15)& (4-16).

**Table (4-7): Effect of sulfate content in fine aggregate on Rebound number of SCC**

Mix Notation	SO <sub>3</sub> content % by weight of fine aggregate	Total SO <sub>3</sub> content % by weight of cement	Rebound number		
			28 (days)	90 (days)	180 (days)
ML0	0.16	3.22	28.1	28.8	29.5
ML1	0.5	3.79	29.6	30.9	31.9
ML2	1.0	4.62	28.5	29.1	30.5
ML3	1.5	5.45	-	28.6*	29.6*
MP0	0.16	3.07	27.9	28.9	29.2
MP1	0.5	3.63	28.7	30.0	30.4
MP2	1.0	4.47	28.3	29.4	30.1
MP3	1.5	5.31	-	29.2*	29.5*
MH0	0.16	3.02	28.0	28.7	28.9
MH1	0.5	3.58	29.2	30.2	30.5
MH2	1.0	4.42	27.6	28.4	29.0
MH3	1.5	5.25	-	28.2*	28.7*

\* Wetting and drying curing.

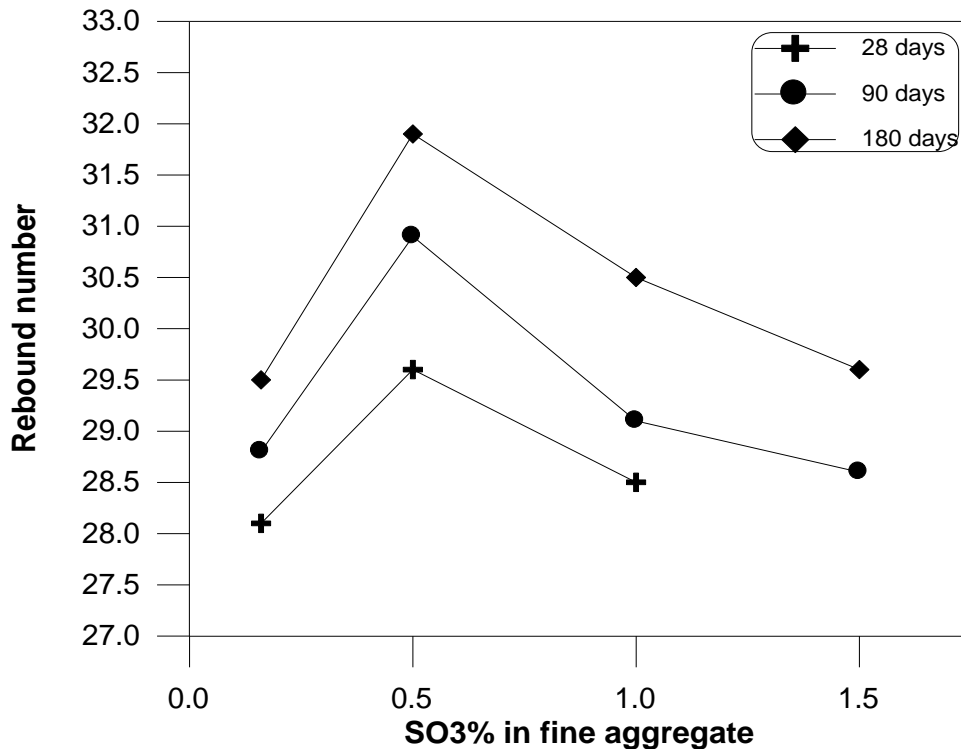


Fig. (4-14): Relationship between rebound number and SO<sub>3</sub> content in fine aggregate at different age with limestone powder filler.

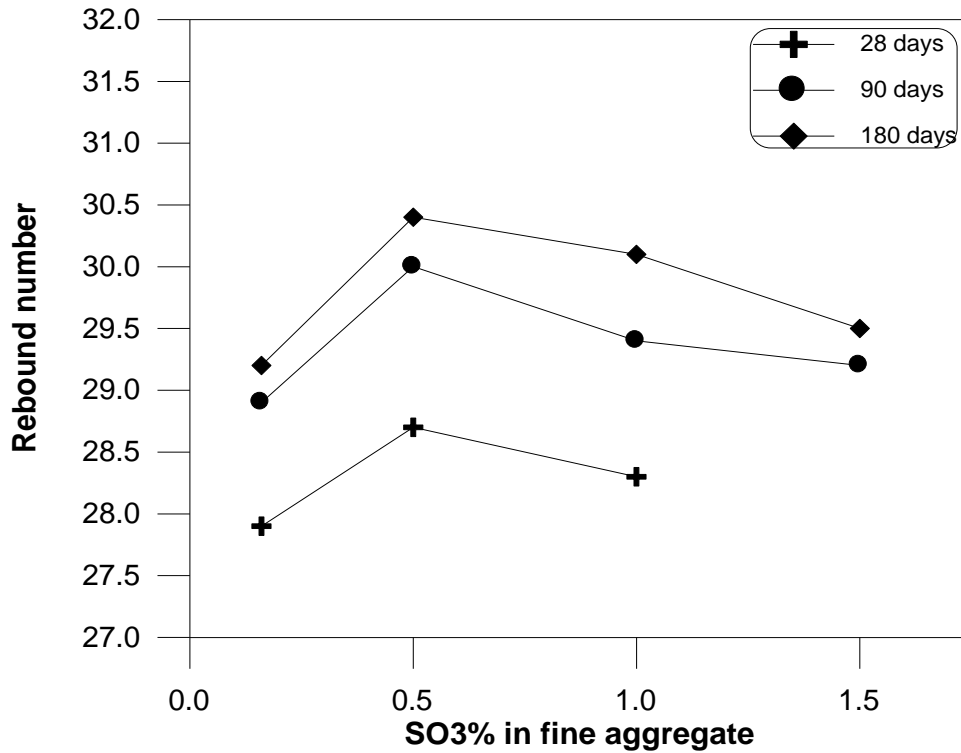


Fig. (4-15): Relationship between rebound number and SO<sub>3</sub> content in fine aggregate at different age with pigment filler.

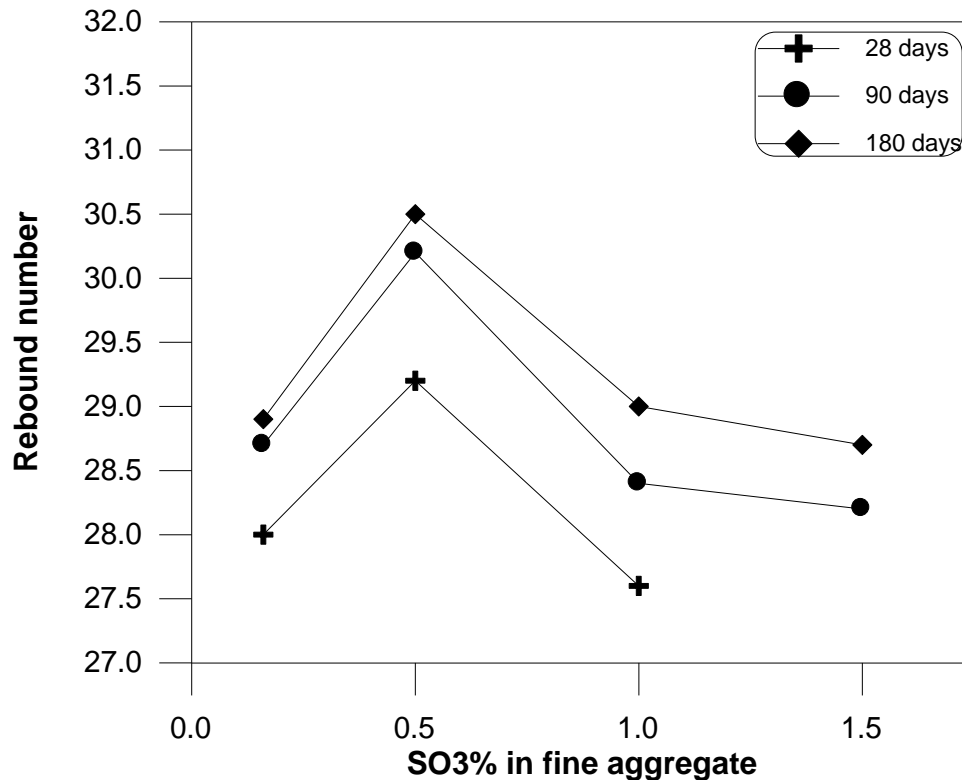


Fig. (4-16): Relationship between rebound number and SO<sub>3</sub> content in fine aggregate at different age with hydrated lime filler.

From the results of rebound number shown in Figs. (4-14), (4-15)&(4-16), it can be said that :

1. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 0.5) %, this leads to an increase in the rebound number in the range (5.3 to 8.1)% , (2.9 to 4.1)% and (4.3 to 5.5)% at ages of 28, 90&180 days for ML1, MP1 and MH1 respectively.
2. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1)% , this leads to an increase in the rebound number in the range (1.4 to 3.4)% , (1.4 to 3.1)% at ages of 28, 90&180 days for ML2 and MP2 and a decrease in the rebound number in the range (1.4 to 0.3)% at ages of 28, 90&180 days for MH2 .
3. When SO<sub>3</sub> in fine aggregate increases from (0.16 to 1.5)% , this leads to a decrease in the rebound number in the range (0.7 to 0.3\*) % , (1.7 to

0.7) % at ages of 90&180 days for ML3 and MH3 and increase in the rebound number in the range(1.0 to 1.1) at all ages for MP3.

\* Increasing in the rebound number.

**4.** It can be noticed that the values of rebound number were low because the higher content of fines (fine aggregate + powder) in the concrete.

# **Chapter 5** **Conclusions and Recommendations for Future Work**

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## **5.1 Conclusions :-**

Based on the experimental of the present work, the following conclusions can be drawn:

- 1- The hydrated lime filler gives less workability than limestone powder and pigment filler .
- 2- There is an optimum gypsum content at which the compressive strength is maximum, beyond which content the compressive strength decreases. The optimum gypsum content for these mixes is about (0.5% by weight of fine aggregate) and it is equal to (3.79% by weight of cement) for mixes containing limestone powder filler, while it is equal to (3.63% by weight of cement) for mixes containing pigment filler and it is equal to (3.58% by weight of cement) for mixes containing hydrated lime filler.
- 3-There is a reduction in strength at age (90 days) for self compacting concrete while at later ages (180 days) the reduction in strength decreases. The reduction is positively correlated with the increase in  $SO_3$  present in fine aggregate.
- 4-The self compacting concrete which contains pigment filler gives improvement in the mechanical properties and non destructive tests with increasing curing time at sulfate content 1%, 1.5% by wt. of fine aggregate when compared with SCC that contains limestone powder and hydrated lime fillers.
- 5- The wetting and drying curing will deplete of  $SO_3$  in ages less than for moist curing.

6-The influence of sulfates on the splitting tensile strength, flexural strength and static modulus of elasticity is found to be similar to that of compressive strength.

7- The values of rebound number are low.

## **5.2 Recommendations for Future Work :-**

1- Study the resistance of self compacting concrete containing different types of fillers to internal sulfate attack by measuring the expansion of the concrete by the length change test and autoclave test at early ages.

2- Study the resistance of self compacting concrete to internal sulfate attack by using sulfate resisting Portland cement.

3- Investigating the effect of high percentages of  $SO_3$  on mechanical properties of SCC at early ages.

4- An investigation is required to study the durability of self compacting concrete incorporating high reactive metakaolin exposed to external sulfate attack.

## References

- 1- Suksawang ,N., Nassif, H., Najm, S.," *Evaluation of Mechanical Properties for Self -Consolidating, Normal, and High-Performance Concrete (HPC)* ", New Jersey Department of Transportation (NJDOT) and the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers, 2006, pp.3.
- 2- Ozawa, K., Maekawa, K., Kunishima, M., and Okamura, H., " *Performance of Concrete Based on the Durability Design of Concrete Structures* ", Proceedings of the Second East Asia-Pacific Conference on Structural Engineering and Construction, 1989.
- 3-Sandberg, R. R., " *Concrete Durability* " 2005, pp.1-2. ([http://www.sandberg.co.uk/labs/cm\\_conc\\_durability.php](http://www.sandberg.co.uk/labs/cm_conc_durability.php)).
- 4- Corrosion-Club.com " *Durability and Degradation Mechanisms* " pp. 1-3. ( <http://www.corrosion-club.com/concreteintro4.htm>).
- 5- السامرائي . مفيد " *تحديد نسبة الأملاح في الرمل* "، المركز القومي للمختبرات الإنشائية ، مجلة البناء الحضاري، العدد(1) ، السنة الأولى، 1977، ص 38-52.
- 6- Holschemacher, K., and Klug, Y., " *A Data Base for the Evaluation of Hardened Properties of SCC* ", Leipzig Annual Civil Engineering Report (LACER), No.7, 2002, pp.123-134.
- 7- Okamura, H., Maekawa, K., and Ozawa, K. " *High Performance Concrete* " Gihodo Publishing, 1993.
- 8- Steffen Grunewald " *Performance-based design of self-compacting fibre reinforced concrete* " Delft University of Technology , 2004, pp.1-233.
- 9- Ashok, H.," *Mix Design and Testing of Self-Consolidating Concrete Using Florida Materials* ", Report No. BD503,The Florida Department of Transportation, 2004, pp.10,( [http://www.dot.state.fl.us/research-center/Completed\\_Proj/Summary\\_SMO/FDOT\\_BD503\\_rpt.pdf](http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_SMO/FDOT_BD503_rpt.pdf) ) .

## References

- 10- EFNARC, "**Specification and Guidelines for Self-Compacting Concrete**", February 2002, pp.1-32, (www.efnarc.org) .
- 11- Tattersall, G.H., Banfill, P.F.G. "**The Rheology of Fresh Concrete**", Pitman Books Limited, London, 1983, ISBN: 0273085581.
- 12- Schultz, M.A., and Struble, L.J., "**Use of Oscillatory Shear to Study Flow behavior of Fresh Cement** ", Cement and Concrete Research, Vol.23, 1993, pp.273–282.
- 13- Larson, R.G., "**The Structure and Rheology of Complex Fluids** ", Oxford University, Press, Oxford, 1999.
- 14- Sheinn, A.M. , " **Some Major Issues of Self-Compacting Concrete** " National University of Singapore, 2001, pp. 75-77.
- 15- Ferraris C.F., and Larrared, D., "**Modified Slump Test to Measure Rheological parameters of Fresh concrete** ", Cement, Concrete and Aggregates, Vol.20, No.2, 1998, pp.241-247
- 16- Okamura, H., Ouchi, M., "**Self Compacting Concrete** ", Journal of Advanced Concrete Technology, Vol.1, No.1, 2003, pp.5-15.
- 17- Newman, J., and Choo, B.S., "**Advanced Concrete Technology** ", 1<sup>st</sup> Edition, Elsevier Ltd., UK, 2003, Ch.9, pp.1-23.
- 18- Okamura, H. and Ouchi, M., "**Self compacting concrete-Development, present and future** ", Proc. of the first international RILEM symposium on Self-compacting concrete, Stockholm, 1999, pp.3-14.
- 19- Ralf, A.B., and Sika, A.G., "**Self-compacting Concrete, Modern Concrete & Admixture Technology**", RCMA-Conference, Kuala Lumpur, May 2000.
- 20- Stephen, D., "**Evaluation of Self -Consolidating Concrete** ", Virginia Transportation Research Council, VTRC 03-R13, 2003, pp.1-15  
([http://www.virginiadot.org/vtrc/main/online\\_reports/pdf/03-r13.pdf](http://www.virginiadot.org/vtrc/main/online_reports/pdf/03-r13.pdf)).
- 21- Okamura, H., Ouchi, M., Hibino, M. and Ozawa, K., " **A rational Mix Design Method for Mortar in Self-compacting Concrete** ", the 6<sup>th</sup> East-Asia

## References

Pacific Conference on Structural Engineering & Construction, Vol.2, 1998, pp.1307-1312.

22- Kennedy, C.T., " *The Design of Concrete Mixes* ", Proceedings of the American Concrete Institute, Vol.36,1940, pp.373-400.

23- Jin-Keun Kim, Sang Hun Han, Yon Dong Park and Jae Ho Noth, " *Material Properties of Self-flowing Concrete* ", Journal of Material in Civil Engineering, 1998.

24- The European Guidelines for Self-Compacting Concrete, May 2005, pp.16, ( <http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf> ).

25- Petersson, O. , " *Workability* " ,Task 2, Swedish Cement and Concrete Research Institute ,1999. pp.1-56.

26- Specifying constituent materials for concrete to BS EN 206-1/BS 8500 , "*Additions* " ,2002,pp.1,( <http://www.cementindustry.co.uk/pdf/Additions%20for%20Concrete%20Aug%202002.pdf> ).

27- BS 7979, Specification for limestone fines for use with Portland cement.

28- Ayano, Baba, Masanori, Kawanaka, Ryouichi, , Ryou and Sakata, "*Effects of particle size characteristics of limestone powder on flowability of self-compacting high performance concrete*" , Zairyo/ Journal of the society of Materials science, Japan, Vol. 51, No.10, 2002, pp.1099-1104 .

29- BS EN 12878, Pigments for the colouration of building materials based on cement and/or lime – Specification and methods of test.

30- Collepari, M., "*Advances in Chemical Admixtures for Concrete* " , Advances in Cement and Concrete, Editors: M.W.Grutzeck and S.L. Sarkar, Durham USA, 2003, pp. 257-291.

31- Cement and Concrete Institute, "*Admixtures for Concrete* " , Midrand , 2001, ([http://cnci.org.za/inf/leaflets\\_html/admix.html](http://cnci.org.za/inf/leaflets_html/admix.html))

32- Rahman, M.A. and Nehdi, M., "*Rheology of Cement Pastes Using Various Accessories* " Conference proceedings: First North American

## References

- Conference on the Design and Use of Self - Consolidating Concrete , Nov. 12-13, 2002, Center for Advanced Cement-Based Materials, 2002, pp.47-52.
- 33- Ozawa, K., Maekawa, K., Kunishima, M. and Okamura, H., " ***Development of high performance concrete based on the durability design of concrete structures*** " Proceedings of the second East-Asia and Pacific Conference on Structural Engineering and Construction, Vol.1, 1989, pp.445-450.
- 34- Okamura, H., and Ozawa, K., " ***Mix-Design for Self-Compacting Concrete*** ", Concrete Library of the Japanese Society of Civil Engineers, No. 25, 1995, pp.107-120.
- 35-Ouchi M., " ***Testing and Mix Design of Self-compacting Concrete***", Kochi University of Technology, Japan, 2003.
- 36- Domone P.L., Jin J. and Chai H.W., " ***Optimum Mix Proportioning of Self-compacting Concrete*** ", Innovation in Concrete Structures: Design and Construction, Proceedings of Creating with Concrete, University of Dundee, 1999.
- 37- Tviksta ,Mr. Lars-Göran, " ***End product - Guidelines*** ", Task 9, No.10 , Swedish cement and concrete Research, 2000, pp.1-48.
- 38-König, G., Holschemacher, K., Dehn, F., Weiße, D., " ***Self Compacting Concrete - Time Development of Material Properties and Bond Behavior*** ", Proceedings of the Second International Symposium on Self-Compacting Concrete, Tokyo, 2001, pp. 507-516.
- 39- ASTM C78-84, " ***Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Two Points Loading )*** ", Annual Book of ASTM Standard, Vol. 04.02, 2003.
- 40- ASTM C496-86, " ***Standard Test Method for Splitting Tensile of Cylindrical Concrete Specimens***", Annual Book of ASTM Standard, Vol. 04-02, 1989, pp.259-262.
- 41- Ouchi, M., Nakamura, S., Osterberg, T., Hallberg, S., and Lwin, M.,

## References

- "*Applications of Self-compacting Concrete in Japan, Europe and the United States* ", Kochi University of Technology, Japan, 2003, pp.8.
- 42- Neville, A.M., "*Properties of Concrete*", Longman Group, Ltd., 4<sup>th</sup> and Final Edition, 2000, pp.508-509, 595-596.
- 43- Sonebi, M., Bartos, P.J.M. , Zhu, W. , Gibbs, J. and Tamimi, A., "*Properties of Hardened concrete*" ,Task 4 , Partner : Advanced concrete Masonry centre, University of Paisley, Scotland, United kingdom , 2000 , pp.48-73.
- 44-ASTM C469-87 a, "*Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression* ", ASTM International.
- 45-Mindess, S. and Young, F., "*Concrete* ", Edited by Prentice-Hall, Inc., Englewood Cliffs, USA, New Jersey, 1981, pp.671.
- 46- ERMCO 98 – The European Ready-mix Concrete Organization "*Improving the durability of concrete structure* ", pp.1-4.
- 47- Matthey, D. and Lowry D., "*Concrete degradation by thumasite form of sulphate attack*", Department of Geology, Royal Holloway University of London, TW20 0EX, UK, pp.1.
- 48- Bensted, J., "*Chemical Considerations of Sulfate Attack*", World Cement Technology, Vol.12, No.4, 1981, pp.178-184.
- 49- Jackson, N. and Dhir, R.K., "*Civil Engineering Materials* ", 5<sup>th</sup> Edition, Macmillan Press LTD, 1996, pp.534.
- 50- Tian, B., and Cohen, M.D., "*Does Gypsum Formation During Sulfate Attack on Concrete Lead to Expansion?*", Cement and Concrete Research , Vol.30, No.1, 2000, pp.117-123.
- 51- Wafa, F.F., "*Accelerated Sulfate Attack on Concrete in A Hot Climate*", Cement, Concrete and Aggregates, Vol.16, No.1, 1994, pp.31-35,( Cited by Ref. 89).
- 52- Al-Khalaf, M.N. and Yousif, H.A.," *Concrete Admixture* " Mousel University press, 1991, pp.368.

## References

- 53-Mehta, P.K., "*Sulfate Attack on Concrete - A Critical Review*", Materials Science of Concrete III, The American Ceramic Society, 1993 pp. 105-130.
- 54- Pauri, M. and Collepardi, M., "*Thermo –Hydrometrical stability of thaumasite and ettringite*" ,II Cemento, No.86,1989, pp.177-184,( Cited by Ref. 59).
- 55- Al-Qaisi, W.A., "*The Activity of Sulfate Contaminating Fine Aggregate in Concrete*", M.Sc. Thesis, University of Baghdad, College of Engineering, 1989.
- 56- Al-Rawi, R.S., Ali, N.H., Shallal, A.R. and Al-Salihi, R.A., "*Effective Sulfate Content in Concrete Ingredients*", 4<sup>th</sup> Scientific and Engineering Conference, Baghdad, 1997,pp.18-20.
- 57- Al-Rawi, R.S., "*Some Problems in Concrete Manufacture in The Arab Homeland and Suggested Remedial Measures*",  
مؤتمر مواد البناء العربية و التحديات الاقتصادية- القاهرة, 2000,pp.669-681.
- 58- Al-Kadhimi, T. K. and Hamid, F. A., "*Effect of Gypsum Present in Sand on the Properties of Concrete*" , BRC-Journal, Vol.2, No.2, 1983, pp.17-41.
- 59- Collepardi, M., "*Ettringite Formation and Sulfate Attack on Concrete*", Civil Engineering Faculty, Leonardo Da Vinci, Politechnic Milan, Italy, 2000, pp.1-17 . E- mail:collepardi@polimi.it .
- 60- Troxell, G.E., Davis, H.E. and Kelley, J.W., "*Composition and Properties of Concrete*", 2<sup>nd</sup> edition, McGraw-Hill Book Co., New York, 1968,pp.171.
- 61- Lerch, W., "*The Influence of Gypsum on The Hydration and Properties of Portland Cement Pastes*", ASTM Proceedings, Vol.46, 1946, pp.1252-1292, (Cited by Ref. 90).
- 62- Al-Khalaf, M., "*Effect of Sulfates in Sand on Properties of Concrete*", Journal of Iraqi Engineers Society, 49, 1973.
- 63- Al-Rawi, R.S., "*Gypsum Content of Cements Used in Concrete Cured by Accelerated Methods*", Journal of Testing and Evaluation, Vol.5, No.3, 1977, pp. 231-237.

## References

- 64- Taylor, H.F.W., "***Chemistry of Cement-Iraq***", A Lecture given at Building Research Center Baghdad, Building Research Center, Scientific Research Foundation, 22 January 1976.
- 65- Hobbs, D.W., "***The Influence of SO<sub>3</sub> Content on The Behavior of Portland Cement Mortars*** ", World Cement Technology, Vol.8, No.4, 1977, pp.75-85, (Cited by Ref. 90).
- 66- Al-Rawi, R. S. "***Effect of Pozzolan on concrete Subjected to external and internal sulfate attack*** " 5<sup>th</sup> International Symposium of Concrete Technology , 1981, pp. 237.
- 67- Al-Rawi, R. S. "***Internal sulfate attack in concrete related to gypsum content of cement with pozzolan addition*** " ,ACI-RILEM , Joint symposium , Monterey , Mexico , 1985, pp. 543 .
- 68- Al-Salihi, R.A., "***Proposed Revision of Iraqi Specifications for Concrete Ingredients to Cope with Post War Era***" , M.Sc. Thesis, University of Baghdad, College of Engineering ,1994,pp.139.
- 69- Odler, I., "***Interaction between Gypsum and the C-S-H Phase formed in C<sub>3</sub>S Hydration***", 7<sup>th</sup> International Congress on The Chemistry of Cement, Vol.IV, Paris, 1980, pp.493-495.
- 70- Taylor, H.F.W., "***Cement Chemistry***" 2<sup>nd</sup> Edition, Thomas Telford Publishing, London, 1997, pp. 459, (Cited by Ref. 59).
- 71- Lawrence, C. D., "***Physiochemical and mechanical properties of Portland Cements*** " , Lea's Chemistry of Cement and Concrete , 4<sup>th</sup> Editions , Arnold publisher , Edited by P.C. Hewlett , 1998 , pp. 343-419,(Cited by Ref. 59).
- 72- Divet, L., and Randriambololona, R.,"***Delayed Ettringite Formation: The Effect of Temperature and Basicity on The Interaction of Sulfate and C-S-H Phase***", Cement and Concrete Research, Vol.28, No.3,1998, pp.357-363.
- 73- Idorn, G.M., "***Deterioration of Concrete by Delayed Ettringite Formation***",1999, (<http://www.gmic.dk/deter-def.htm>) .

## References

- 74- Collepardi, M., " *Damage by Delayed Ettringite Formation – A Holistic Approach and New Hypothesis* ", Concrete International , Vol. 21, No. 1 , 1999, pp. 69-74,( Cited by Ref. 59).
- 75- Hansen, W.C., "*Discussion on Significance of Test for Calcium Sulfate in Hydration Portland-Cement Mortar*", ASTM Proceedings, Vol.61, No.10, 1961, pp.1038-1043.
- 76- Mehta, P.K., "*Mechanism of Sulfate Attack on Portland Cement Concrete-Another Look* ", CCR, Vol.13, No.3, 1983, pp.401-406.
- 77- Kadhum, D.Z., "*The Effect of the Strength of concrete on its Resistance to Internal Sulfate Attack*", M.Sc. Thesis, Al-Mustansiriya University, College of Engineering, 2001.
- 78- Alwash, J.J., "*Effect of Sulfates in Fine Aggregate on drying Shrinkage Cracking in End Restrained Concrete Members*" M.Sc. Thesis, University of Babylon, College Of Engineering, 2005.
- 79- Iraqi Organization of Standards, *IOS 5: 1984*, for Portland cement.
- 80- Iraqi Organization of Standards, *IOS 45: 1984*, for Aggregate.
- 81- Emborg M., " Mixing and Transport ", Brite EuRam, Task 8.1, (June 2000).
- 82- Petersson, O. , "*Preliminary Mix Design* " ,Task 1, Swedish Cement and Concrete Research Institute ,1997. pp.41.
- 83- British Standard Institution, "*Method for Determination of Compressive Strength of Concrete Cubes* ", B.S.1881: part 116: 1983, pp.3 .
- 84- BS 4408: Part 5 "*Measurement of the velocity of ultrasonic pulses in concrete* ", British Standards Institution, 2 Park Street , London W1A 2BS, 1974, pp 1-19.
- 85- BS 1881: Part 202 - *Testing Concrete*. Recommendations for surface hardness testing by rebound hammer, 1986.
86. Abdul-Latif, A.M., "*Optimum Gypsum Content in Concrete and Cement Mortar*", Ph.D. Thesis, University of Baghdad, 2001.
- 87- Meissner, H.S., Cook, H.K., Gonnerman, H.F., Hansen, W.C., Mc Coy, W.J.,

## References

Tremper, B. and Wilsnack, G.C., " *The Optimum Gypsum Content of Portland Cement* ", ASTM Bulltin, 1950,pp.39-45.

88- Al-Rawi, R.S. and Mattar, S.G.,

"مقاومة الخرسانة المسلحة بالألياف الحديدية لهجوم الكبريتات الداخلية", المؤتمر الثالث لنقابة

المهندسين الأردنيين, عمان, 2001, ص. 292-301. (Cited by Ref. 90).

89- Borhan, T.M., "*Concrete's Strength Development as Related to MgO and SO<sub>3</sub> Contents in Cement* ", M.Sc. Thesis , University of Baghdad, College of

90- Bajai, Engineering, 2002 .

A.H., "*Resistance of High Performance Concrete to External and Internal Sulfate Attack* " M.Sc. Thesis, University of Technology , College of Engineering ,2005 .

91- 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 .

92- Yousif , S.H., " *Effect of Sulphates on Lean and Medium Richness Concrete* ", M.Sc. Thesis,University of Baghdad ,College of Engineering, 1981,pp.104 ,( Cited by Ref. 86).

93- Al-Kafaji, J.A.J. , "*Some Mechanical Properties of Accelerated Cured High Strength Concrete Cylinders* ", Ph.D. Thesis, AL-Mustansiriyah University, College of Engineering , 2001.