**جمهورية العراق**

**وزارة التعليم العالي**

**والبحث العلمي**

# تأثير نوع المادة المالئة ونسبة الماء إلى المسحوق على بعض الخواص الميكانيكية للخرسانة ذاتية الرص

رسالة

مقدمة إلى

قسم الهندسة المدنية

في كلية الهندسة-جامعة بابل

وهي جزء من متطلبات نيل شهادة ماجستير علوم في الهندسة المدنية

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ربيع الأول-١٤٢٧ نيسان-٢٠٠٦

**Republic of Iraq**

**Ministry of Higher Education**

# EFFECT OF TYPE OF FILLER AND WATER TO POWDER RATIO ON SOME MECHNICAL PROPERTIES OF SELF COMPACTING CONCRETE

A THESIS

SUBMITTED TO THE COLLEGE OF ENGINEERING OF BABYLON UNIVERSITY IN FULFILLMENT OF PARTIAL REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CIVIL ENGINEERING

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١٤٢٧

# Supervisor Certificate

Supervisor Certificate

We certify that the thesis titled "**Effect of Type of Filler and Water to Powder Ratio on Some Mechanical Properties of Self-Compacting Concrete**" was prepared by "***Esam Mohammed Ali***", under our supervision at Babylon University in fulfillment of partial requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING**.

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*Esam M. A. Al-Mosawy*

Dedecation

# Dedecation

*To My Masters*

*To My Mother*

*To The Candle of The House*

*To My Brothers and Sisters For Their Support*

*Esam M. A. Al-Mosawy*

# LIST OF SYMBOLS

The symbols used in this thesis generally are as follows:

| Symbol | Description |
|---|---|
| A.E.A | Air entraining agents. |
| βp | The volumetric ratio of water to powder at which all voids among solid particles are just filled with water. |
| Ec | Static modulus of elasticity. |
| $F_{t}$ ١٥٠ | Splitting tensile strength in MPa for cylinders of ١٥٠ mm diameter. |
| $F_{t}$ ١٠٠ | Splitting tensile strength in MPa for cylinders of ١٠٠ mm diameter. |
| $f'_c$ | Compressive strength. |
| FSCC | Fiber reinforced self compacting concrete. |
| HSC | High strength concrete. |
| I | Metakaolin calcined for ١/٢ hr. |
| II | Metakaolin calcined for ١.٠ hr. |
| III | Metakaolin calcined for ١.٥ hrs. |
| MCS | Civil mixes with sand. |
| | Civil mixes with pigment. |

| | |
|---|---|
| MCP | Civil mixes with limestone. |
| MCL | Civil mixes with cement. |
| MCC | Civil mixes with metakaolin. |
| MCMK | Civil self-compacting concrete mix. |
| MC | Housing self-compacting concrete mix. |
| MH | Housing mixes with pigment. |
| MHP | Housing mixes with sand. |
| MHS | Housing mixes with limestone. |
| MHL | Housing mixes with cement. |
| MHC | Normally vibrated concrete. |
| NVC | Normal strength concrete. |
| NSC | Reference civil. |
| RC | Reference housing. |
| RH | Relevant standard (References). |
| RS | Self-compacting concrete. |
| SCC | Housing self-compacting concrete. |
| SCCH | Civil self-compacting concrete. |
| SCCC | Self-compacting concrete with steel fibre. |
| SFRSCC | Super-plasticizer. |

| | |
|---|---|
| SP | Fine aggregate vol. to total aggregate vol. |
| S/A | Self-compacting concrete mix with W/P=٠.٣. |
| $S_{٣٠}$ | Self-compacting concrete mix with W/P=٠.٤. |
| $S_{٤٠}$ | Self-compacting concrete mix with W/P=٠.٥١. |
| $S_{٥١}$ | Self-compacting concrete mix with W/P=٠.٦٢. |
| $S_{٦٢}$ | Viscosity modifying agents. |
| V.M.A | Ultra-sonic pulse velocity. |
| U.P.V | Ultra-high performance self-compacting concrete. |
| UHPSCC | Water to cement ratio. |
| W/C | Water to filler ratio. |
| W/F | Water to powder (cement+filler) ratio. |
| W/P | |

# الخلاصة

تهدف هذه الدراسة لبيان تأثير نسبة الماء إلى المواد الناعمة، نوع المادة المالئة وطريقة الإنضاج المستخدمة على قابلية تشغيل الخرسانة الطرية وبعض الخواص الميكانيكية للخرسانة المرصوصة ذاتيا المتكونة من المواد المتوفرة محليا. نوع واحد من الخرسانة تم تصميمه في هذا العمل يسمى الخرسانة الاعتيادية أو المنزلية. لقياس قابلية التشغيل، استخدمت عدة طرق مثل فحص الانسياب, زمن الانسياب, الصندوق على شكل حرف L , الصندوق على شكل حرف U, الصندوق على شكل حرف V. إن الخواص الميكانيكية التي تمت دراستها هي مقاومة الانضغاط , مقاومة الانشطار, مقاومة الانثناء ومعامل المرونة الثابت. بالإضافة إلى ذلك, أجريت طريقتان لا اتلافيتان هما سرعة الموجات فوق الصوتية وفحص ارتداد المطرقة.

بناءا على نتائج وظروف العمل, من الممكن إنتاج خرسانة مرصوصة ذاتيا من المواد المتوفرة محليا والمكونة لهذا النوع من الخرسانة وان الخرسانة المرصوصة ذاتيا المنتجة تكون حساسة لنسبة الماء إلى المواد الناعمة ونوع المادة المالئة المستخدمة.

تراوحت نتائج الانسياب بين (٦٣٨-٧٣٨) ملم، بينما تراوحت نتائج زمن الانسياب بين (٢.٥-٥.١) ثانية، تراوحت نسبة الانسداد (ع$_{٢}$/ع$_{١}$) للصندوق على شكل L بين (٠.٨-٠.٩)، فرق الارتفاع (ع$_{١}$-ع$_{٢}$) لملا الصندوق على شكل U تراوح بين (٠-١.٥) سم والزمن اللازم لاجتياز بوابة القمع على شكل V يتراوح بين (٦-١٢.٤) ثانية.

كانت خواص مقاومة انضغاط الخرسانة عند ٧, ٢٨ و ٩٠ يوما بين (٢٢.٥-٣٢.٥) نت/ملم$^{٢}$, (٣٣-٥٨) نت/ملم$^{٢}$ و(٤٥.٥-٦٧.٦) نت/ملم$^{٢}$, مقاومة الانشطار بين (٤.٣-٥.٩٣) نت/ملم$^{٢}$ , (٤.٨٦-٦.٦٢) نت/ملم$^{٢}$ و(٥.٢٥-٧.٠٠) نت/ملم$^{٢}$, مقاومة الانثناء بين (٢.٧٢-٦.٩٨) نت/ملم$^{٢}$, (٣.٦٤-٧.٧٥) نت/ملم$^{٢}$ و(٤.١١-١٠.٠٥) نت/ملم$^{٢}$, معامل المرونة الثابت بين (٣٥.٧١-٤١.١٥) كيلو نت/ملم$^{٢}$ بعمر ٢٨ يوما, سرعة الموجات فوق الصوتية بين (٤.١١-٤.٩٥٨) كم/ثا, (٤.٤٦٦-٥.٣٩٨) كم/ثا و(٤.٨٣٥-٥.٥١٩) كم/ثا و تراوحت قيم رقم الارتداد بين (٣٠-٤٠), (٣٣-٤٢.٥) و(٣٦-٤٤).

لقد أشارت النتائج المستخلصة من هذا البحث إن زيادة نسبة الماء إلى المسحوق بمقدار من (٤٠ الى ٦٢) % يقلل من مقاومة الانضغاط بمقدار ٢٢.٧ % , مقاومة الانشطار بمقدار ١٩.٩ % , مقاومة

الانثنــاء بمقـدار ٤٦ % , معامـل المرونــة الثابـت بمقـدار ٩.٢ % , سـرعة الموجـات فـوق الصــوتية بمقـدار ١٢.٦ % و رقـم الارتـداد بمقـدار ١٥.٨ % . كـذلك وجـد أيضـا أن هنالـك تحسـنا فــي خـواص الخرسانة عند تعرضها للإنضاج بـالرش وعنـد استخدام مسحوق الميتاكـاؤلين المحـروق بدرجـة حـرارة ٧٤٤ م ° لفترة ساعة ونصف كمادة مالئة.

# Abstract

The aim of this study is to find the influence of water to powder ratio, type of filler and curing condition on workability of the fresh concrete and some of the mechanical properties of self-compacting concrete made from locally available materials. One type of concrete is designed in this work called normal or housing concrete. To determine the workability, different test methods are adopted in this research such as slump-flow, T٥٠ slump-flow, L-box, U-box and V-funnel. The mechanical properties studied are compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity. Further more, two non-destructive test methods, ultra-sonic pulse velocity and rebound hammer test are used.

Based on the results of this work, it is possible to produce SCC from locally available materials which satisfied the requirements of this type of concrete and it can be stated that SCC produced is sensitive to the water to powder ratio and the type of filler used.

The results of slump-flow range between (٦٣٨-٧٣٨) mm, T٥٠ range between (٢.٥-٥.١) sec., the blocking ratio ($H_{٢}/H_{١}$) of L-box ranges between (٠.٨-٠.٩), the filling height ($U_{١}-U_{٢}$) of U-box ranges between (٠-١.٥) cm and the funnel time of V-funnel ranges between (٦-١٢.٤) sec.

The compressive strengths at ٧, ٢٨ and ٩٠ days range between (٢٢.٥-٣٢.٥) MPa, (٣٣-٥٨) MPa and (٤٥.٥-٦٧.٦) MPa respectively, splitting tensile strengths range (٤.٣-٥.٩٣) MPa, (٤.٨٦-٦.٦٢) MPa and (٥.٢٥-٧.٠) MPa, flexural strengths range (٢.٧٢-٦.٩٨) MPa, (٣.٦٤-٧.٧٥) MPa and (٤.١١-١٠.٠٥) MPa, static modulus of elasticity ranges (٣٥.٧١-٤١.١٥) GPa at ٢٨-days, U.P.V. ranges

(٤.١١-٤.٩٥٨) km/sec, (٤.٤٦٦-٥.٣٩٨) km/sec and (٤.٨٣٥-٥.٥١٩) km/sec, and rebound number ranges (٣٠-٤٠), (٣٣-٤٢.٥) and (٣٦-٤٤).

The results obtained from this study indicate that increasing W/P ratio from (٤٠) to (٦٢) decreases the compressive strength by ٢٢.٧ %, splitting tensile strength by ١٩.٩ %, flexural strength by ٤٦ %, static modulus of elasticity by ٩.٢ %, ultra-sonic pulse velocity by ١٢.٦ % and rebound number by ١٥.٨ %. Also, it can be seen that there is enhancement in most of the investigated properties of concrete when exposed to sprinkling curing at low water to powder ratio and when using metakaolin type III powder as filler.

**CHAPTER TWO: LITERATURE REVIEW**

# LIST OF SYMBOLS

The symbols used in this thesis generally are as follows:

| Symbol | Description |
| --- | --- |
| SCC | Self-compacting concrete. |
| U.P.V | Ultra-sonic pulse velocity. |
| SCCH | Housing self-compacting concrete. |
| SCCC | Civil self-compacting concrete. |
| SFRSCC | Self-compacting concrete with steel fibre. |
| RH | Reference housing. |
| RC | Reference civil. |
| W/C | Water to cement ratio. |
| W/F | Water to filler ratio. |
| SP | Super-plasticizer. |
| MHL | Housing mixes with limestone. |
| MHC | Housing mixes with cement. |
| S/A | Fine aggregate vol. to total aggregate vol. |

| | |
|---|---|
| V.M.A | Viscosity modifying agents. |
| A.E.A | Air entraining agents. |
| W/P | Water to powder (cement+filler) ratio. |
| NVC | Normally vibrated concrete. |
| NSC | Normal strength concrete. |
| HSC | High strength concrete. |
| UHPSCC | Ultra-high performance self-compacting concrete. |
| Ec | Static modulus of elasticity. |
| $f'_c$ | Compressive strength. |
| | |
| | Housing mixes with pigment. |
| | Housing mixes with sand. |

| | |
|---|---|
| | Civil mixes with sand. |
| MHP | Civil mixes with pigment. |
| MHS | Civil mixes with limestone. |
| MCS | Civil mixes with cement. |
| MCP | Civil mixes with metakaolin. |
| MCL | Civil self-compacting concrete mix. |
| MCC | Housing self-compacting concrete mix. |
| MCMK | self-compacting concrete mix with W/P=٠.٣. |
| MC | self-compacting concrete mix with W/P=٠.٤. |
| MH | self-compacting concrete mix with W/P=٠.٥١. |
| $S_{٣٠}$ | self-compacting concrete mix with W/P=٠.٦٢. |
| $S_{٤٠}$ | Metakaolin calcined for ١/٢ hr. |
| $S_{٥١}$ | Metakaolin calcined for ١.٠ hr. |
| $S_{٦٢}$ | Metakaolin calcined for ١.٥ hrs. |
| I | |
| II | |
| III | |

# LIST OF TABLES

| | | |
|---|---|---|
| ٤-٥<br><br>٤-٦ | of **fc**. | |

**CH AP TE R ON E IN**

**١.١ *General*:**

**ODUCTION**

In recent years, a lot of studies were done on how to improve the performance of concrete, especially on topics regarding how to increase the strength, durability and flowability of concrete. At the same time, there were a number of reports published on how to evaluate and predict those performances. High strength concrete has become one of the hottest topics since ١٩٨٠, and it is now possible to have structures that are built with concrete over ١٠٠ MPa compressive strength [١].This kind of excitement has also triggered further development on the construction techniques and materials used for such concrete. At the same time, there was concern on the maintenance of concrete structures and how it is possible to minimize the cost of maintenance, and to prolong the life of concrete. There is a number of activities at the moment on how to combine both strength and durability into flowability [٢]. However, high workable concrete is still something quite unknown to many researchers, while conventional concrete tends to present a problem with regard to an adequate consolidation in thin sections or areas of congested reinforcement which leads to a large volume of entrapped air voids and compromises the strength and durability of concrete. Using Self-Compacting Concrete (SCC) can minimize this problem since it was designed to consolidate under its own mass [٣].

SCC describes a concrete with the ability to compact itself only by means of its own weight without the requirement of vibration .It fills all voids, reinforcement spaces ,even in highly reinforced concrete members and flows free of segregation nearly to level balance [١,٣]. SCC has been described as "the most revolutionary development in concrete construction for several decades ". Due to its specific properties, SCC may contribute to a significant improvement of the quality of concrete structures and open up new field for the application of concrete [٤].

SCC is different from the conventional concrete in that it has a lower viscosity and thus, a greater flow rate even when pumped .As a consequence, the pumping pressure is lower, reducing wear and tear on pumps and the need for cranes to deliver concrete in buckets at the job site [٥]. The use of SCC offers many benefits to the construction in the practice; the elimination of the compaction works results to reduce the cost of placement, the shortening of the construction time and therefore it is an improvement in productivity.

## ١.٢ Benefits and Uses of SCC:

### ١.٢.١

The use of SCC is spreading world wide because of its very attractive properties in fresh state as well as after hardening .The use of SCC leads to a more industrialized production ,reduce the technical costs of in situ cast concrete constructions ,improve the quality ,durability and reliability of concrete structures and eliminate some of the potential for human error .It will replace manual compaction of fresh concrete with a modern semi-automatic placing technology and in that way improve health and safety on and around the construction site (٦) .

Further benefits of SCC are (٧):

١. Self-leveling, fill all voids, no segregation, easy to deliver and its materials are available locally.
٢. High performance, durability and workability.
٣. Improve surface finish, construction schedule and design flexibility.
٤. Reduce labor costs, equipment on job site, safety, shorten construction time and reduce over all in-place costs.

### ١.٢.٢ Uses:

١. Bridges and structural application.
٢. Pumped concrete and repair applications.
٣. Utility application and hard to reach areas.
٤. Pre-cast and pre-stressed, architectural applications and areas with congested reinforcement such as columns and walls.

## ١.٣ Research significance:

The main purpose for this research is to evaluate the effect of water to powder ratio on some of the mechanical properties of SCC. The investigated properties were ٧, ٢٨ and ٩٠ days compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity, Schmidt rebound hammer test and Ultra-sonic Pulse Velocity (U.P.V), to ٤ water to powder ratios. In fact, the main goal of this research is to furnish the mechanical properties data of SCC to be defined as a set of requirements in terms of hardened concrete and to develop a mix design process. Another aim in this research is to assess the effect of curing conditions on some of the mechanical properties of SCC in the hardened state. Another objective of the study is to find the effect of the time of calcining metakaolin on properties of fresh and hardened states for the SCC.A total of ٣٦٨ specimens of different series of SCC with different: water to powder ratio, type of filler used, curing condition and the calcining time of metakaolin were cast. Complementary tests have also been done to characterize more precisely the mechanical properties of SCC to select good combinations of components.

## ***١.٤ Objectives and scope:***

The objective of this research is to produce a concrete having the desirable properties in the fresh state to satisfy the SCC requirements by combining flow properties of matrix in fresh state, while preserving the strain hardening behavior. To satisfy the SCC performance in both fresh and hardened states, the processing parameters which affect flow properties were carefully controlled in order to minimize disturbance of the micromechanical optimization for strain hardening performance of hardened SCC.

The fundamental objective of this research is to provide information on the hardened properties of SCC produced using available local raw materials in Iraq to support the practical work in assessing the practicability of actually building with SCC, and to facilitate the introduction of SCC technology into a general construction practice. One basic category of concrete was considered, namely, housing or normal concrete. The concrete was produced in civil engineering laboratory, and the following mechanical properties were tested: compressive strength, splitting tensile strength, flexural strength, and static elastic modulus, in addition to, two non-destructive tests" Schmidt rebound hummer and Ultra-sonic pulse velocity".

From previous description it could be summarized these objectives:

١. Evaluate the effect of water to powder ratio on fresh and hardened properties of SCC.
٢. Investigate the effect of filler type on fresh and hardened properties of SCC.
٣. Investigate the effect of curing conditions on the mechanical properties of SCC.
٤. Investigate the effect of time of calcining on efficiency of metakaolin in SCC.

## ١.٥ Thesis layout:

The present research consists of five chapters:-

Chapter ٢ is concerned with literature review on SCC. Chapter ٣ will go over the tests carried out throughout the experimental work, the procedure adopted and the properties of the materials used, Figure (١-١).

The results of the experimental work have been presented and discussed in chapter ٤. The conclusions and a number of suggested commendations for further researches have been mentioned in chapter ٥.

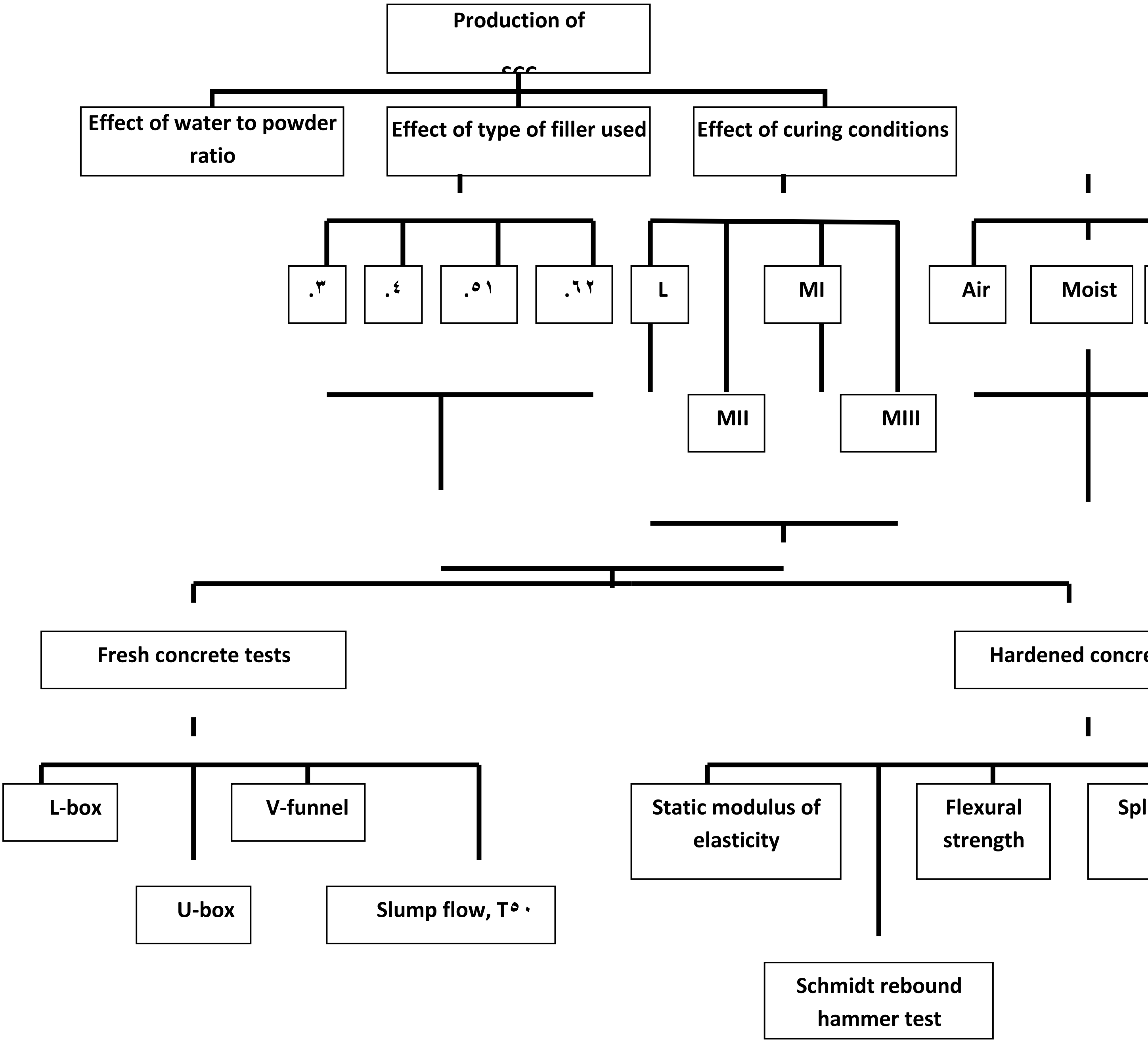



Figure (١-١): Flow chart of the experimental work.

# CHPTER TWO

# LITERATURE REVIEW

## ٢.١ General:

SCC was first developed in Japan ١٩٨٠ in order to reach durable concrete structures. Since then, several investigation have been carried out to achieve a rational mix design for standard concrete, which is comparable to normal concrete [٨]. SCC is defined so that no additional inner or outer vibration is necessary for compaction. It is compacting itself due to its self-weight and is de-aerated almost completely while flowing in the formwork [٩]. In structural members with high percentage of reinforcement it fills also completely all voids and gaps. SCC flows like "HONEY" and has nearly a horizontal concrete level after placing [١٠].

With regard to its compaction, SCC consists of the same components as conventionally normal concrete, which are cement, aggregates, water, additives and/or admixtures. However, the high amount of superplasticizer for reduction of the liquid limit and for better workability, the high powder content, as well as the use of viscosity agents to increase the viscosity of concrete are factors to be taken into account [١١]. Flash-calcined kaolins had higher water absorption capacities, and thus required more water to achieve suitable workability [١٢].

In principle, the properties of the fresh and hardened self-compacting concrete, which depend on the mix design, should not be different from the properties of normally vibrated concrete. One exception is only the consistency. Moreover, since normal slump method could not be used effectively, a new evaluation method must be developed. With all these uncertainties, it is necessary to quantify the most basic properties of the concrete with the use of the mechanism of the particles, and fluid mechanics.

There is a need to develop a method or a way of measure to quantify the flowability of this so called self-compacting concrete (SCC) [٩].

## ٢. ٢ Historical background:

The data available indicated that self-compacting concrete, (self-leveling and self-consolidating), and cohesive concretes were firstly studied in ١٩٧٥-١٩٧٦ by **Collepardi M.** [١٣, ١٤]. At that time the maximum slump level admitted by **ACI** [١٥] was ١٧٥ mm. Moreover, case histories concerning placing of self-leveling concretes without any vibration at all were published after the year ١٩٨٠ [١٦-٢٠]. With the advent of super-plasticizers, flowing concretes with slump level up to ٢٥٠ mm were manufactured with no or negligible bleeding. In the middle of seventies, it was suggested by **Collepardi** [١٣, ١٤] to define "rheoplastic" as a concrete which, besides being very flowable is also very cohesive and therefore has a low tendency to segregation and bleeding.

The most important basic principle for flowing and cohesive concretes including SCC is the use of SP combined with a relatively high content of powder materials in terms of Portland cement, mineral additions, ground filler and/or very fine sand. A partial replacement of Portland cement by fly ash was soon realized to be the best compromise in terms of rheological properties, resistance to segregation, strength level and crack freedom, particularly in mass concrete structures exposed to restrained thermal stresses produced by the heat of hydration of the cement [١٨, ١٩].

**Ozawa K**. et al [٢١] made the first international workshop on SCC held in Kochi, Japan in ١٩٨٨, and then he authored his first paper on SCC in ١٩٨٩. He and other collegues [٢٢] presented a paper on the same project at the international conference on concrete held in Istanbul in ١٩٩٢. These presentations accelerated the international interest in SCC.

Throughout efforts by **Ozawa** and his collegues (٢٢), more intensive research thrived, especially in large construction companies in Asia. Hence, SCC was used in many structures, including buildings, bridge towers and bridge girders (٢٣). Positive attributes of SCC include safely, reduced labor and construction time, and improved quality of the finished product.

Increasing the concrete strength was always one of the main desires of concrete technology. Since more than ٢٠ years high strength concrete with compressive strength ranging from ٥٠ MPa up to ١٣٠ MPa have been used worldwide in tall buildings and bridges with long spans or buildings in aggressive environments. Building elements made of high strength concrete are usually densely reinforced. The small distance between reinforcing bars may lead to defects in concrete (٢٤). If high strength concrete is self-compacting, the production of densely reinforced building element from high strength concrete with high homogeneity would be an easy work. SCC is a concrete that flows and compacts only under gravity. It fills the whole mould completely without any defects. The usual SCC has a compressive strength in the range of (٦٠-١٠٠) MPa (٢٥).

Japan has used SCC in bridge, building and funnel constructions since the early of ١٩٩٠. In the last five years, a number of SCC bridges have been constructed in Europe. In the United States, the applications of SCC in high way bridge construction are very limited at this time. However, the U.S pre-cast concrete industry is beginning to apply the technology to architectural concrete. SCC has high potential for wider structural applications in high way bridges (٢٦).

## ٢.٣ Selection and properties of Raw materials:

### ٢.٣.١ Aggregates:

#### ٢.٣.١.١ Fine

The maximum size of the aggregate depends on the particular applications and it is usually limited to ٤.٧٢ mm. The particle size smaller than ٠.١٢٥ mm contributes to the powder content [٢٧].

**Dirch H.** et al [٢٨] studied ten different sands in the experimental program; five natural and five artificial, each pair having identical grading curves but a different particle shape and a surface texture. They concluded that:

- Increasing the fineness of sand particles leads to increasing yeild stress and plastic viscosity.
- Increasing the aspect ratio (fine/total) leads to increasing yeild stress and plastic viscosity.
- The surface texture appears to be of minor importance.

Thus, the rheological properties of self-compacting mortars can be tailored for special purposes by the choice of cement, filler and sand.

**Su K.** et al [٢٩], studied the effect of sand ratio (S/A= fine aggregate volume to total aggregate volume) on the elastic modulus of self-compacting concrete. They used various S/A ratio concretes which were cast and tested then the modulus of elasticity of SCC was compared with the modulus of elasticity of normal concrete. Slump flow test, slump test and U-box test were carried out to evaluate concrete flowability. They found that the flowability of

SCC increases with the increase in S/A. However, the modulus of elasticity of SCC is not significantly affected by S/A when total aggregate volume was kept constant.

**Cho W**. et al [٣٠] found that, when a higher volume fraction of aggregate is used in the mix, the elastic modulus of the composite should be computed by introducing a third phase (voids) into the composite. For the mix with lower volume fraction of aggregate, because the volume of voids are relatively small in comparison with the volume of other components, two phases approach are appropriate for evaluating the elastic modulus of the composite.

### *٢.٣.١.٢ Coarse aggregate:*

During the production of SCC, tests on coarse aggregate grading and moisture content should be carried out more frequently than usual concrete, since the SCC is more sensitive than normal concrete to variations in such properties. It was noticed that an increase in surface moisture content by (١) % will lead to an increase in slump flow by about (١٠٠) mm. The normal size of the coarse aggregate used to produce SCC is generally between (٥-٢٠) mm. During producing SCC, particle shape, size and surface texture are very important to be considered and controlled [٢٧].

Aggregate makes up (٦٠-٨٠) % by volume of normal concrete, thus, the properties of hardened concrete are influenced considerably by the aggregate, while in SCC the coarse aggregate makes up (٣٠-٣٤) % of the concrete volume; therefore, it has a lower effect on the properties of hardened SCC.

**Budi and Karsten** [٣١] found that the modulus of elasticity of gravel influenced more significant the modulus of elasticity of concrete specimens. This was caused by the high volumetric content of aggregate in concrete composite. They concluded that, for the production of unconfined high performance concrete with ductile behavior, the compressive strength of aggregate must be as maximum in the range about ٢ times of the planned concrete strength. And the modulus of elasticity of aggregate in the range of maximum ١.٥ times that of the cement matrix. A very high compressive strength of aggregate is not useful, besides, using a proper amount of silica fume with compatible super-plasticizer is absolutely necessary [٣١]. In consequence, bond failure is avoided and the fracture surfaces pass through the aggregate as well as through the hardened cement paste under both, compressive and tensile loading [٣٢].

When the volume of coarse aggregate in concrete exceeds a certain limits, the opportunity for collision or contact between coarse aggregate particles increases rapidly and there is an increase in risk of blockage when the concrete passes through spaces between steel bars [٣٣].

The optimum coarse aggregate content depends on the following parameters:-

- Maximum aggregate size. The lower the maximum aggregate size, the higher proportion of coarse aggregate.
- Crushed or round aggregate. For round aggregate a higher content can be used than for crushed aggregate.

Aggregate surface moisture content may affect the content of free water in two ways:

- Aggregate surface moisture content is higher than expected.
- Aggregate surface moisture content is lower and / or the aggregate absorbs moisture [٣٤].

### ٢.٣.٢

The friction between the aggregate limits the spreading and the filling ability of SCC, this is why SCC contains a high volume of paste (cement + additions + water + air), typically (٣٣٠-٤٠٠) kg/m$^{٣}$, the role of which is to maintain aggregate separation (no blocking). SCC also has a high volume of fine particles (< ٨٠*١٠$^{-٦}$) m in order to ensure sufficient workability while limiting the risk of segregation or bleeding. Nevertheless, in order to avoid excessive heat generation, the Portland cement is generally partially replaced by mineral admixtures like limestone filler or fly ash (cement should not be used as a filler) [٣٥].

**Jianxin and Holger** [٣٦] found that the replacing of ٣٠ % of cement by quartz powder, the slump flow increased from ٥١٠ mm to ٦٢٠ mm and because of high binder content, (٩٥٠ kg/ m$^{٣}$ of cement + filler) and low water to powder ratio, concrete shows a higher autogenously shrinkage than conventional concrete.

Selection of the type of cement will depend on the over all requirements for the concrete, such as strength, durability, etc.$C_{٣}A$ content higher than ١٠ % may cause problems in poor workability retention. The typical content of cement is (٣٥٠-٤٥٠) kg/m$^{٣}$. More than (٥٠٠ kg/m$^{٣}$) increases the shrinkage, less than (٣٥٠ kg/m$^{٣}$) may only suitable with the inclusion of reactive filler type such as fly ash, silica fume, etc [٢٧].

**Hanehara and Yamada** [٣٧] pointed out that slight fluctuation of cement characteristics affect the performance of super-plasticizer, and to clarify which characteristics affect the performance of super-plasticizer, several kinds of cement should be used to produce the compatibility phenomena.

### ٢.٣.٣ Admixtures:

Super-plasticizers are essential components of the SCC to provide the necessary workability. Other types of admixtures may be incorporated as necessary, such as viscosity modifying agents (VMA) for stability, air entraining admixtures (AEA) to improve freeze-thaw resistance, retarders for control of setting, etc. V.M.A. admixtures are not specially covered in EN ٩٣٤-٢; ٢٠٠٠, like other admixtures do, but should conform to the general requirements in the standard of test methods of SCC. The most important admixtures are the super-plasticizers (high range water reducers), used with a water reduction greater than ٢٠ %. The use of V.M.A. gives more possibilities of controlling segregation when the amount of powder is limited. These admixtures help to provide a very good homogeneity and reduce the tendency to segregation [٢٧].

**David and Sheinn** [٣٨] noticed that a super-plasticizer was very important to lower the water demand while achieving high fluidity. It is a surface active agent causing dispersion there by reducing the friction between and among the powder particles. The common super-plasticizer used was a new generation type based on polycarboxylated polyether.

**Jianxin and Holger** [٣٦] concluded that the application of new super-plasticizers and powders in a high performance concrete gives the opportunity to produce SCC that reaches a compressive strength of more than (١٥٠ MPa). These concretes show a very good workability in the fresh state, also the hardened concrete shows excellent quality.

**Orjan P.** [٣٩] concluded that the use of higher admixture contents to increase the blocking ratio can be obtained however to the cost of a significant separation tendency of recipe and the use of viscosity agent increases mainly the viscosity and makes the concrete more cohesive with fewer risks for separation.

### ٢.٣.٤ Additions:

Additions are commonly used in SCC due to the need for substantial contents of fine particles. All additions conforming to EN standards are suitable [٢٧]. Due to the special rheological requirements of SCC, both inert and reactive additions are commonly used to improve and to maintain the workability, as well as to regulate the cement content and so reduce the heat of hydration [٤٠]. Additions are generally divided into:

١. General suitability as type I (semi-inert) addition is established for:

- Filler aggregate conforming to EN ١٢٦٢٠.
- Pigments conforming to EN ١٢٨٧٨.

٢. General suitability as type II (pozzolanic or latent hydraulic) addition is established for:

- Fly ash conforming to EN ٤٥٠.

- Silica fumes conforming to EN ١٣٢٦٣.
- Ground granulated blast furnace slug conforming to BS ٦٦٩٩.

**Collepardi M.** [٤٠] suggested that the important basic principles for flowing and cohesive concretes including SCC is the use of SP combined with a relatively high content of powder materials in terms of Portland cement, mineral additions, ground filler and / or very fine sand. A partial replacement of Portland cement by fly ash was soon realized to be the best compromise in terms of rheological properties, resistance to segregation, strength level and crack freedom, particularly in mass concrete structures exposed to restrained thermal stresses produced by the heat of hydration of cement.

**Chiara F.** et al [٤١] reported a study on the influence of mineral admixtures on rheology of cement paste and concrete by using six types of fillers. They found that some of the fillers give an improvement in rheological properties like ultra-fine fly ash while silica fume represent the worst. It was found that the replacement of cement by silica fume results in an increase in the water demand to maintain the rheological properties of the control mix. And other mineral admixtures like metakaolin, coarse fly ash, fly ash, and fine fly ash gave results between silica fume and ultra-fine fly ash.

**Paul and Robert** [٤٢] found that the characteristics of the calcined shale were found to improve the cohesion of the concrete mixture and therefore provide better control of segregation, without the necessary of VMA, in addition, the total cementitious content needed in the natural-pozzolan-modified concrete was found to be some what lower than the Portland cement content required for the conventional SCC mixtures. A natural pozzolan content of (٣٠ %) by weight of cement was found to be optimum for preventing segregation and achieving sufficient early age strength.

The calcining temperature plays a central role in the reactivity of the resulting metakaolin product. **Joy M.** [١٢] found the effects of calcining temperature on the strength development of metakaolin-lime pastes. He reported that ٧٠٠ °C to be optimal and later showed that calcination below this temperature results in a less reactive material containing more residual kaolinite. Above ٨٥٠ °C, he reported, recrystallization began and reactivity declined, as kaolin had begun to convert to relatively inert ceramic materials, such as spinel, silica, and mullite. Samples of approximately ٤٥٠ mg were heated to ٩٠٠ °C at a rate of ١٠ °C/min in dry air atmosphere. The heating process, illustrated by differential thermal analysis (DTA), is shown in Figure (٢-١).

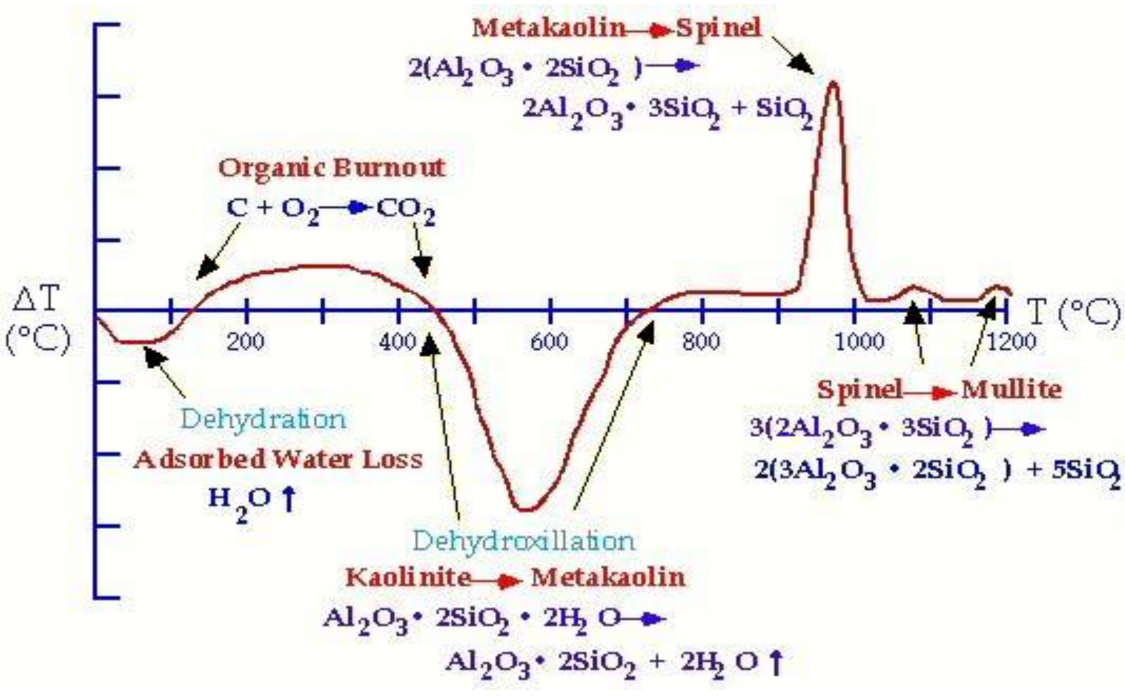



Figure (٢-١): Thermogram of kaolin [١٢].

## ٢.٤ Mix design:

In designing the SCC mix it is most useful to consider the relative proportions of the key components by volume rather than by mass. In the event that satisfactory performance can not be obtained, then consideration should be given to fundamental redesign of the mix [٢٧]. Depending on the apparent problem above, the following courses of action might be appropriate to:

- The use of additional or different types of filler.
- Modify the properties of sand and gravel.
- The use of VMA, if not already included in the mix.
- Adjust the dosage of SP and / or VMA.
- The use of alternative types of SP (and / or VMA) which may be more compatible with local materials.
- Different dosage rates of admixtures to modify the water content, and hence the water / powder ratio.

**Okamura** [٤٣] suggested an example of designing SCC mixes. The sequence is determined as:

١. Designation of desired air content:

Air content may generally be set at ٢ % by concrete volume, or a higher value specified where freeze-thaw resistance is to be desired.

٢. Determination of coarse aggregate volume:

Coarse aggregate volume is defined by bulk density. Generally coarse aggregate content (D>٥mm) should be between (٥٠-٦٠) % of total mix.

٣. Determination of fine aggregate content:

Sand, in the context of the mix composition procedure is defined as: all particles which are larger than (٠.١٢٥mm) and smaller than (٥mm). Sand content is defined by bulk density. The optional volume content of sand in the mortar varies between (٤٠-٥٠) percent depending on paste properties.

٤. Designing paste composition:

Initially water to powder ratio, (W/P) for zero flow (βp) is determined in the paste, with the chosen proportions of cement and additions. Flow cone tests with water to powder ratios by volume are performed with the selected powder composition. (βp) as shown in Figure (٢-٢) is the volumetric ratio of water to powder at which all voids among solid particles are just filled with water.

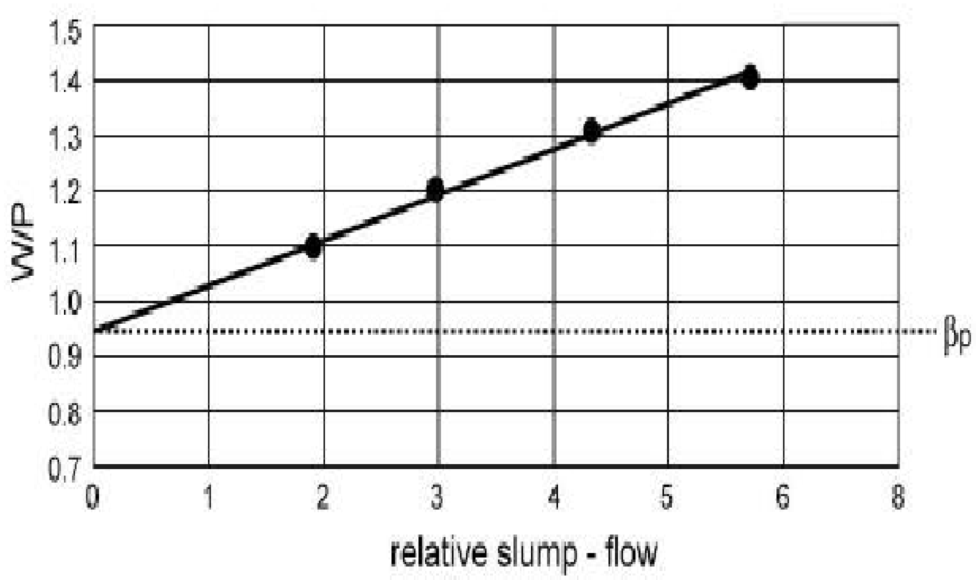



Figure (٢-٢): Determination of W/P ratio [٤٣].

٥. Determination of the optimum volumetric water to powder ratio and super-plasticizer dosage in mortar:

Tests with flow cone and V-funnel for mortar were performed at varying water to powder ratios in the range of (٨٠-٩٠) % depending on the amount of powder content in the mixture.

**David and Sheinn** [٣٨] reported that mix designs of SCC must satisfy the critiria on filling ability, passing ability and segregation resistance. The most common method of mix design to satisfy these critiria is the (general method ) developed by various researchers at the univercity of Tokyo [٤٤,٤٥]. Since then many attempts have been made to modify this method to suit local conditions. Experience in Japan and Europe showed that there were wide variations of materials and proportions that could be used to produce satisfactory SCC, with certain key factors fall within certain limits. These limits are summarized in Table (٢-١). In achieving economical mixes, the powder content should be kept to a minimum because the cement and some of fillers are expensive items.

Table (٢-١): Range of mix constituents [٤٤,٤٥].

| ***Constituent*** | ***By volume %*** | ***By weight (kg/m$^{٣}$)*** |
|---|---|---|
| Gravel | (٣٠-٣٤) ----av. (٣٢) | ٧٥٠-٩٢٠ |
| Sand | (٤٠-٥٠) of mortar vol….av. (٤٧) | ٧٧٠-٩٠٠ |
| Powder | ------- | ٤٥٠-٦٠٠ (٥٠٠) |
| Water | (١٥٠-٢٠٠) ١/m$^{٣}$ ----- av.(١٨٠) | ١٥٠-٢٠٠ |
| Paste | (٣٤-٤٠) -----av. (٣٥) | ___ |

**Klaus and Yvette** [٤٦] summarized a mix coposition of SCC in coparison with normal vibrated concrete (NVC) as shown in Figure (٢-٣).

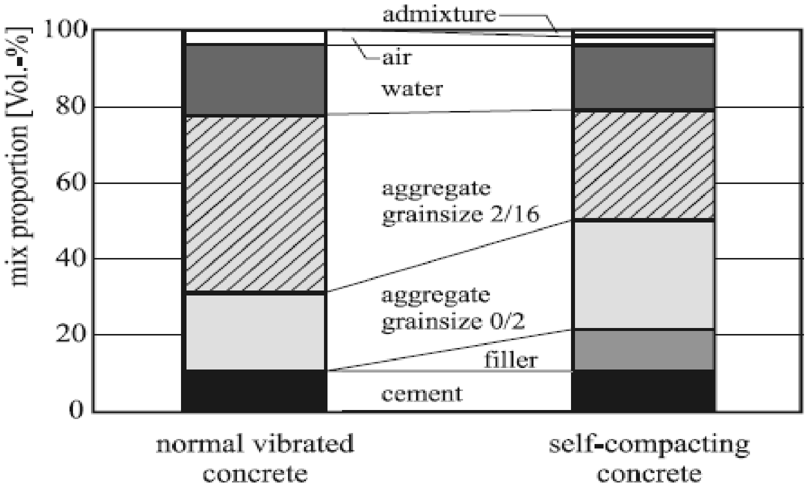



Figure (٢-٣): A comparison between SCC and NVC [٤٦].

## ٢.٥ Mixing procedure:

There are no requirements for any specific mixer type. Forced action mixers, including paddle mixers, free fall mixers, including truk mixers, and other types can all be used. The mixing time necessary should be determined by practical triales. Generaly, mixing time need to be longer than conventional mixes [٢٧].Time of addition of admixtures is important, and procedures should be agreed with the supplier after plant triales. If the consistence has to be adjusted after initial mixing, then it generaly be done with the addmixtures.

**Jianxin and Holger** [٣٦] summarized a mixing consequence that all concretes have been mixed in an intensive mixer with the following procedure: all dry materials were mixed till a homogeneous mixture was built up, ٢ minute after mixing, water and SP have been added and the mixture was mixed about ٦ min. till a flowing and homogenous concrete was formed.

**Dirch H.** et al [٢٨] suggested this mixing procedure:

- Aggregate and ٢/٣ of the water.
- ٦٠ seconds of mixing .
- ١٠ minutes rest in order to achieve saturation of the aggregate.
- cement and filler are added immediately before the final mixing .
- the remaining ١/٣ of the water, including additives, are added during the first ١٥ sec of the final mixing period.
- ٩٠ sec mixing.

**Bernabeu and Laborde** [٤٧] reported a mixing sequence as below:

- air entraining agent +water+٥٠٪ of aggregate +cement +filler+SP
- mixed for ٢٠ sec. and then adding the remaining aggregate .
- mixed for ٣٠ sec.

For the preparation of fresh SCC mixes, all of the dry particles were mixed in a llobart mixer equiped with a planetary rotating blade. Water was added to form the basic mortar matrix. To ensure the adsorption of the SP used onto the cement particles, the SP was first added as a solution, followed by the V.M.A [٤٧,٤٨]. The separate addition of water and SP prevents a sudden increase in the viscosity as caused by false setting. Figure (٢-٤) shows a mixing procedure at the ready mixed concrete plant for full size pours [٤٩].

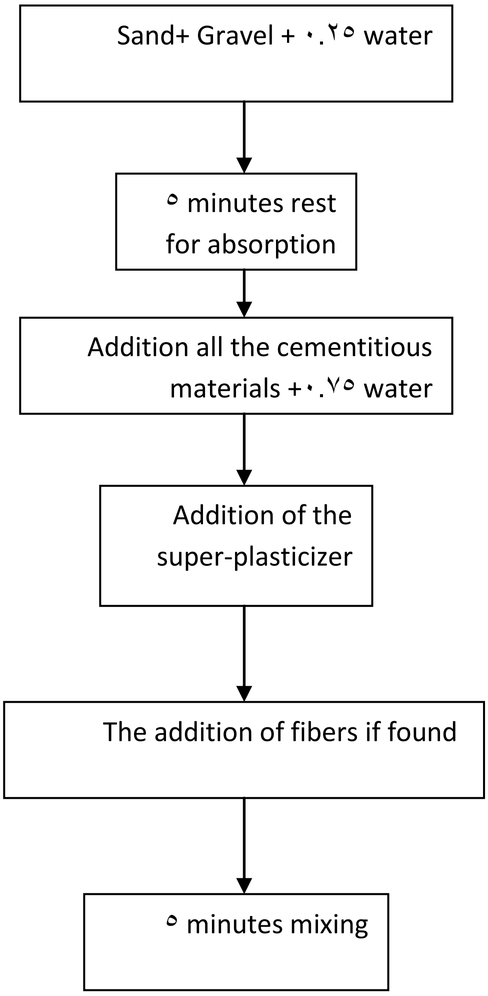



Figure (٢-٤): Mixing procedure according to **Sonebi** et al [٤٩].

## ٢.٦ Workability measurement:

The American Society for Testing and Materials (ASTM) and the American Concrete Institute (ACI) are curently working on identifying proper SCC test methology [٥٠]. The characteristics of SCC, resistance to bleeding and segregation, high early and ultimate strengths as well as fluidity, make this new creature in construction materials a little challenging to create uniform tests methology.

Slump testing, widely used for identifing the workability of concrete, is not applicable for SCC. It has flow charactristics that the slump test does'nt currently measure properly. One possible test method is the “slump-flow test”, which measure the slump flow in diameter. A nother suggested test method is the “U-flow test”. This test simulates the flow of concrete through a volume containing reinforcing steel bars. Other test methods, include the “V-flow, J-ring, L-flow, Flow box and rheometers [٢٧].

The workability of SCC is higher than the highest class of consistence described within EN ٢٠٦ and can be characterized by the following properties:

- filling ability.
- passing ability.
- segregation resistance.

Filling ability: is the ability of SCC to flow into and fill compeletely all spaces within the formwork, under its own weight. Passing ability: is the ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking. Segregation resistance (Stability): is the ability of SCC to remain homogenous in composition during transporting and placing [١٢,١٨,٢٣,٤٨]. For the quality control, two test methods are generally sufficient to monitor production quality. Typical combinations are slump-flow and V-funnle or slump flow and J-ring. With consistent raw material quality, a single test method operated by a trained and experienced technician may be sufficient [٢٧].

**Lars G**. [٦] reported some suggestions on suitability of test methods as shown in Tables (٢-٢), (٢-٣) and (٢-٤) respectively.

Table (٢-٢): Some suggestions on suitability test methods [٦].

| Method | Mobility | Passibility | Segregation Resistance | Viscosity |
|---|---|---|---|---|
| Slump-flow | XX | n.a | X | n.a |
| T٥٠ cm | n.a | n.a | n.a | X |
| L-box | n.a | XX | X | X |
| GTM | n.a | n.a | XX | n.a |

Notations: XX= suitable X= acceptable

n.a= not applicable

Table (٢-٣): Suggestions on suitability of different test methods for fibre reinforced SCC [٦].

| Method | Mobility | Passibility | Segregation | Viscosity | Steel fibre distribution |
|---|---|---|---|---|---|
| Slump-flow | XX | n.a | n.a | n.a | n.a |
| T٥٠ cm | n.a | n.a | n.a | X | n.a |
| J-ring | X | XX | n.a | n.a | n.a |

| | | | | | |
|---|---|---|---|---|---|
| L-box | X | X | n.a | n.a | n.a |
| GTM | n.a | n.a | XX | n.a | n.a |
| Fibre content | n.a | n.a | n.a | n.a | X |

Table(٢-٤): Test methods of SCC [٦,٢٧].

| Property | Methods | | |
|---|---|---|---|
| | Laboratory Mix design | Field (QC) | Modification of test according to max agg |
| Filling ability | Slump flow T٥٠, | Slump flow T٥٠, | None |
| Passing ability | L-box U-box | J-ring | Different openings L, U, J-ring |
| Segregatio resistanc | GTM, V funnel ٥ min | GTM, V funnel ٥ min | None |

Table (٢-٥): Description on suitability of different test methods for SCC, not including steel bars [٣٩].

| **Methods** | **Site** | **Lab.** | **Mobility** | **Blocking** | **Segregation** | **Viscocity** |
|---|---|---|---|---|---|---|
| Slump-flow | X | X | X | N | X | N |

| | | | | | | |
|---|---|---|---|---|---|---|
| T٥٠ cm | X | X | N | N | X | XX |
| L-box | | X | N | XXX | XX | X |
| Orimet | X | X | X | | XX | XX |
| V-funnel | X | X | X | | XX | XX |
| J-ring | X | X | | XX | N | N |
| O+J | X | X | X | XX | XX | XX |
| GTM | | | | | XXX | |

Notations:

XXX=most suitable　　XX=suitable

X=acceptable　　N=not relevant

### ٢.٦.١ Limitations and criteria of workability tests:

SCC should have slightly different criteria than normally vibrated concrete depending on what kind of construction it is used for, and if the part of construction is horizontal or vertical. Construction with a high demand on surface without pores can have more special demands on rheological behavior or/ and casting process [٦].

#### ٢.٦.١.١ Criteria for slump-flow and T٥٠ cm:

Civil engineering, (high strength) SCC has for strength and durability reasons a lower W/C around ٠.٤, in this case the criteria could depend on the total fines amount and of course the W/C ratio. When the amount of the filler and cement is as high as (٥٥٠-٦٠٠) kg/$m^{٣}$ it could permit slump-flow to reach between (٦٧٠-٧٣٠) mm. Other wise the criteria (٦٠٠-٧٠٠) mm is normally valid. May be (٦٠٠) mm could be to low in some cases. If the precision in production was high the criteria could be (٦٥٠-٧٠٠) mm because optimum slump-flow was near (٧٠٠) mm. When casting horizontal constructions the target value for the slump-flow was lower than the vertical constructions if a finishing device was used or a slope should be constructed. T٥٠ was very dependent on W/C, for vertical constructions SCC with slump-flow of (٧٠٠) mm, T٥٠ could be around (٤) second. For horizontal constructions SCC with slump-flow of (٦٥٠) mm, T٥٠ could be around (٧) sec.

Housing building SCC, (normal strength concrete) has a relatively high W/C; the slump-flow value should reach between (٦٠٠-٧٠٠) mm. Over (٧٠٠) mm the risk for segregation of coarse aggregate is high, at least when only filler was used to control the viscosity of paste. T٥٠ could be lower than for SCC for civil engineering, (depending on admixture). The stability criteria should always be reached.

### ٢.٦.١.٢ L-box and V-funnel:

The only criterion for L-box is the blocking ratio ($H_{٢}/H_{١}$), which mean the ability of SCC to pass between steel bars. This ratio should be more than ٠.٨ regardless what type of construction that should be built. The shape of the L-box can be different depending on construction type as in civil and house building. The stability criteria should always be reached. Table (٢-٦) shows a suggestion of criteria for different test methods.

Table (٢-٦): Suggested criteria values for workability tests [٦].

| Application | L-BOX<br>% | Slump flow<br>(mm) | T٥٠<br>Sec | V-funnel<br>Sec | Orimet<br>Sec |
|---|---|---|---|---|---|
| Civil eng.<br>Vertical | ٠.٨ | ٦٥٠-٧٢٥ | ٣-٧ | ٥-١٥ | ٢-٢٠ |
| Civil eng.<br>Horizontal | ٠.٨ | ٦٠٠-٦٥٠ | ٣-٧ | ٥-١٥ | ٢-٢٠ |
| Housing<br>Vertical | ٠.٨ | ٦٠٠-٧٠٠ | ٢-٥ | ٥-١٥ | ٢-٢٠ |
| Housing<br>Horizontal | ٠.٨ | ٦٠٠-٧٠٠ | ٢-٥ | ٥-١٥ | ٢-٢٠ |

**Other researchers** [٢٣, ٢٧, ٣٣] gave these requirements to be fulfilled at the time of placing. Likely changes in workability during transport should be taken into account in production.

Table (٢-٧) remarked some typical acceptance criteria for SCC with max aggregate size up to (٢٠) mm. Special care should always be taken to ensure no segregation of the mix was likely as, at percent, there was not a simple and reliable test that gives information about segregation resistance of SCC in all practical situations [٨].

Table (٢-٧): Acceptance criteria for SCC with maximum aggregate size up to ٢٠ mm [٢٣, ٢٧, ٣٣].

| METHODS | UNIT | TYPICAL RANGE VALUES | |
|---|---|---|---|
| | | Minimum | Maximum |
| Slump flow | mm | ٦٥٠ | ٨٠٠ |
| T٥٠ slump flow | Sec | ٢ | ٥ |
| J-ring | mm | ٠ | ١٠ |
| V-funnel | Sec | ٦ | ١٢ |
| V-funnel at ٥ min. | Sec | ٠ | ٣ |
| L-box | % | ٨٠ | ١٠٠ |
| U-box | mm | ٠ | ٣٠ |
| Fill box | % | ٩٠ | ١٠٠ |
| GTM screen stability | % | ٠ | ١٥ |
| Orimet | Sec | ٠ | ٥ |

**David and Sheinn** [٣٨] suggested some major limits according to workability tests in Table (٢-٨).

Table (٢-٨): Some major limits according to workability tests [٣٨].

| Test | Properties | Limits |
|---|---|---|
| Slump-flow | Filling ability, visual observation of segregation | Diameter>٦٥٠mm<br>T٥٠<١٢ sec. |
| L-box | Filling, passing, visual observation of segregation | $H_٢/H_١$>٠.٨ Filling height>٣٠٠ mm |
| U-box | Filling ability,passibility | Flow time ١٠-٢٠sec. |
| V-funnel | Segregation resistance | Surface settlement <٠.٥ % |
| Surface settelment | Segregation resistance | Penetration depth <٨ mm |
| Penetration Test | Segregation resistance | Segregation coef.< ٧ % |
| Segregation | Segregation resistance | ٧٠٠ mm column |

## ٢.٦.٢ Rheology of SCC:

The rheological behavior of a fluid such as cement paste, mortar or concrete is most often characterized by at least two parameters, τ٠ and η, as defined by the **Bingham** equation [٥١].

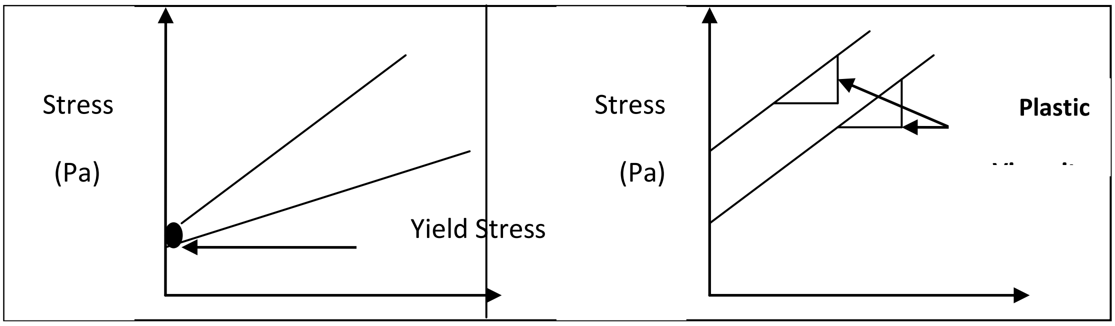
$$\tau = \tau_0 + \eta\gamma \qquad \text{----------- (٢-١)}$$

Where: τ= shear stress , τ٠= yield stress

η= viscosity , γ= shear rate

The yield stress and plastic viscosity were the **Bingham** parameters that characterize the flow properties of material. For special concretes, such as SCC, a third parameter might be necessary to correctly represent the shear rate-shear stress relationship [٥١]. Other equations have been used for describing the concrete flow, because uncertain circumstances concrete flow does not obey the **Bingham** equation [٥٢, ٥٣]. The cement paste on the other hand was either described as a Newtonian fluid (τ.= ٠, η>٠) or a Bingham fluid (τ.> ٠, η>٠), as shown in Figure (٢-٥). Figure (٢-٥) explained why if only one of the two parameters was determined, prediction of a material field performance might not be correct. To determine the yield stress and the viscosity of the cement paste, mortar or concrete, the instrument must be able to measure stresses generated at a minimum of two different shear rates [٥٤]. Therefore, only one of the two parameters can be estimated.

**Tattersall G.** [٥٥] was the pioneer in developing a concrete rheometer with controlled shear rates capable of measuring the stresses in concrete. Presently, three commercially available rheometers exist capable of varying shear rate (γ). Figure (٢-٦) shows some of the idealized types of curves that can be obtained when shear stress is plotted against shear rate. All the curves depicted could be described by one of the equations of the Table (٢-٩).




Shear rate ($S^{-١}$) Shear rate ($S^{-١}$)

a=Identical yield stress but different plastic viscosity.

b=identical plastic viscosity but different yield stress.

Figure (٢-٥): Definition for Bingham parameters for concrete flow [٥٢, ٥٣].

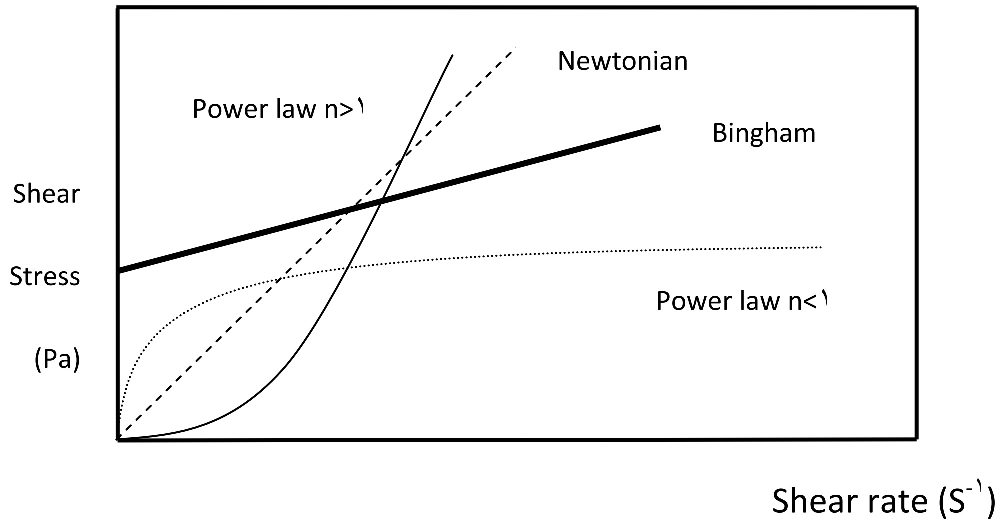



Figure (٢-٦): Bingham Rheology model [٥١, ٥٦].

Table (٢-٩): Equations relating shear stress and shear rate [٣٨, ٤١, ٥١].

| **Equation name** | **Equation** |
|---|---|
| Newtonian | $\tau = \mu * \gamma$ |
| Bingham | $\tau = \tau_{.} + \mu * \gamma$ |
| Vom Berg and Ostwald W. | $\tau = \tau + B \sinh^{-١}(\gamma / c)$ |
| Robertson and Stiff | $\tau = a(\gamma + c)^{b}$ |
| Eyring | $\tau = a\gamma + B \sinh^{-١}(\gamma / c)$ |
| Power equation | $\tau = A * \gamma$<br>n=١ Newtonian flow<br>n<١ shear thickening<br>n>١ shear thinning |
| Herschel and Bulkelly | $\tau = \tau_{.} + k * \gamma$ |

Where: τ= shear stress τ.= yield stress

μ= viscosity γ= shear rate

A¸a¸B¸b¸c¸k= constants

## ٢.٧ The effect of curing conditions:

The surface of SCC tends to dry faster than the conventional concrete because there is little or no bleed water at the surface. Initial curing should therefore be commended as soon as few hours after placing in order to minimize the risk of plastic shrinkage cracking [٢٧]. In order to obtain good concrete, the place of an approximate mix must be followed by curing in a suitable environment during the early stages of hardening. Curing is the name given to procedures used for promoting the cement hydration, and consists of temperature control and moisture movement from and into the concrete [٥٧].

**Saeed** [٥٧] examined three types of curing on high-strength concrete, which they were:

A. Moist curing in water for ٧ days followed by air curing inside the laboratory at (٢٦-٣٠) ˚C until testing age.
B. Moist curing in water until testing age.
C. High temperature curing; by placing the specimens in a water curing tank placed in a controlled temperature room. The curing temperature was (٦٠+٢)˚C for six days then these specimens were air cured.

She found that the compressive strength for B curing was more than A curing at ٧ days and the rate of increase in ٢٨ and ٩٠ days compressive strength for HSC was greater than those of NSC. The rate of increase in strength was (٢-١٢) % for all mixes, as shown in Figure (٢-٧), also, the results of

٢٨ days splitting tensile strength for concrete with different strength levels and curing types showed that the splitting tensile strength was more affected by drying than compressive strength, and the effect of curing conditions on HSC was greater than NSC. The reduction in ٢٨ days splitting tensile strength was (٢-٢٠) % for all mixes as shown in Table (٢-١٠); this was because the mechanism of failure involves the direct tension and drying shrinkage.

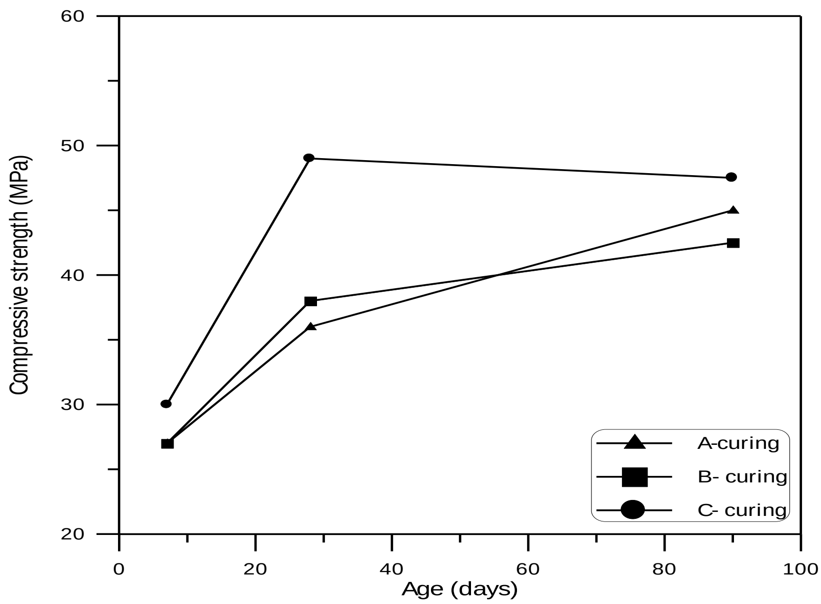



Figure (٢-٧): Compressive strength development of ١٥٠ mm cubes with age for mixes cured at varying conditions [٥٧].

Table (٢-١٠): Splitting tensile strength in MPa for different specimen size and curing conditions at ٢٨ days [٥٧].

| Mix | Method of curing | | |
|---|---|---|---|
| | A | B | C |
| [illegible] | Ft ١٥٠=٢.٨٤<br>[illegible] | ٢.٩<br>[illegible] | ٢.٩٧<br>[illegible] |
| ٢ | ٣.٤<br>٤.١٤ | ٣.٩٥<br>٤.٥ | ٣.٩<br>٤.٦٢ |
| ٣ | ٣.٧٥<br>٤.٧١ | ٤.٥<br>٥.٦ | ٤.٣٢<br>٥.٠ |
| ٤ | ٤.٥<br>٤.٩ | ٥.٣<br>٥.٠ | ٥.١٣<br>٥.٥٨ |

$F_{t\,١٥٠}$= Splitting tensile strength in MPa for cylinders of ١٥٠ mm diameter.

$F_{t\,١٠٠}$= Splitting tensile strength in MPa for cylinders of ١٠٠ mm diameter.

**Sonebi M.** et al [٤٩] investigated the effect of curing conditions on strength development of the SCC and reference mixes, and the air cured strengths relative to water cured strengths as presented in Figure (٢-٨). They found that the compressive strength of air-dried specimens was lower than that of the corresponding water cured specimens. However, the extent of strength reduction due to the insufficient curing (in air) up to an age of ٩٠ days depending on the strength grade and the type of filler in the mix. It appears that the SCC mixes, with limestone filler were less affected by air curing, and that air cured strengths were reduced less than those of reference concretes. As shown in Figure (٢-٨), at ٢٨ and ٩٠ days, the relative strength ratios for housing SCC were higher than those for the corresponding reference mix (RH) of about (٧١-٦٥) % respectively. This difference could be attributed to the acceleration effect of the limestone powder and also possibly the enhanced water retentivity of the SCC mixes. For civil SCC, the strengths up to the age of ٩٠ days were more affected by air curing, and the strength reduction due to the air curing was greater than the corresponding reference mix. Such a difference in sensitivity to curing conditions was normal for mixes containing reactive fillers, as continued presence of water was required for the cement hydrates- filler reaction to continue.

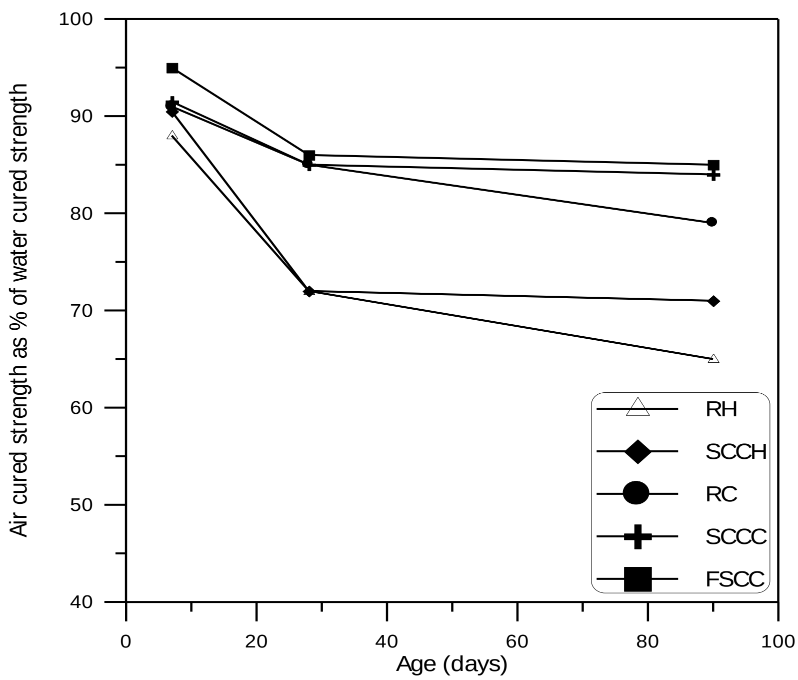



Figure (٢-٨): Effect of curing conditions on compressive strength [٤٩].

RH= reference housing.

SCCH= housing self compacted concrete.

RC= reference civil.

SCCC= civil self compacted concrete.

FSCC= fiber reinforced self compacted concrete.

## ٢.٨ Mechanical properties:

It is well known that the properties of concrete are affected by cementitious matrix, aggregate, and the transition zone between these two phases. Reducing the water to cement ratio and the addition of pozzolanic admixtures like silica fume are often used to modify the microstructure of the matrix and to optimize the transition zone. The reducing of the water to cement ratio results in a decrease in porosity and distribution of capillary pores in matrix [٤٢]. In high performance concrete, water to cement ratio ranges usually between (٠.٢٨-٠.٣٨), while in ultra-high performance concrete the water to cement ratio is even lower than (٠.٢)[٥٨]. On the other hand, decreasing water to cement ratio negatively influenced the flowing ability of the fresh concrete. Special attention must be paid to ensure the extremely high flowing ability required in SCC. According to the design method for conventional SCC proposed by **Okamura H.** et al [٥٩], the volume of coarse aggregate, fine aggregate and paste consisting of powder, (<= ٠.١٢٥) mm, plus water are approximately ٢٠ % by volume, ٥٠ % by volume and ٣٠ % by volume respectively.

In the case of ultra-high strength SCC with very low water to powder ratio, paste volume should be increased. Another way to increase concrete flowing ability was minimizing the voids among the particles of the powder mixture composed with cement, filler and other fine components. Voids among powder particles could be evaluated by the water demand βp. βp was the volumetric ratio of water to powder material, at which all voids among solid particles are just filled with water. It can be determined according to the relationship between relative slump-flow and volumetric water to powder ratio $V_w / V_P$ as shown in Figure (٢-٢). SP was ٢ % in powder mass. The intercept point with the ordinate is βp. The βp with a low value of ٠.٣١٩ indicates a high packing density of the granular mixture composed from cement, micro silica and quartz powder.

Flow tests were carried out on pastes containing different water to powder ratios or different SP dosages with a flow cone as in conventional SCC. The results showed that the SP dosage of more than ٢ % of powder mass could not improve the flowing ability of the paste any more. The relative slump-flow was calculated from measured slump flow as following: $£_m = (d/d_٠)^٢ - ١$

---------- **(٢-٢)**

Where: **$£_m$:** is the relative slump flow

**d:** the flow diameter= $(d_١ + d_٢)/ ٢$

**$d_٠$:** flow cone diameter.

## ٢.٨.١ ***Compressive***

In all SCC mixes compressive strength of standard cube specimens were comparable to those of traditional vibrated concrete made with similar water to cement ratios- if any thing strengths were higher. There is a little difficulty in producing SCC with characteristics cube strength up to (٦٠ MPa) [٤٥].

**Frank D.** et al [٤] summerized these results from ١٥٠ mm cubes and (١٥٠*٣٠٠) mm cylinders. The specimens were cured in water for ٢٨ days to avoid changing in curing conditions. They noticed that the high early compressive strength and the high splitting tensile strength of the SCC were due to the use of fly ash. Such concrete types normally have slower strength development because of the lower hydration rate of he fly ash. Therefore, it is difficult to compare the compressive strength with conventional concrete aged ٢٨ days [٦٠].

**Klaus and Yvette** [٤٦] found that after ٢٨ days the reached compressive strength of SCC and normally vibrated concrete of simimlar composition does not differ significantely in the majority of the test results. Isolated cases, however, showed that for the same water to cement ratios, slightly higher compressive strengths were reached for SCC. The comparison of hardening process shows that the strength development of SCC and conventional concrete was similar . Some of the published test results showed that the increase in the cement content and a reduction in the filler content at the same time increases the initial concrete strength and the ultimate strength [٦١,٦٢]. For young SCC aged up to ٧ days, the relative compressive strength spreads to a greater extent as given in the **CEB-FIB** Model Code ١٩٩٠ [٣٦]:

$$\mathbf{Ec= ٢٠.٥*(fc/١٠)^{١/٣}} \quad \text{-------------(٢-٣)}$$

Where: Ec= modulus of elasticity in GPa

fc= compressive strength in MPa

whereas higher values as well as lower ones were reached, especially, if limestone powder was used, higher compressive strengths were noticable at the beginning of the hardenning process.

**Sonebi M.** et al [٤٩] measured a standared cube measuring ١٥٠ mm demoulded one day after casting and cured with wet hessian and plastic sheeting. Specimens were then cured in water at ٢٠ ˚C, until testing age. The results of standared compressive strength at ٢٨ days showed that the specfic characteristics cube strength was ٣٥ MPa for housing mixes and ٦٠ MPa for civil mixes. The results indicates that the actual strength of SCC mixes were at the upper end of the normal range for the designed strengths, while the reference mixes were at the lower end. As normal concrete, the compressive strength of SCC was strongly affected by water to cement ratio and filler type. Results indicated that at similar water to cement ratio, strengths of SCC mixes, using limestone powder as a filler, were significantely higher than the corresponding reference mixes. The relatively faster strength development for housing SCC mixes, particularly at early ages, was believed to be mainly due to the inclusion of fine particles of limestone powder, which may have an accelerating effects on $C_٣S$ hydration and early strength [٦٣]. The civil SCC mixes, which contained ground granulated blast slag instead of limestone powder, had a lower strength at ١ and ٧ days than the corresponding reference mix but developed significantely higher strength at ٢٨ dys and beyond. This was due to the slower, but prolonged reaction (hydraulic and pozzolanic) between cement hydration products and slag filler, which contribute significantely to strength [٦٤]. Results also indicated that there was no significant difference in pattern of strength development for all the mixes studied.

### ٢.٨.٢ Splitting tensile strength:

The tensile strength was assessed indirectly by the splitting test on cylinders and flexural test on prisms. For SCC, both the tensile strength themselves, and the relationships between tensile and compressive strengths were of a similar order to those of traditional vibrated concrete [٦٥]. All parameters which influence the characteristics of the microstructure of the cement matrix and of interfacial transition zone were of decisive importance in respect of tensile load bearing behavior (٦٦).

**Klaus and Yvette** (٤٦) found that, in about ٣٠ % of all data points a higher splitting tensile strength was stated compared to **CEB- FIP** Model code ٩٠ for normally vibrated concrete, as shown in Figure (٢-٩):

$$ft= ٠.٣٠١ \sqrt{fc}^{\,٠.٦٧} \quad \text{---------------} \quad (٢\text{-}٤)$$

Where: ft= splitting tensile strength (MPa).

$f_c$= compressive strength (MPa).

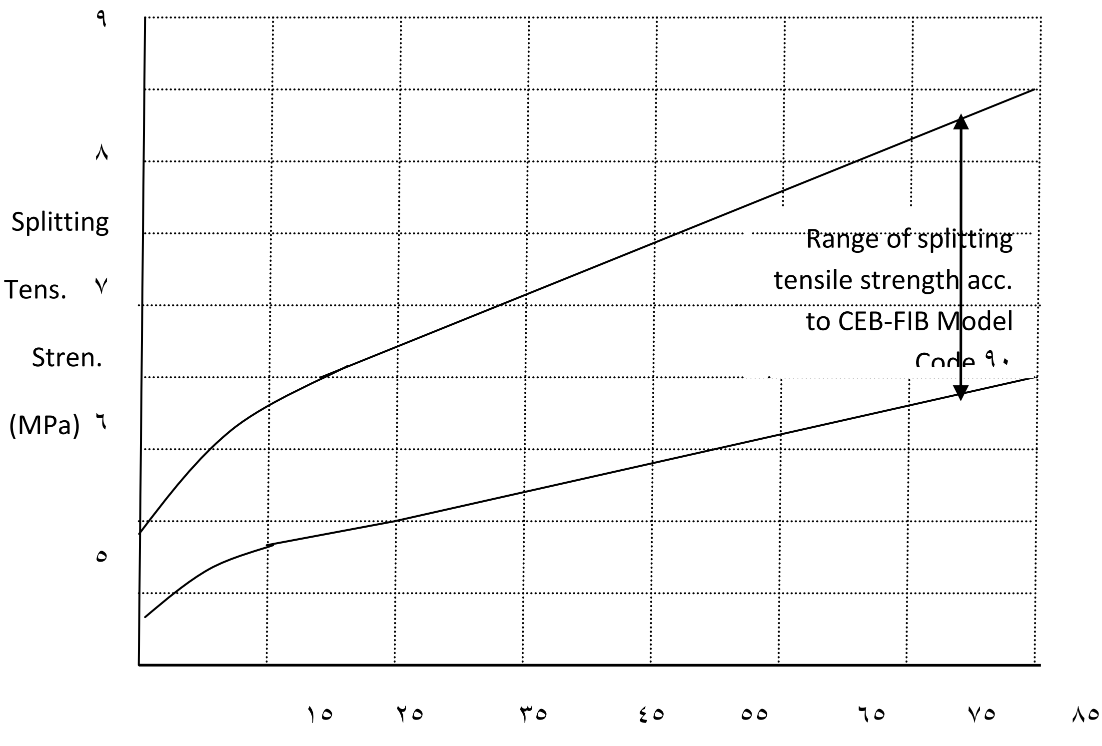



Figure (٢-٩): Splitting tensile strength of SCC in comparison to **CEB- FIB** Model Code ١٩٩٠ (٤٦).

Hence it appears the tendency of a higher splitting tensile strength of SCC than the normal vibrated concrete was given by the better microstructure, especially the smaller total porosity and the more even pore size distribution within the interfacial transition zone of SCC. Further, on denser cement matrix was presented due to the higher content of ultra-fines. The time development of tensile strength of SCC and normal vibrated concrete were subjected to a similar dependence, only few publications about SCC referred to more rapidly increase of the tensile strength opposite to the compressive strength.

**Frank D.** et al [٤] agreed with this trend. They noticed that the high early compressive strength and the high splitting tensile strength of SCC were due to the use of fly ash. Such concrete types normally have a slower strength development because of the lower hydration rate of the fly ash. Therefore, it is difficult to compare the splitting tensile strength and compressive strength with conventional concrete aged ٢٨ days [٦٠]. Within the test results series, the concrete properties would be measured after ٥٦ days.

**Jianxin and Jorg** [٦٧] determined the mechanical properties of ultra- high performance SCC. The compressive strength, splitting tensile strength and modulus of elasticity are shown in Table (٢-١١). The specimens were demoulded ٢ days after casting, and then they were cured in water at ٢٠ ˚C till ٣ days before testing. In Table (٢-١١), it could be seen that the difference between compressive strength determined on cubes and cylinders was not significant. This indicates that the compressive strength of ultra-high performance SCC was not so strongly depending on slenderness of test specimens as conventional high strength concrete. This was the same case as in conventional SCC. This phenomenon could be explained by the high powder content and the small size of coarse aggregate.

Table (٢-١١): Composition and properties of Ultra-High Performance Self-Compacting Concrete, (UHPSCC) at ٢٨ days [٦٧].

| **Mix No.** | | Unit | ١ | ٢ | ٣ | ٦ | ٤ | ٥ |
|---|---|---|---|---|---|---|---|---|
| Water to powder ratio | | % | ٠.٤٣١ | ٠.٤٣١ | ٠.٤٨٧ | ٠.٥٤٣ | ٠.٤٨٧ | ٠.٤٨٧ |
| Density of concrete | | kg/$m^{٣}$ | ٢٣٢٠ | ٢٥٢٥ | ٢٥٦٨ | ٢٥٩٠ | ٢٥٤٧ | ٢٥٦٤ |
| Compressive Strength | Cube ١٠٠*١٠٠ | MPa | ١٤٩.٨ | ١٦٠.٧ | ١٦٦.٢ | ١٦٠.٦ | ---- | ---- |
| | Cylinder ١٠٠*٢٠٠ | MPa | ١٥٥.٧ | ١٥٥.٩ | ١٥١.٤ | ١٤٨.٧ | ١٥١.٢ | ١٥٠ |
| Splitting Strength | Cylinder ١٠٠*٢٠٠ | MPa | ----- | ٨.٧ | ٨.٦ | ٨.٥ | ---- | ---- |
| E-modulus | Cylinder ١٥٠*٣٠٠ | GPa | ٤٨.١ | ٥٠.٢ | ٥٢.٩ | ٥٣.٩٥ | ----- | ----- |

**Kong J.** et al [٦٨] reported that, to verify the strain-hardening behavior of the SCC specimens made without any external consolidation, the specimens were cured in air for ٤ weeks, following by water curing for ٢ days. From the tensile stress-strain curves, the first crack strength, ultimate tensile strength and ultimate tensile strain were measured. They concluded that the tensile strength increased to (٣.٨-٤.٦) MPa with the formation of multiple cracks, after the formation of the first crack at (٢-٣) MPa, the ultimate tensile strain was approximately (١-١.٢) %. The mechanical performance of SCC, however, was not as good as that of high strength SCC prepared at a lower W/C ratio of ٠.٢٨, a higher fibre volume fraction of ٠.٠١٥, and a fibre length of ١٩ mm. The ultimate tensile strain was ٣.٤ %. The reduced performance was likely due to lower interfacial bonding force and fibre volume fraction in the SCC. Therefore, further improvement of mechanical performance of SCC was recommended.

### ٢.٨.٣ Flexural strength:

The flexural strength behavior of SCC specimens was examined by **Burge T.** et al [٦٩]. They reported that, moist cured specimens have higher flexural tensile strength or modulus of rupture than air dried specimens. Moist cured specimens were tested at the age of ٩٠ days, had a flexural strength in the range of ١٠ % of the ACI ٣٦٣R-٩٢ recommended equation[٦٩]:

**Ec= ٣.٣٢ ($f_c$) ^٠.٥^ + ٦.٩** ---------------- (٢-٥)

Where: **Ec**= the modulus of elasticity (GPa)

**$f_c$**= the compressive strength (MPa)

Typical cracking patterns of SCC and referenced beams at ultimate load were very similar with four point flexural tests of the beam. At the service load level, cracking in the flexural span was composed predominantly of vertical cracks perpendicular to the direction of maximum principle stress produced by pure moment. Cracking outside the pure bending zone starts similar to flexural cracking but, as the shear stresses became important, more inclined cracks appeared [٥١]. Series housing and civil engineering concrete gains more flexural strength than that for normal vibrated concrete due to the formation of new hydration products in the pores and microcracking, and less pores in the microstructure of the concrete of all mixes. This was due to the fact that SCC includes more paste and less coarse aggregate, and includes filler powder and much water reducing admixtures.

**Malhotra** [٧٠] found that the flexural strength of mixes studied varies from (٦-٨.٧) MPa. The beams were moist cured and then tested in flexural according to BS ١٨٨١; part ١١٨, provides for a similar test procedure, except that the standard specimens dimensions were (١٥٠*١٥٠*٧٥٠) mm.

**Habeeb** [٧١] reported different relationships between modulus of rupture and compressive strength as follows:

$$f_r = ٠.٢٣ + ٠.١٢ f_c - ٢.١٨ * ١٠^{-٤} f_c^{٢} \quad \text{-------------- (٢-٦)}$$

$$f_r = ٠.٦٦ (f_c)^{١/٢} \quad \text{-------------- (٢-٧)}$$

**Victor C.** et al [٤٨] used four point bending test to evaluate the mechanical properties of SCC. The specimen dimension was (١.٢٧*٧.٦*٣٠.٥) cm. The specimens were loaded with a constant cross head speed in two steps. In fact, the test results showed slightly lower modulus of rupture for the specimens with vibration applied. This could be attributed to the possible phase separation in a fresh mix caused by vibration. The four point load test confirmed that strain hardening behavior and strength of composite material were in sensitive to the presence or obsence of the external consolidation process using the SCC developed in that research.

### ٢.٨.٤ Modulus of elasticity:

As it is known, the modulus of elasticity of normally vibrated concrete depends on the proportions of the Young's moduli of the individual components and their percentages by volume. Thus, the modulus of elasticity of concrete increases for high contents of aggregate of high rigidity, whereas it decreases with increasing hardened cement paste content and increasing porosity. A relative small modulus of elasticity could be expected, because of the high content of ultra-fines and additives as dominating factors and, accordingly, minor occurrence of coarse and stiff aggregates at SCC. Indeed, it was shown by analyzing the data base that the modulus of elasticity of SCC can be up to ٢٠ % lower compared with normal vibrated concrete having the same compressive strength and made of the same aggregates [٤٦]. Nevertheless, it was mainly still in the range of the **CEB-FIB** Model Code ٩٠, equation (٢-٣), for normally vibrated concrete as shown in Figure (٢-١٠).

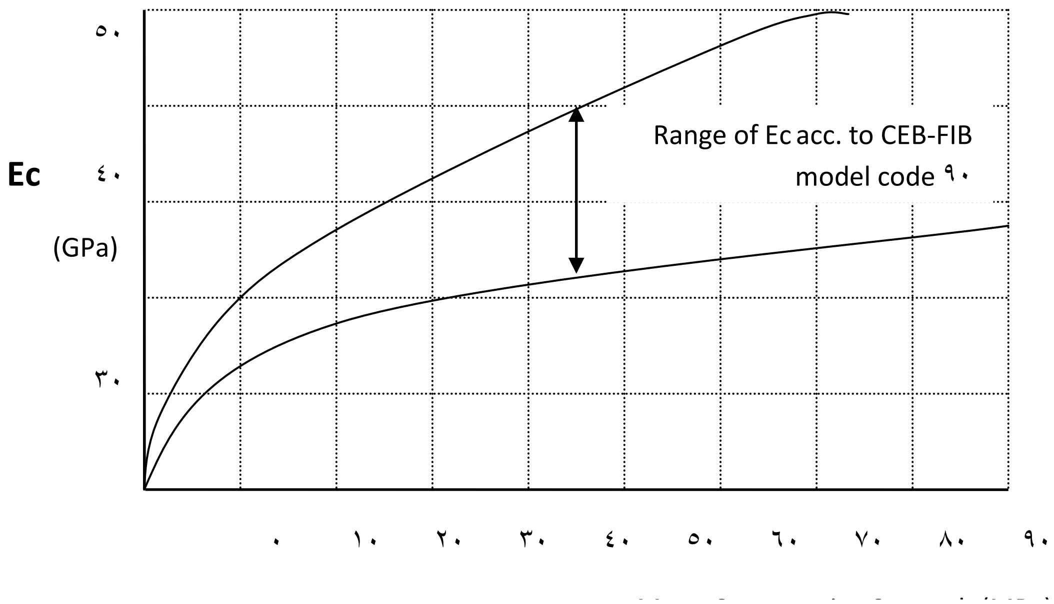



Figure (٢-١٠): Modulus of elasticity of SCC in comparison to **CEB-FIB** Model Code ٩٠ [٤٦].

**Sonebi M.** et al [٤٩] determined the static modulus of elasticity in compression. End capped (١٥٠*٣٠٠) mm cylinder specimens were cured in water and tested at ages of (٤ to ١٣) months for different mixes as shown in

Table (٢-١٢). They concluded that the static modulus of elasticity of civil engineering mixes was higher than those of housing and corresponding reference mixes by ١٨.٦ % and ١٧.٩ % respectively. For easier comparison, the ratios of (Ec), modulus to square root of cylinder compressive strength for all the mixes were also included, as a relationship in the form of Ec/ $(f_c)^{٠.٥}$ has been widely reported. They found that the results in Table (٢-١٢), indicated that the SCC mixes had the same relationship between modulus of elasticity and compressive strength as the reference mixes. The Ec/ $(f_c)^{٠.٥}$ were also close to the value of ٤.٧٣ recommended by ACI ٣١٨-٩٥ for structural calculations, applicable to normal weight concrete [٤٩]:

**Ec= ٤.٧٣ $(f_c)^{٠.٥}$ ------------------ (٢-٨)**

Where: Ec= the modulus of elasticity (GPa)

$f_c$= the compressive strength of cylinders (MPa)

Table (٢-١٢): Static modulus of elasticity of different SCC mixes compared to reference mixes [٤٩].

| Test results | Concrete mix | | | | |
|---|---|---|---|---|---|
| | RH | SCCH | RC | SCCC | FSCC |
| Age at testing | ١٣ | ٤ | ٨ | ١١ | ٧ |
| $E_c$ GPa | ----- | ٣٤.١ | ٣٤.٤ | ٤١.٩ | ٣٧.٧ |
| $E/(f_c)^{٠.٥}$ ratio | ----- | ٤.٩٢ | ٤.٩ | ٤.٤٣ | ٥.٤٣ |

**Abed** [٧٢] found that, static modulus of elasticity for concrete mixes containing limestone as a filler was higher than that of cement, fine sand and pigment by (١,١١,١٠.٢) % for civil concrete and (١.٢, ٦.٢, ٥) % for housing concrete at ages ٢٨ and ٩٠ days respectively, while concrete mixes containing metakaolin as a filler were higher than those of limestone, cement, fine sand and pigment by (٠.٣, ٠.٩,٤.٥,٣.٦) % and (٠.٨,٠.٦,٥.٥,٥.٥) % for civil concrete mixes at ages ٢٨ and ٩٠ days respectively. The values of modulus of elasticity at age of ٢٨ days range from (٣٣.٣-٣٧.٣) GPa and (٣٦.٩-٣٨.٨) GPa for housing and civil engineering concrete respectively, while the values of Ec of age ٩٠ days ranged from (٣٥.٨-٣٨.٢) GPa and (٣٧.٦-٣٩.٩) GPa for housing and civil engineering concrete respectively as shown in Figures (٢-١١), (٢-١٢) and (٢-١٣).

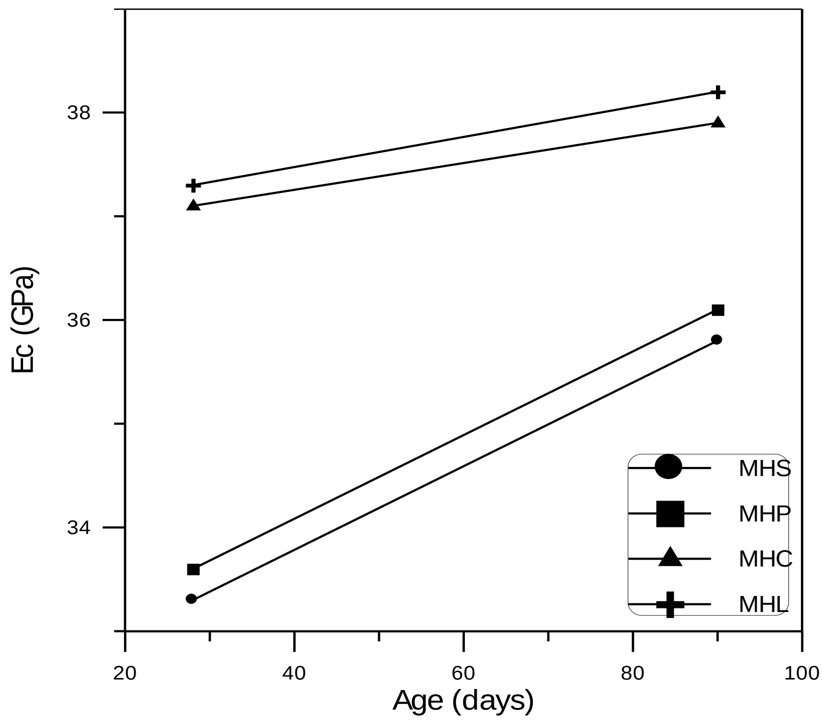



Figure (٢-١١): Relationship between static modulus of elasticity and age of housing concrete [٧٢].

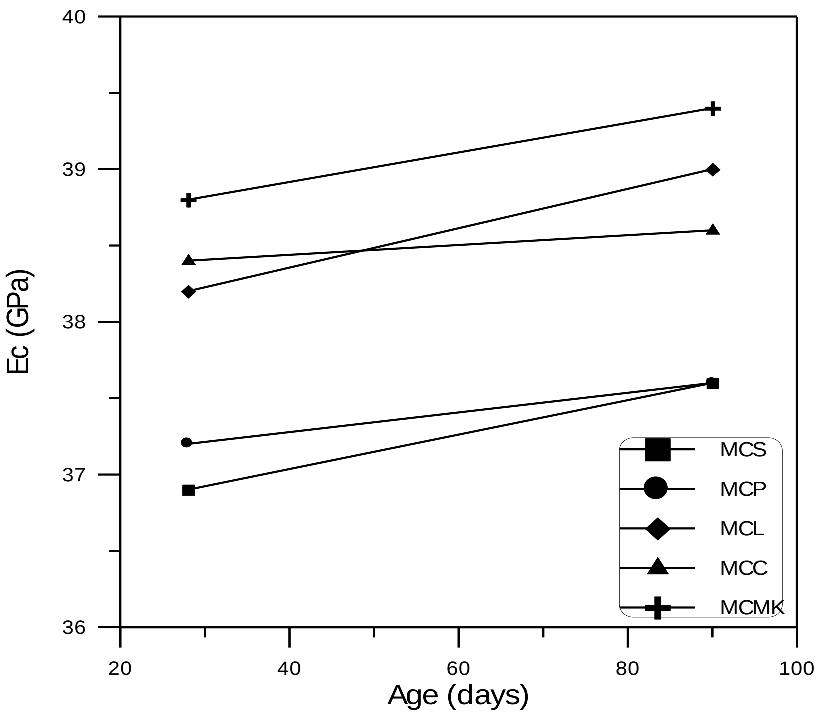



Figure (٢-١٢): Relationship between Ec and age for civil engineering concrete [٧٢].

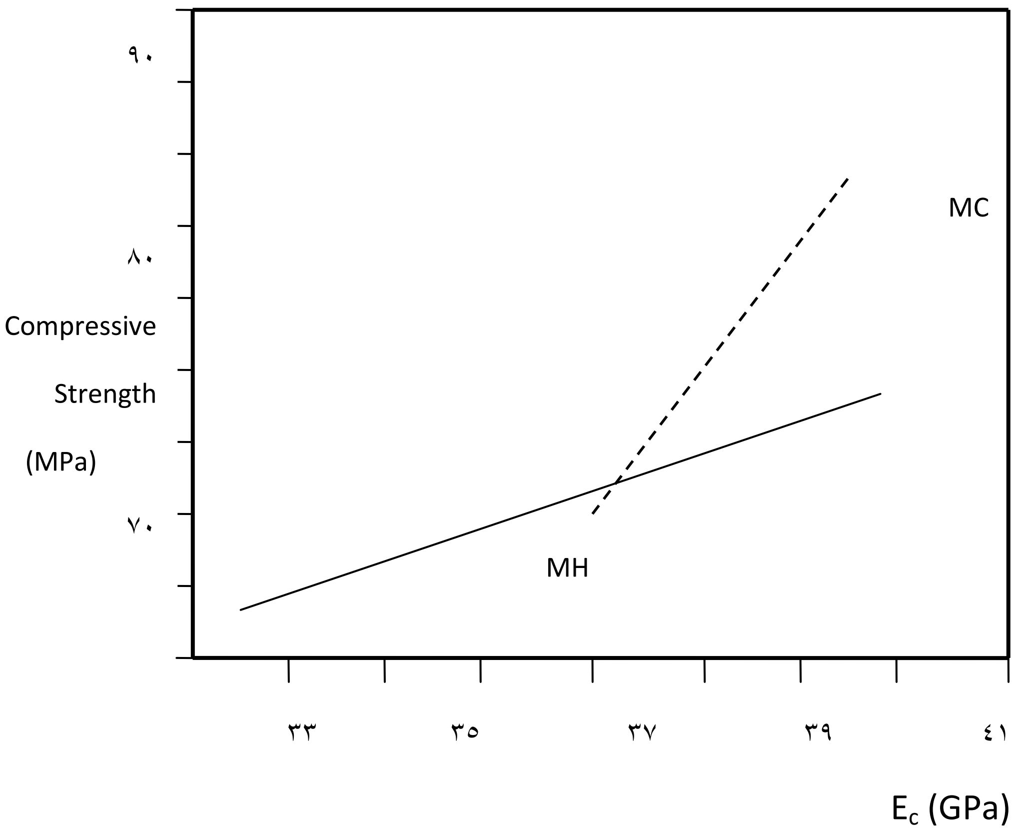


Figure (٢-١٣): Relationship between the static modulus of elasticity and compressive strength [٧٢].

### ٢.٨.٥ Non- destructive

#### ٢.٨.٥.١ Schmidt rebound hammer

The surface hardness of concrete members was tested by the "**Schmidt rebound hammer**". This testing by hammer estimates the surface hardness by rebound number which could be taken as a measure of the concrete strength and percentage of voids. A few, if any, number of research work had dealt with the effect of water to powder ratio on the non-destructive testing of SCC [٧٣].

**Sonebi M.** et al [٤٩] investigated the in-situ characteristics of SCC using a digital apparatus, namely, Digi-Schmidt hammer, which automatically records the rebound number for each testing. Testing was carried out at the ages ٧, and ٢٨ days, and minimum of ٤٠ readings were taken at each location along the height of columns and along the length of beams. Variations of rebound number along the height of the columns and along the length of beams, all SCC and reference concretes used were recorded and presented in Table (٢-١٣). The quality of in-situ concrete properties in the columns and beams were assessed by rebound hammer number, for uniformity in near surface properties. They concluded that the housing SCC mix containing lime stone powder achieved significantly higher in-situ strength than corresponding reference mix (RH), properly due to the accelerating, and densifying effect of the filler. There were no significant differences in uniformity of in-situ properties between the SCC mixes and the corresponding reference mixes; the properties of the SCC mixes were marginally more uniform.

Table (٢-١٣): Statical variations of rebound number for columns and beams at ٢٨ days [٤٩].

| In-situ rebound Number | Results for columns | | | Results for beams | | |
|---|---|---|---|---|---|---|
| | mean | $V_f$ % | No. of points | mean | $V_f$ % | No. of points |
| RH | ٣٧.٣ | ١١ | ١٦٠ | ٣٣.٧ | ٨.٥ | ٨٠ |
| SCCH | ٣٥.٧ | ٧.٧ | ١٦٠ | N/A | N/A | N/A |
| RC | ٤٦.٥ | ٦.٩ | ١٦٠ | ٤٢.٣ | ٤.٤ | ٨٠ |
| SCCC | ٤٦ | ٤.٧ | ١٢٠ | ٤٠.٥ | ٨.٦ | ٨٠ |
| FSCC | N/A | N/A | N/A | ٤٣.٣ | ٧.٥ | ٨٠ |

Note:

N/A=not applicable.

### ٢.٨.٥.٢ Ultra-Sonic Pulse Velocity:

The U.P.V. test is a useful tool for assessing the uniformity of concrete and detecting cracks, voids or honeycombing. It gives useful information about the size of micro-cracked zone and on crack growth and the interior structure of the concrete element. The pulse velocity of concrete is affected by variety of factors; the composition and maturity of concrete, the geometry of section being tested, and condition at test time all affect the measured pulse velocity of Portland cement concrete [٧٣].

SCC is denser than normally vibrated concrete because of its reduced porosity, which favors the ultrasonic pulse velocity travel to be faster than normally vibrated concrete. The pulse velocity is affected by number of factors which are:

- Smoothness of the contact surface.
- Path length; decreasing path length increases the pulse velocity.
- U.P.V. is not sensitive to temperature in the range of ٥ to ٣٠ ˚C. At higher temperatures, the pulse velocity decreases, and the temperature below freezing, pulse velocity increases.
- Pulse velocity increases with the increase in the moisture content.
- For a given pulse velocity, the compressive strength is higher for older specimens [٧٤], as shown in Figure (٢-١٤).

**Abed** [٧٢] observed that there was an increase in U.P.V. values with age for all mixes. Series MHL, MHS and MCMK show an increase in U.P.V. at ages ٢٨ to ٩٠ days while less increase was seen for other mixes, as shown in Figure (٢-١٥). This could be attributed to the continued hydration and dissolution of various filler particles, and the increase in the density of concrete. The results were ranged between (٣.٨٩-٥.٣١١) km/sec. for all the SCC mixes.

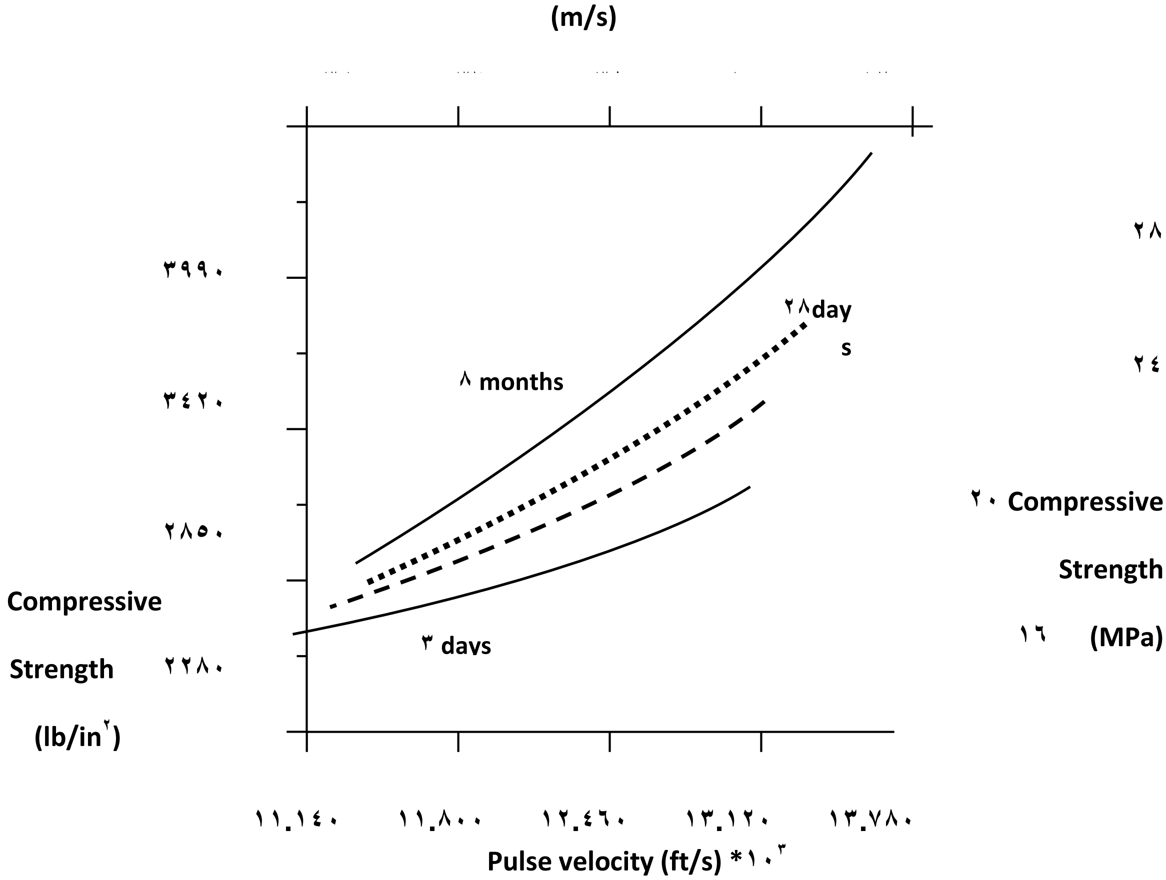



Figure (٢-١٤): Influence of age of concrete on the correlation between pulse velocity and strength by **Stirrup V.** et al (٧٤).

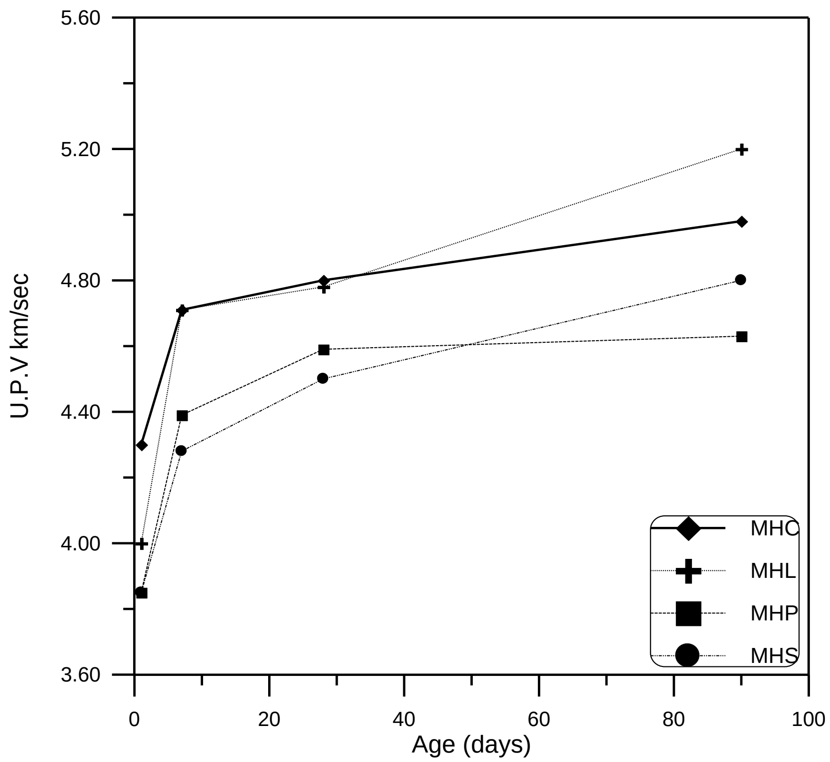



Figure (٢-١٥): Relation between U.P.V and age for housing concrete [٧٢].

**Saeed** [٥٧] found that the results of U.P.V were ranged between (٤.٢٢-٥.١٢) km/sec for all cylinders and cubes with different sizes and curing conditions. She noticed that for medium strength level concrete, U.P.V increased more than for high strength concrete due to the higher heat of hydration for mixes containing higher cement contents which may result in internal fissures or micro cracks due to the difference in the coefficient of thermal expansions of concrete ingredients. This trend showed that lean concrete mixes were more favorable for continuous moist curing than those of rich concrete mixes. Further, moist cured specimens showed an increase in U.P.V values as compared with specimens which moist cured for ٧ days then air cured at laboratory. This could be attributed to the fact that wave travels faster through water-filled void than through air-filled one.

# CHAPTER THREE

# MATERIALS AND EXPERIMENTAL WORK

## ٣.١ The experimental

In order to study the effect of water to powder ratio on mechanical properties of SCC, compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity as well as the determination of rebound number and pulse velocity were carried out on the SCC produced from locally available materials. The compressive strength of concrete specimens was tested on ١٠٠ mm cubes; the splitting tensile strength was tested on cylinders with a diameter of ١٠٠ mm and a height of ٢٠٠ mm, while ١٥٠ mm diameter and ٣٠٠ mm height of cylinder specimens were tested for the modulus of elasticity, the flexural strength was tested on prisms of (١٠٠*١٠٠*٤٠٠) mm.

The work consisted of four series of SCC mixes, namely **$S_{٣٠}$**, **$S_{٤٠}$**, **$S_{٥١}$** and **$S_{٦٢}$**, to investigate the effect of several factors. The factors are water to powder ratio, curing conditions, type of filler and time of calcening metakaolin on the mechanical properties of SCC. The details of the test series are shown in Table (٣-١).

Table (٣-١): Details of test series.

| Mix Notation | Type of filler | W/P (%) |
|---|---|---|
| S٣٠ | Limestone<br>Metakaolin I<br>Metakaolin II<br>Metakaolin III | ٣٠ |
| S٤٠ | Limestone<br>Metakaolin I<br>Metakaolin II<br>Metakaolin III | ٤٠ |
| S٥١ | Limestone<br>Metakaolin I<br>Metakaolin II<br>Metakaolin III | ٥١ |
| S٦٢ | Limestone<br>Metakaolin I<br>Metakaolin II<br>Metakaolin III | ٦٢ |

٣.٢

٣.٢.١

Ordinary Portland Cement (O.P.C.) manufactured by the new cement plant of Kufa was used throughout this investigation. This cement complied with the Iraqi specification No.٥/ ١٩٨٤ (RS١). The chemical and physical properties are presented in Tables (٣-٢) and (٣-٣) respectively.

Table (٣-٢): Chemical composition of cement. The test was made in the constructional materials laboratory of University of Babylon.

| Oxide | % | IQS (RS١) No.٥:١٩٨٤ |
|---|---|---|
| CaO | ٦٠.٧٩ | |
| SiO٢ | ٢٠.٧٥ | |
| Al٢O٣ | ٦.٢٠ | |
| Fe٢O٣ | ٣.٠٠ | |
| MgO | ٤.١١ | ≤٥.٠ |
| SO٣ | ٢.٣٢ | ≤٢.٨ |
| Free lime | ٠.٥١ | |
| L.O.I | ٢.٠٠ | ≤٤.٠ |
| **Compound Composition** | **%** | **IQS (RS١) No.٥:١٩٨٤** |
| C٣S | ٣٧.٢٦ | |
| C٢S | ٣١.٣٩ | |
| C٣A | ١١.٣٥ | |
| C٤AF | ٩.١٢ | |
| L.S.F | ٠.٨٨ | ٠.٦٦-١.٠٢ |

Table (٣-٣): Physical properties of cement. The test was made in the constructional materials laboratory of University of Babylon.

| Physical properties | Test results | IQS (RS١) No.٥:١٩٨٤ |
|---|---|---|
| Fineness, Blaine,cm٢/gm | ٣١٢٤ | ٢٣٠٠≥ |
| Setting time, Vicat method<br>Initial; hrs:min<br>Final ; hrs:min | ١:٤٥<br>٣:٤٦ | ١:٠٠ ≥<br>١٠:٠٠≤ |
| Compressive strength MPa<br>٣ days<br>٧ days<br>٢٨ days | ٢٠<br>٢٧<br>٣٣ | ≥١٥<br>≥٢٣ |

### ٣.٢.٢ Fine aggregate:

Natural sand from AL-Akaidur region was used. The results of physical and chemical properties of the sand are listed in Table (٣-٤). Its grading conformed to the BS ٨٨٢: ١٩٩٢ (RS٢) type F.

Table (٣-٤): Properties of fine aggregate.

| Sieve size (mm) | Passing % | BS ٨٨٢:١٩٩٢ (RS٢) Limitations |
|---|---|---|

| | | |
|---|---|---|
| ١٠.٠٠ | ١٠٠ | ١٠٠ |
| ٥.٠٠ | ١٠٠ | ٨٩-١٠٠ |
| ٢.٣٦ | ٩٤ | ٦٠-١٠٠ |
| ١.١٨ | ٨٤ | ٣٠-١٠٠ |
| ٠.٦٠ | ٦٦ | ١٥-١٠٠ |
| ٠.٣٠ | ٣٧ | ٥-٧٠ |
| ٠.١٥ | ٣ | ٠-١٥ |
| **Properties** | **Results** | **BS ٨١٢:١٩٩٠ (RS٣)** |
| S٠٣ content | ٠.٤٣٢ | ≤٠.٥ |
| Clay | ٢.٣ | ≤٣.٠ |
| Specific gravity | ٢.٦٥ | |
| Absorption % | ١.٦ | |

### ٣.٢.٣ Coarse aggregate:

The coarse aggregate was AL-Nibaee gravel with a maximum size of ١٤ mm as shown in Table (٣-٥). The coarse aggregate used in this research is complying with BS ٨٨٢: ١٩٩٢ (RS٢).

Table (٣-٥): Properties of coarse aggregate.

| Sieve size In (mm) | Passing % | BS ٨٨٢: ١٩٩٢ (RS٢) Limitations |
|---|---|---|

| | | |
|---|---|---|
| ٤٠ | ١٠٠ | ١٠٠ |
| ٢٠ | ١٠٠ | ١٠٠ |
| ١٤ | ٩٧ | ٩٠-١٠٠ |
| ١٠ | ٨٤ | ٥٠-٨٥ |
| ٥ | ٦ | ٠-١٠ |
| pan | ٠ | ٠ |
| **Properties** | **Results** | **BS ٨١٢: ١٩٩٠ [RS٣]** |
| Sulphate content So$_{٣}$ % | ٠.٠٧٩٩ | ≤ ٠.١ |
| Clay % | ٠.٦ | ≤ ١.٠ |
| Specific gravity | ٢.٦٤ | |
| Absorption % | ٠.٧ | |

### ٣.٢.٤ Water:

Tap water was used for both mixing and curing of concrete.

### ٣.٢.٥ Super-plasticizer:

To achieve high workability needed to produce SCC, super-plasticizers (high range water reducers) were used. A super-plasticizer known as Ura-plast SF was used in producing SCC.

According to ASTM C٤٩٤-٩٢ (RS٤), this SP is classified as type F and G, because it has the capability of more than ١٢٪ water reduction for a given consistency and it has a retarding effect on the SCC. The normal dosage for the Ura-plast is between ١-٥ liters per ١٠٠ kg of cement. The typical properties of SP are shown in Table (٣-٦).

Table (٣-٦): Properties of SP.

| **Main Action** | **Concrete Super-plasticizer** |
|---|---|
| Subsidiary effect | Hardening retarder |
| Form | Viscous liquid |
| Color | Dark brown |
| Relative density | ١.١ at ٢٠ ˚C |
| Viscosity | ١٢٨+/-٣٠ cps at ٢٠ ˚C |
| pH value | ٦.٦ |
| Transport | not classified as dangerous |

## ٣.٢.٦ Limestone

Limestone powder which has been brought from market city is used to increase the amount of powder content (cement + filler) in the SCC mixes. The particle size less than ٠.١٢٥ mm was used to increase the workability and density of the SCC. This type of filler conformed to BS ٨٥٠٠-٢, ٤.٤ (RS٦). The chemical composition of limestone powder is shown in Table (٣-٧).

Table (٣-٧): Chemical composition of limestone powder. The test was made in the environmental laboratory of University of Babylon.

| Oxide | % |
|---|---|
| CaO | ٥٢.٧٦ |
| SiO٢ | ١.٤٠ |
| Al٢O٣ | ٠.٧٠ |
| MgO | ٠.١٠ |
| | ٠.١٧ |

| | |
|---|---|
| $Fe_{٢}O_{٣}$ | ٢.٩١ |
| $SO_{٣}$ | ٤٠.٦٠ |
| L.O.I | |

### ٣.٢.٧ Metakaolin:

Metakaolin is a highly pozzolanic material produced by calcining the clay, using an oven at temperatures of (٧٤٤ ˚C). The particle size should not be more than ٠.١٢٥ mm in order to achieve high workability and reactivity when added as a part of cement weight.

To evaluate the time of calcining metakaolin on mechanical properties of SCC, three types of metakaolin namely, “type I, type II and type III”, were used to enhance the workability of concrete. Type I was calcined for ½ hr, type II was calcined for ١.٠ hr and type III was calcined for ١.٥ hrs at the same temperature (٧٤٤ ˚C) for all three types. All types shall conform to BS ٨٥٠٠-٢, ٤.٤ (RS٦). The chemical composition of kaolin and the three types of metakaolin are shown in Table (٣-٨).

Table (٣-٨): Chemical composition of kaolin and metakaolin. The test was made in the environmental laboratory of University of Babylon.

| Oxide | Kaolin | Type I | Type II | Type III |
|---|---|---|---|---|
| $SiO_٢$ | ٥٢.٢٧ | ٦٨.٨٤ | ٧١.٨٨ | ٧٤.٠٠ |
| $Fe_٢O_٣$ | ١.١٢ | ٣.٥٢ | ٤.٠٨ | ٤.٨٠ |
| $Al_٢O_٣$ | ١٣.٨٣ | ١٢.٧٤ | ٩.٩٦ | ٧.٧٨ |
| CaO | ١٠.٠ | ٦.١٤ | ٥.٩٣ | ٥.٤٤ |
| MgO | ٦.٥ | ٦.١٦ | ٥.٧٨ | ٤.٤٥ |
| $SO_٣$ | ١.٣٢ | ٠.٨٦ | ١.٠٢ | ١.٢٨ |
| L.O.I | ١٤.٠٦ | ١.٤٠ | ١.٢٩ | ١.٢٧ |

## ٣.٣ Mix Preparations:

### ٣.٣.١ Mix design:

Four groups of self-compacting concrete mixtures with water to powder ratios of (٠.٣, ٠.٤, ٠.٥١ and ٠.٦٢), namely (**$S_{٣٠}$, $S_{٤٠}$, $S_{٥١}$** and **$S_{٦٢}$**) were designed and tested. Water to powder ratio was defined as the weight of water divided by the weights of cement and filler.

The concrete was designed according to the Japanese mix design system [٢٧]. During the first ٤٨ hrs, the specimens were left in the molds then cured in water until the time of testing.

### ٣.٣.٢ Mix Proportions:

The proportions of concrete mixes are summarized in Table (٣-٩).

Table (٣-٩): Mix proportions (kg/m٣).

| Mix Notation | Cement (kg/m٣) | Filler (kg/m٣) | Sand (kg/m٣) | Gravel (kg/m٣) | W/P ( %) | SP by weight of cement (%) |
|---|---|---|---|---|---|---|
| **S٣٠** | ٤٠٠ | ٨٠ | ٩١٢ | ٧٦٠ | ٣٠ | ٤ |
| **S٤٠** | ٤٠٠ | ٨٠ | ٩١٢ | ٧٦٠ | ٤٠ | ٤ |
| **S٥١** | ٤٠٠ | ٨٠ | ٩١٢ | ٧٦٠ | ٥١ | ٤ |
| **S٦٢** | ٤٠٠ | ٨٠ | ٩١٢ | ٧٦٠ | ٦٢ | ٤ |

A lot of trial mixes were done in the constructional materials laboratory to find a suitable mix that satisfy the requirements of self-compacting concrete in the fresh state as well as at hardening. Table (٣-١٠) shows the mix proportion details of fresh and hardened concrete properties in preliminary investigations.

Table (٣-١٠): Mix proportions in preliminary investigations.

| | **Test series** | ١ | ٢ | ٣ | ٤ | ٥ | ٦ | ٧ |
|---|---|---|---|---|---|---|---|---|
| **Mix** | | | | | | | | |

| Proportions | Units | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cement | kg/m$^{٣}$ | ٣٠٠ | ٣٢٠ | ٣١٢ | ٢٨٠ | ٣٦٨ | ٣٢٠ | ٣٢٠ |
| Filler | kg/m$^{٣}$ | ٢٦٤ | ١٦٠ | ١٣٠ | ٢٤٥ | ١٦٠ | ١٦٠ | ١٦٠ |
| Sand | kg/m$^{٣}$ | ٧٢٩ | ٩١٢ | ٩٨١ | ٨٦٥ | ٨٠٠ | ٩١٢ | ٩١٢ |
| Gravel | kg/m$^{٣}$ | ٧٥٠ | ٧٦٠ | ٨٣٨ | ٧٥٠ | ٧٨٥ | ٧٦٠ | ٧٦٠ |
| W/C | % | ٠.٤١ | ٠.٤١ | ٠.٤١ | ٠.٤ | ٠.٥٥ | ٠.٧ | ٠.٥٦ |
| W/F | % | ---- | ٠.٣٥ | ٠.٣٥ | ٠.٢٨ | ٠.٣٣ | ٠.٤ | ٠.٤ |
| SP | l/m$^{٣}$ | ٣ | ٤.١ | ٨ | ٤.٢ | ٨ | ٨ | ٨ |
| U-box | cm | ٦ | ٤ | --- | --- | --- | ٣ | ٢ |
| L-box | % | --- | --- | ٣٣ | ١٧ | --- | ٩٥ | ٨٥ |
| V-funnel | sec | --- | --- | ١٥ | --- | --- | ٧ | ٧ |

| Compressive Strength | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ٣-days | MPa | | | | | | ١٥ | ١٩ |
| ٧-days | MPa | | | | | | ١٧ | ٢١ |
| ٢٨-days | MPa | | | | | | ١٨ | ٣٧ |

## ٣.٣ Mixing of concrete:

A total of sixteen batches based on the mix design of self-compacting concrete discussed earlier in Table (٣-٩), have been prepared in this research. The procedure used for mixing the batches was as follows:

- Predetermined quantities of fine aggregate (sand) and ١/٣ water were added to the mixer and mixed for ١ minute.
- Predetermined quantities of cement, filler and ١/٣ (water plus SP) were added to the mixer and mixed together for ٣٠ sec.
- A half of the gravel and ١/٣ (water plus SP) were added and mixed for ٣٠ sec.
- The final half of gravel and ١/٣ SP were added to the mixer and mixed for ١ minute.

No vibration or compaction has been applied to the SCC specimens; all specimens have been cast and cured according to BS ٥٣٢٨: ٤: ١٩٩٠ (RS٥).

## ٣.٤ Testing of fresh concrete:

It is important to appreciate that none of the test methods for SCC has yet been standardized, and the tests described are not yet perfected or definitive [٢٧]. The methods presented here are descriptions rather than fully detailed procedures, which have been devised specially for SCC. In considering these tests, there are a number of points which should be taken into account:

- One principle difficulty in devising such tests is that they have to assess three distinct, thought related, properties of SCC- its filling ability (flowability), its passing ability (Passibility) and its segregation resistance (stability). No single test so far devised can measure all three properties.
- There is no clear relation between test results and performance at site.
- The test methods and values are stated for max aggregate size of up to ٢٠ mm; different test values and/or different equipment dimensions may be appropriate for other aggregate sizes.
- In performing the tests, concrete should be sampled in accordance with BS ٥٣٢٨:٤:١٩٩٠ (RS٥).

### ***٣.٤.١ Slump flow test and T٥٠ cm test:***

The slump flow is used to assess the horizontal free flow of SCC in the absence of obstructions (flowability, stability).

**Procedure**

- About ٦ litters of concrete are needed to perform the test.
- Moisten the base plate and the inside of slump cone.

- Place base plate on level stable ground and the slump cone centrally on the base plate and that a concentric diameter of ٥٠ cm is marked on the plate.
- Fill the cone with the scoop, do not tamp, simply strike of the concrete level with the top of the cone with trowel.
- Remove any surplus concrete from around the base and cone.
- Raise the cone vertically and allow the concrete to flow out freely.
- Start the stop watch and record the time taken for concrete to reach the ٥٠ cm spread circle, (this is T٥٠ cm).
- Measure the final diameter of concrete in two perpendicular directions.
- Calculate the average of the two measured diameters, (this is slump-flow in mm).

### ٣.٤.٢ L-box test:

This test assesses the flow of concrete, and also extent to which it is subjected to blocking by reinforcement. It indicates the slope of concrete when at rest. This is an indication of passing ability, or the degree to which the passage of concrete though the bars is restricted. This apparatus is made according to the Japanese design for under water concrete described by **Petersson** [٧٥], as shown in Figure (٣-١).

**Procedure**

- Set the apparatus level on firm ground, ensure that the sliding gate can open freely and then close it.
- Moisten the inside surface of the apparatus, remove any surplus water.

- Fill the vertical section of apparatus with ١٢.٧ liters of concrete.
- Leave it to stand for ١ min.
- Lift the sliding gate and allow the concrete to flow out into the horizontal section.
- When concrete stops flowing, $H_١$ and $H_٢$ are measured.

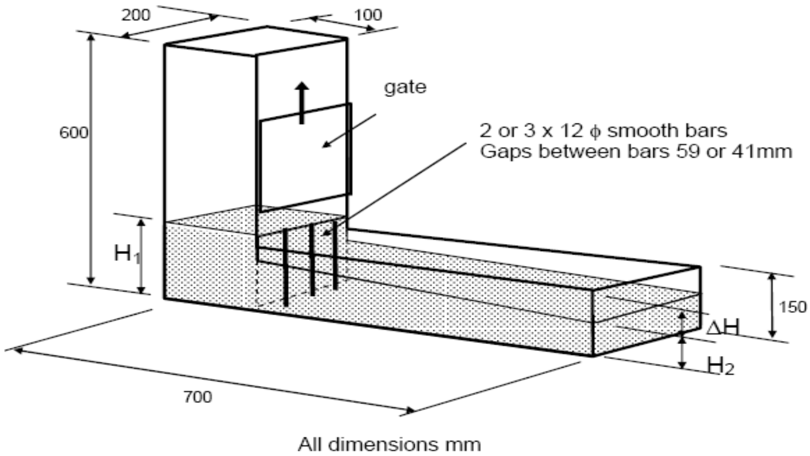



Figure (٣-١١) L-box test (٧٥).

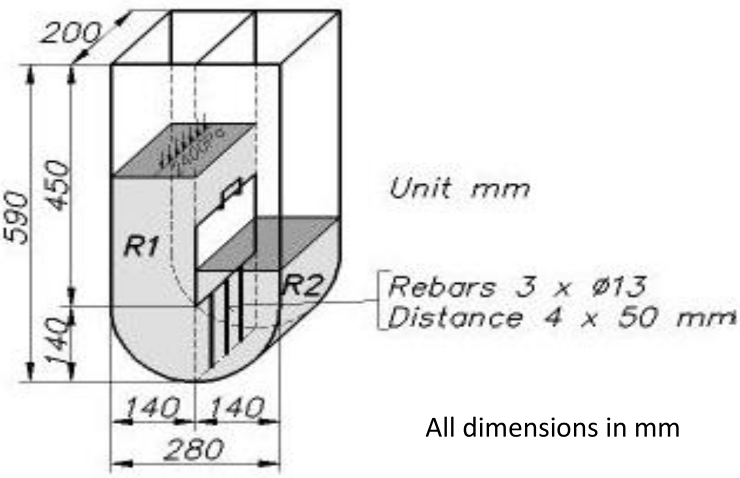
### ٣.٤.٣ U-box test:

This test is used to measure the filling ability of SCC. According to the technology research centre of the Taisei Corporation in Japan (٧٦), the apparatus is presently made.

**Procedure**

- Set the apparatus on firm ground, ensure that the sliding gate can open freely and then close it.
- Moisten the inside surface of the apparatus, remove any water.
- Fill one of the compartments apparatus with ٢٠ liters of SCC.
- Leave it to stand for ١ min.

- Lift the sliding gate and allow the concrete to flow out into the other compartment.
- When concrete is rest, measure the height of the concrete in the compartment that has been filled, in two places and calculate the mean H١. Measure also the height in the other compartment H٢ as shown in Figure (٣-٢).
- Calculate (H١-H٢), the filling height.




All dimensions in mm

Figure (٣-٢): The U-box test [٧٦].

### ٣.٤.٤ V-funnel test:

The V-funnel test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate size up to ٢٠ mm. This apparatus is made according to the Japanese efforts by Okamura et al [٤٣].

**Procedure**

- Set the V-funnel on firm ground.
- Moisten the inside surface of the funnel.

- Keep the trap door open to allow any surplus water to drain.
- Close the trap door and place a bucket underneath.
- Fill the apparatus shown in Figure (٣-٣) completely with concrete without compaction or tamping; simply strike off the concrete level in the top with trowel.
- Open within ١٠ sec. after filling the trap door and allow the concrete to flow out under gravity.
- Start the stop watch and record the flow time.

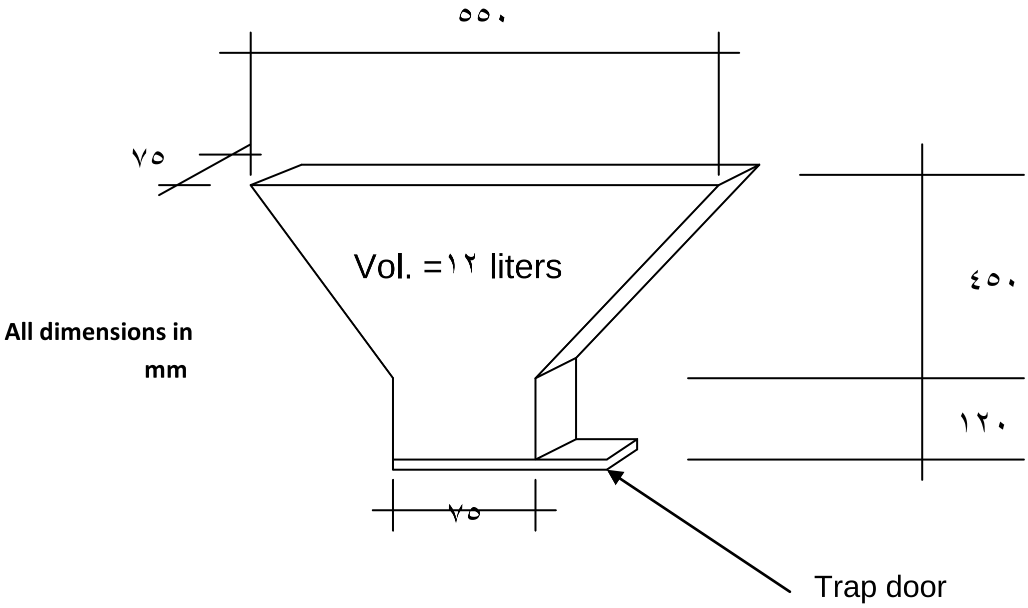



Figure (٣-٣): The V-funnel test [٤٣].

## ٣.٥ Curing Conditions:

Since, SCC was made with low water to powder ratios; water curing is very essential due to the high amount of ultra-fine materials (cement + fillers). Three types of curing are simulated:-

- Sprinkle curing in which all specimens were sprinkling by water once a day until testing age inside the lab.

- Moist curing in water until testing age.
- Air curing in the laboratory until testing age. The test ages were ٧, ٢٨ and ٩٠ days.

## ٣.٦ Hardened Concrete Tests:

### ٣.٦.١ Compressive Strength Test:

Compressive strength was carried out and tested according to BS ١٨٨١: part ١١٦:١٩٨٣ (RS٧). A total number of ١٤٤ cubes of ١٠٠ mm were tested by using a hydraulic compression machine of ٢٠٠٠ kN. All specimens were cured in water until testing age, except those which sprinkled or air-dried. Each result of compressive strength obtained is the average for three specimens.

### ٣.٦.٢ Splitting Tensile Strength Test:

The splitting tensile strength was determined according to the procedure outlined in BS ١٨٨١: part ١١٧: ١٩٨٣ (RS٨). A total number of ٩٦ cylinders (١٠٠*٢٠٠) mm were tested. Cylinders were cast, demolded and cured in a similar way as the cubes. Each splitting tensile strength result was the average of strength for tow specimens. The splitting tensile strength is calculated from the equation:

$$\sigma = \frac{2P}{\pi L D} ---------- (3-1)$$

Where:

P=the applied compressive load.

L=the cylinder length.

D=the cylinder diameter.

### ٣.٦.٣ Flexural Strength Test:

Concrete prisms of dimensions (١٠٠*١٠٠*٤٠٠) mm were cast according to BS ٥٣٢٨:٤:١٩٩٠ (RS٥) procedure. A total number of ٩٦ prisms were tested. The prisms were cast, demolded and cured in a similar manner as the cubes. Modulus of rupture test according to BS١٨٨١:١١٨:١٩٨٣ (RS٩) were performed using two-point load as shown in Figure (٣-٤).

**P/٢** **P/٢**

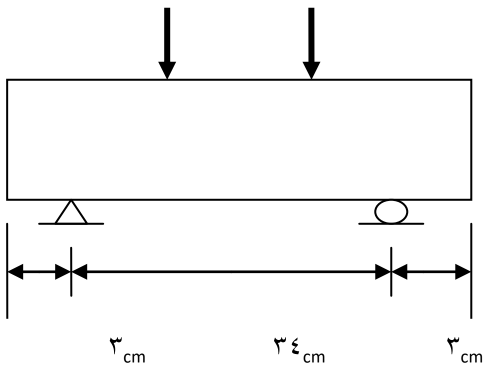



Figure (٣-٤): Two-point load flexural strength test.

Each value of the modulus of rupture was the average of the test results for two specimens. Modulus of rupture is calculated from the simple beam bending formula:

$$R = \frac{pl}{bd^2} ---------- (3-2)$$

Where:

p=maximum applied load , l=span length

b=specimen width , d=specimen depth

This equation is valid only if failure line is within the middle third span. If failure line is outside middle span by not more than ٥ % of the span length, the equation below is used:

$$R = \frac{3pa}{bd^2} ----------(3-3)$$

Where:

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

### ٣.٦.٤ Static Modulus of Elasticity:

The static modulus of elasticity was determined according to BS ١٨٨١:١٢١:١٩٨٣ (RS١٠) specifications. A total number of ٣٢ cylinders (١٥٠*٣٠٠) mm were tested. All specimens were cast, demolded and cured as for the compressive strength cubes. A hydraulic compression machine of ٢٠٠٠ kN is used to apply a compression load until ٤٠ % of the ultimate load. The proving rings used which have a gauge length of ٢٠٠ mm and gauge with an accuracy of ٠.٠١ mm, is made according to BS ١٨٨١:١٢١:٨٣ (RS١٠). The recorded results were the average of readings for two cylinders. The modulus of elasticity may be calculated as follows:

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - \varepsilon_1} --------(3-4)$$

Where:

$E_c$=modulus of elasticity (GPa).

S٢=stress corresponding to ٤٠ % of ultimate load (MPa).

S١=stress corresponding to the longitudinal strain of ٥٠*١٠-٦ (MPa).

$\varepsilon_2$ =longitudinal strain produced by S٢.

$\varepsilon_1$ =٥٠*١٠-٦

### ٣.٦.٥ Non-Destructive Tests:

### ٣.٦.٥.١ 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 percentage of voids. The test method is prescribed by BS ١٨٨١:٢٠٢:١٩٨٦ (RS١١) specifications. The test results of rebound number were the average of five readings to each point.

### ٣.٦.٥.٢ Ultra-Sonic Pulse Velocity:

This test is carried out according to BS ١٨٨١: part ٢٠٣: ١٩٨٦ (RS١٢), using the portable ultra-sonic non-destructive digital indicating tester (PUNDIT) with frequency of ٣٦ kHz to determine wave velocity in concrete specimens. The transit time is recorded in microseconds. Pulse velocity, V, in km/sec is calculated as follows:

$$V = \frac{L}{T} ------------(3-5)$$

Where:

V=ultra-sonic pulse velocity, km/sec.

L=path length, mm.

T=transit time, $\mu$ sec.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## ٤.١ Introduction:

The experimental program was divided into two parts. In the first part sixteen mixes of different ( water to powder ratio, and filler type) were made to be tested in the fresh state, (workability tests), they were, slump-flow, T٥٠ cm slump-flow, U-box, L-box and V-funnel, in order to evaluate the filling ability, passing ability and segregation resistance of the fresh concrete. In the second part, the mechanical properties (compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity in addition to two non-destructive tests, Schmidt rebound hammer test and ultra-sonic pulse velocity) have been studied and discussed.

A total number of ١٤٤ cubes of (١٠٠*١٠٠*١٠٠) mm for a compressive strength determination, ٩٦ cylinders of (١٠٠*٢٠٠) mm for a splitting tensile strength determination, ٣٢ cylinders of (١٥٠*٣٠٠) mm for a static modulus of elasticity determination, ٩٦ prisms of (١٠٠*١٠٠*٤٠٠) mm for the flexural strength determination.

## ٤.٢ The fresh concrete results:

### ٤.٢.١ Slump-flow and T٥٠ cm:

The consistency and workability of the SCC were evaluated by using the slump-flow test. Because of its ease of operation and portability, the slump-flow test is the most widely used method for evaluating concrete consistency in the laboratory and at job sites. The diameter of the concrete flowing out of the slump cone is obtained by calculating the average of two perpendicular measured diameters for determining the slump-flow of the SCC.

The results of the slump-flow range between (٦٣٨-٧٣٨) mm and the results of $T_{٥٠}$ cm range between (٢.٥-٥.١) seconds. These results show that the SCC used is complying with the requirements found in literature [٢, ٥, ١٩, ٢٣] and the SCC used is found to have a good consistency and workability at fresh state.

The water to powder ratio has a small effect on the flowability and workability of the fresh SCC. The results shown in Figures (٤-١), (٤-٢) show that increasing the water to powder ratio from ٣٠ % to ٦٢ % increases in the slump-flow by ١٢ %, while $T_{٥٠}$ cm decreases by ٤٠ %. This behavior can be explained by the high workability of the SCC gained by the additional water content in the mix. The very high flowability of the SCC is due to the use of ultra-fine materials, high sand to aggregate ratio, the use of superplasticizer and low particle size of coarse aggregate. As the particle size decreases, the surface area of the particles increases. The increase in specific surface area of paste gives an indication of workable mixture produced [٧٧].

The type of filler influences the workability of the SCC. The limestone powder gives more workability than metakaolin type (I, II, III) by (٠.٨-٢.٨) %, (١.٢-٣.٩) % and (١.٨-٥.٠) % for slump-flow while less by (٢-٩.٣) %, (١٢.٧-١٦) %

and (٢٠-٣٠) % for $T_{٥٠}$ cm respectively as shown in Figures (٤-١) and (٤-٢). This is due to the shape and size of metakaolin particles which are long, hexagonal plates making obstructions in the fresh mix. Rather, these materials deform by viscous flow, the same manner in which liquid deform; this characteristic property for viscous flow, (viscosity) is a measure of a non-crystalline materials resistance to deformation [٧٨]. The chemical composition of metakaolin particles consists of two layers of ($Si_{٢}O_{٥}$) connected together by weak van der Waals forces. Therefore, as the water to powder increases, the sliding between these two layers becomes easy.

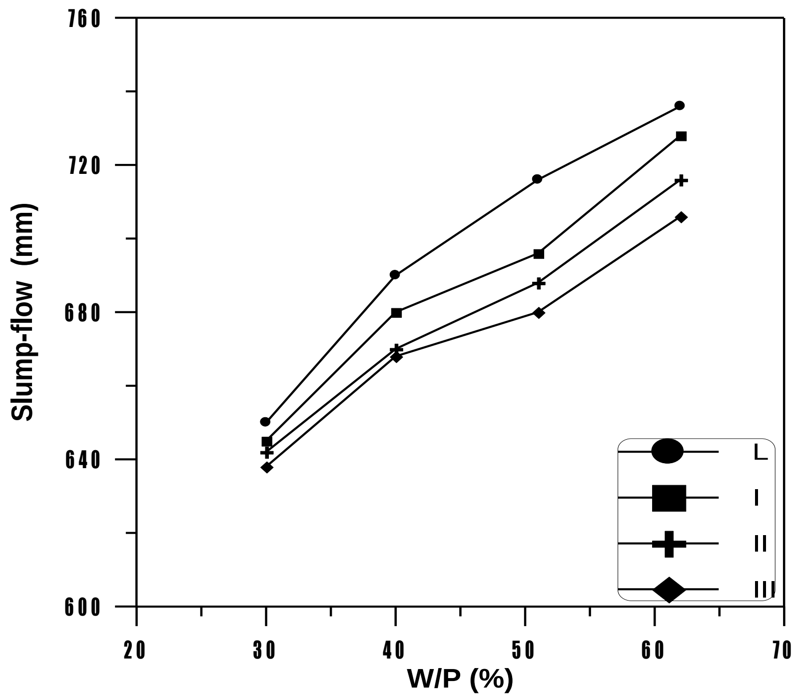



Figure (٤-١): Relationship between slump-flow and W/P ratio at fresh state.

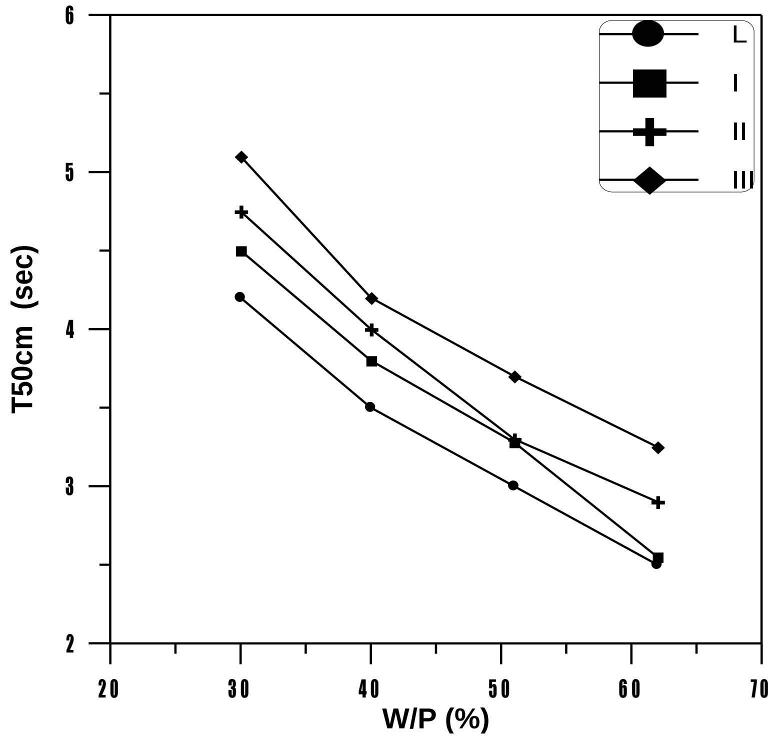



Figure (٤-٢): Relationship between T٥٠ cm and W/P ratio at fresh state.

L= self compacting concrete with limestone.

I = self compacting concrete with metakaolin calcined for ٠.٥ hr.

II = self compacting concrete with metakaolin calcined for ١.٠ hr.

III= self compacting concrete with metakaolin calcined for ١.٥ hr.

The time of calcining metakaolin is one of the important variables in this research; it refers to the duration period in which the metakaolin powders get fired. Figures (٤-٣) and (٤-٤) show that when time of calcining metakaolin increases from (٠.٥ to ١.٠) hrs and (٠.٥-١.٥) hrs the slump-flow decreases by (٠.٥-١.٦) % and (١.١-٣.٠) % while $T_{٥٠}$ cm increases by (٣.٠-١٣.٧) % and (١٠.٥-٢٧.٥) % respectively. The kaolinite used is calcined at a temperature of (٧٤٤) ˚C. During the firing operation, the density is farther increased (with an attendant decrease in porosity) which means, very high softness of the metakaolin is reached, therefore, leading to limit the workability (just like cement). This is when water content is constant. When clay-based materials are heated to elevated temperature, some rather complex and involved reactions occur. One of these reactions is the breaking of some weak van der Waals forces which make the metakaolin obtains more softness. This trend agrees with that obtained by William [٧٨].

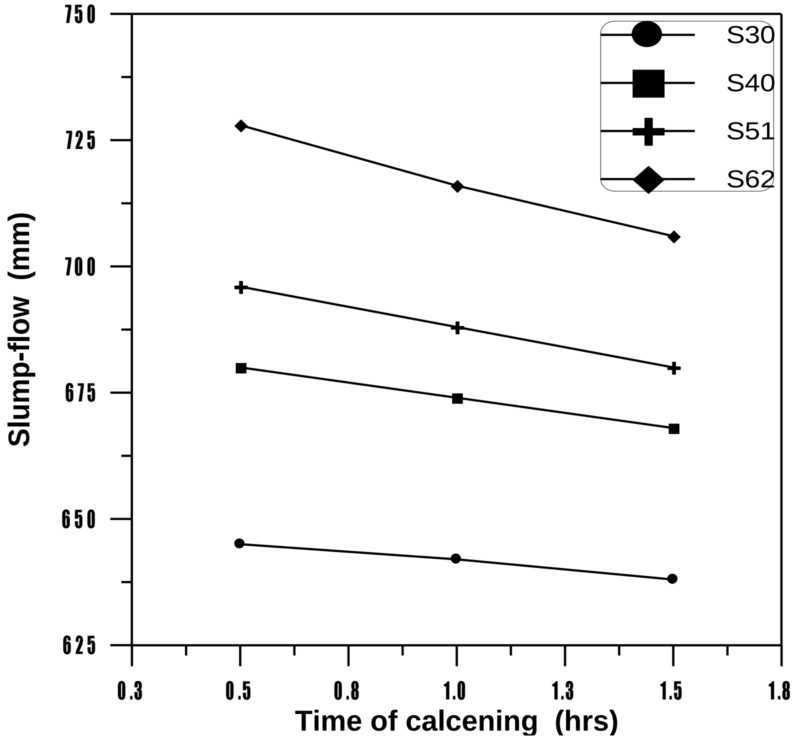



Figure (٤-٣): Relationship between slump-flow and time of calcining metakaolin.

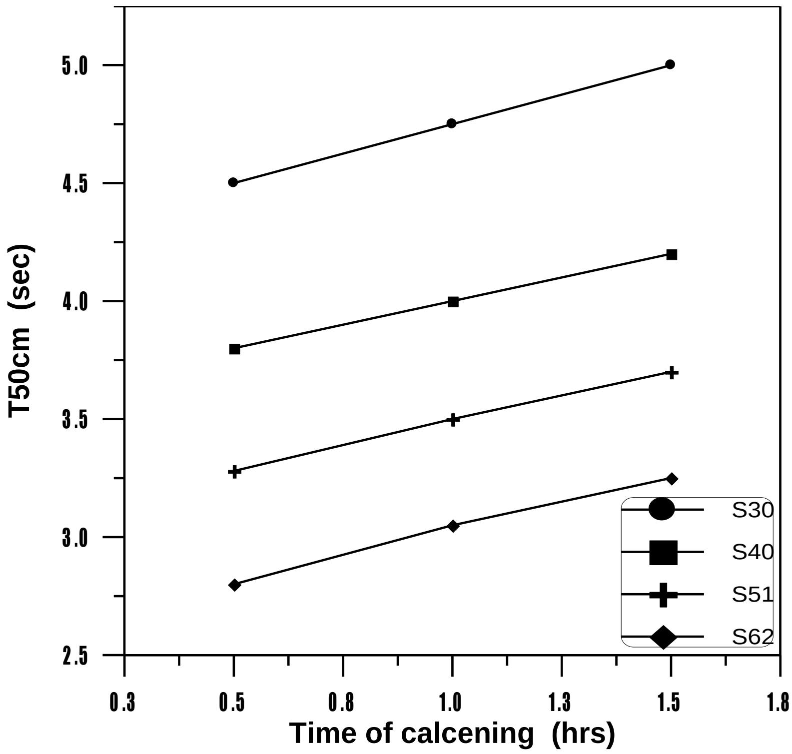



Figure (٤-٤): Relationship between T٥٠ cm and time of calcining metakaolin.

### ٤.٢.٢ U-Box resul

The properties of fresh concrete are presented in Table (٤-١). U-box test is one of the fresh concrete tests which are used to assess the self-compactibility of SCC. The results presented in Table (٤-١) show that the concrete used can be described as self-compacting due to the fact that after opening the sliding gate, the concrete rises in the other half of the U-box to a height greater than ٠.٨٥ of the maximum possible height, (H٢-H١) ranges from (٠-٣) cm.

According to Table (٤-١), the results of U-box range between (٠-١.٥) cm, which is an acceptable limit, and metakaolin type III SCC shows a decrease in the workability by (٢٠, ٤٠, and ٦٠) % compared to metakaolin type (II, I) and limestone powders SCC respectively. This behavior is due to the shape and composition of metakaolin particle; long hexagonal plates, and as time of calcining metakaolin increases the softness increases by breaking these long plates to smaller ones. This trend is in agreement with other researchers [٥, ١٩, ٢٣, ٣٧, and ٧٥].

Table (٤-١): Properties of fresh concrete.

| Mix notation | Type of filler | U١-U٢ (cm) | H٢/H١ (%) | V-time Sec. |
|---|---|---|---|---|
| | **Limitations** | ٠-٣ | ٨٠-١٠٠ | ٥-١٥ |
| S٦٢ | Limestone | ٠ | ٩٠ | ٦ |
| | Metakaolin type I | ٠ | ٨٧ | ٧ |
| | = = II | ٠.٣ | ٨٥ | ٧.٥ |
| | = = III | ٠.٦ | ٨٤ | ٨ |
| S٥١ | Limestone | ٠ | ٨٨ | ٧.٥ |
| | Metakaolin type I | ٠ | ٨٥ | ٨ |
| | = = II | ٠.٤ | ٨٣ | ٨.٨ |
| | = = III | ٠.٨ | ٨٢ | ٩ |
| S٤٠ | Limestone | ٠.٤ | ٨٥ | ٩ |
| | Metakaolin type I | ٠.٦ | ٨٣ | ٩.٥ |
| | = = II | ٠.٨ | ٨٢ | ١٠ |
| | = = III | ١.٠ | ٨٢ | ١٠.٥ |

| | | | | |
|---|---|---|---|---|
| | Limestone | ٠.٧ | ٨٢ | ١١ |
| | Metakaolin type I | ١.٠ | ٨٢ | ١١.٥ |
| **S٣٠** | = = II | ١.٢ | ٨٠ | ١٢ |
| | = = III | ١.٥ | ٨٠ | ١٢.٤ |

### ٤.٢.٣ V-funnel results:

From the results shown in Table (٤-١) it can be seen that the recorded V-time is between (٦-١٢.٤) sec. for all mixes, where shorter time indicates greater flowability. This gives an indication for the high flowability of the SCC mixes, which complying with the requirements of Bilal A. [٢], Okamura H. et al [٣٣] and David and Sheinn [٣٨].

Increasing the water to powder ratio from (٠.٣ to ٠.٤), (٠.٣ to ٠.٥١) and (٠.٣ to ٠.٦٢) results to decrease the V-time by (١٥.٣-١٨.٢) %, (٢٧.٤-٣١.٨) % and (٣٥.٥-٤٥.٥) % respectively. Moreover, metakaolin type III SCC has the longer V-time whereas limestone shows the shortest V-time. The increase in V-time for metakaolin type (I, II, III) SCC than limestone powder SCC is by (٤.٥-١٦.٧) %, (٩.١-٢٥) % and (١٢.٧-٣٣.٣) % respectively. This is due to the high softness of metakaolin used which increased during the firing process and because of the shape and composition of metakaolin particle; long and hexagonal plates. This is in agreement with Paul R. et al [٤٢].

### ٤.٢.٤ L-Box results:

The recorded results in Table (٤-١) show that the blocking ratio ($H_{٢}/H_{١}$) ranges between (٨٠-٩٠) percent for all the SCC mixes. Like other fresh test results, the blocking ratio decreases for metakaolin SCC compared to limestone powder SCC. When time of calcining increases, the fresh mixture becomes stiffer at the same water to powder ratio. This conforms to the other fresh concrete investigations (slump-flow, $T_{٥٠}$ cm, U-box and V-funnel).

From the results shown in Table (٤-١) it can be seen that the decrease in the blocking ratio for metakaolin type III SCC compared to those of type (II, I) and limestone SCC is by (١-١.٢) %, (١.٢-٣.٦) % and (٢.٥-٧.٣) % respectively. This behavior can be attributed to the shape and composition of metakaolin particles and to the higher softness gained during the firing process. These results show that increasing the water to powder ratio from (٠.٣ to ٠.٤), (٠.٣ to ٠.٥١) and (٠.٣ to ٠.٦٢) leads to increase the blocking ratio by (١.٢-٣.٦) %, (١.٢-٧.٣) % and (٥-٩.٨) % respectively. The higher blocking ratio means more workability and if the concrete flows as freely as water, at rest it will be in level ($H_٢/H_١$=١.٠), therefore the closer to this value, the better the flow of concrete.

The time of calcining metakaolin has a significant effect on workability and flowability of the concrete. Increasing the duration period affected the workability of fresh concrete and there is an urgent need for additional water because of the increase in the surface area due to the existence of powders.

## ٤.٣ Hardened concrete results:

### ٤.٣.١ Compressive

Concrete cubes of ١٠٠ mm were tested at ages of ٧, ٢٨ and ٩٠ days. Each value of tests results is the average of three specimens. The average of the tests results are shown in Figures (٤-٥) to (٤-١٣) for normal (housing) SCC mixes of different (water to powder ratio, type of filler used, time of calcining metakaolin and curing conditions). The compressive strength results range between (٢٢.٥-٣٢.٥) MPa, (٣٣-٥٨) MPa and (٤٥.٥-٦٧.٦) MPa at ٧, ٢٨ and ٩٠ days respectively.

From the results of compressive strength shown in Figures (٤-٥) to (٤-٧) it can be seen that the use of super-plasticizers leads to increase the compressive strength due to the decrease in water to powder ratio. Moreover, a decrease in the water to powder ratio from (٠.٦٢ to ٠.٥١), (٠.٦٢ to ٠.٤) and (٠.٦٢ to ٠.٣) leads to increase the compressive strength by (٥.٤-١٣.٦) %, (١٠-٢٢.٧) % and (٢٧.٥-٤٠.١) % at ٢٨ days respectively. This is due to lower initial volume of voids that is needed to be filled by the hydration products and the better dispersion of the powders in the mix. Thus, the SCC used has doubled the compressive strength with respect to that of reference normal vibrated concrete found by Sonebi M. et al [٤٩] and lies under high strength concrete as shown in Figure (٤-١١) due to the inclusion of filler powders which gives a strong, homogenous and dense interface zone between matrix and aggregate.

This is in agreement with what is stated by Budi and Karsten [٣١] and Abed [٧٢].

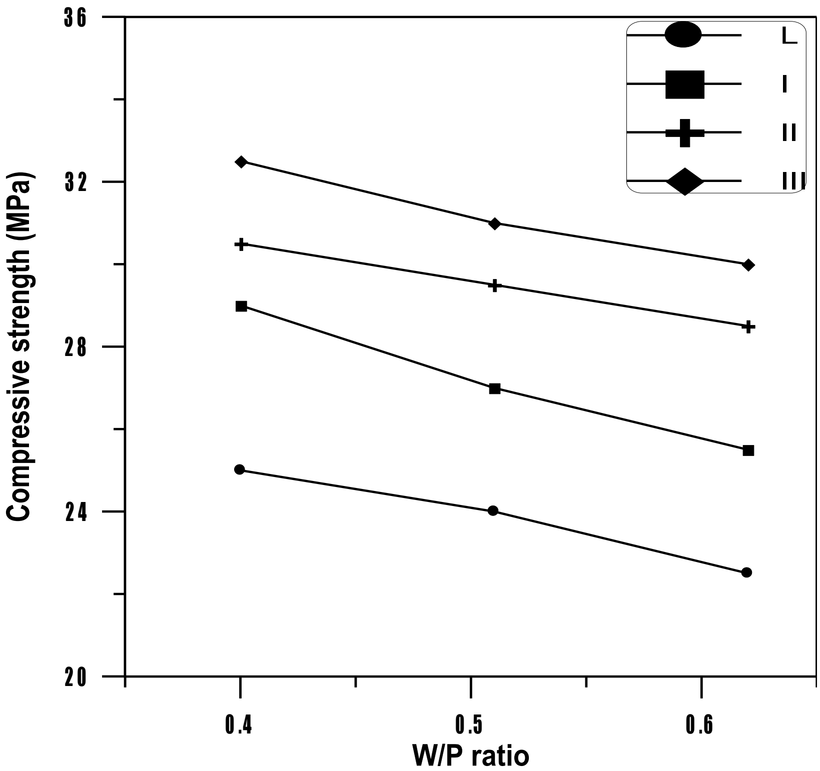


Figure (٤-٥): Relationship between compressive strength at ٧-days and W/P ratio for SCC with different filler types.

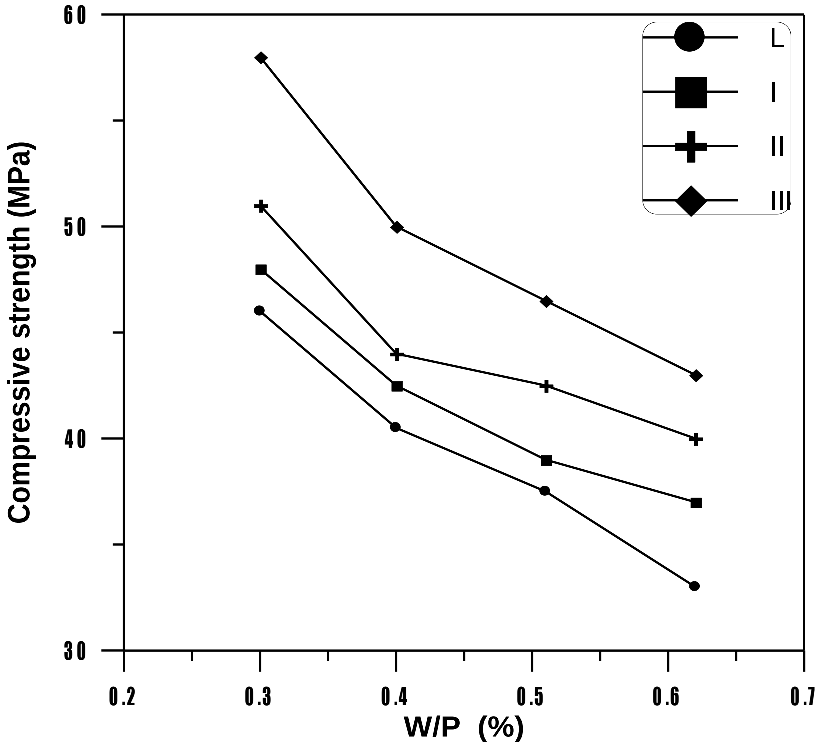



Figure (٤-٦): Relationship between compressive strength at ٢٨-days and W/P ratio for SCC with different filler types.

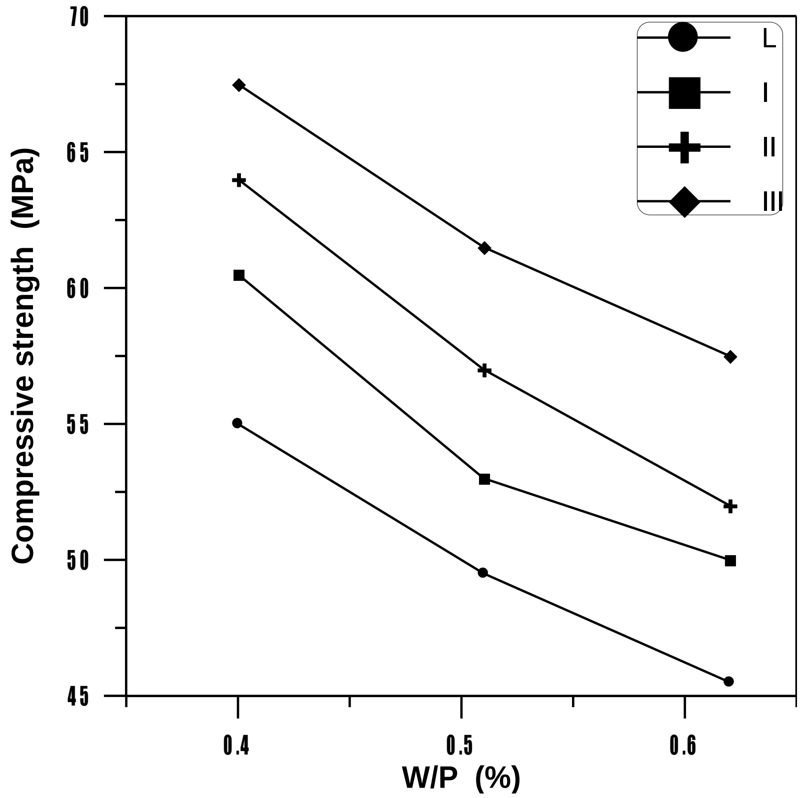



Figure (٤-٧): Relationship between compressive strength at ٩٠-days and W/P ratio for SCC with different filler types.

Figures (٤-٨) to (٤-١٠) show that increasing the time of calcining metakaolin from (٠.٥ to ١.٠) hr leads to increase the compressive strength by (٥.٢-١١.٨) %, (٣.٥-٩.٠) % and (٤.٠-٧.٥) % at ٧, ٢٨ and ٩٠ days respectively and increasing this time from (٠.٥ to ١.٥) hrs increases the compressive strength by (١٢.١-١٧.٦) %, (١٦.٢-٢٠.٨) % and (١١.٦-١٦.٠) % at ٧, ٢٨ and ٩٠ days respectively. This behavior can be explained by the densifing effect of metakaolin with a decrease in the porosity at early ages, while at later ages, in addition to the densifying effect of metakaolin by firing, a pozzolanic reaction with calicum hydroxide released from cement hydration and the filling effect in the voids among cement and other powder particles enhance the strength of concrete.

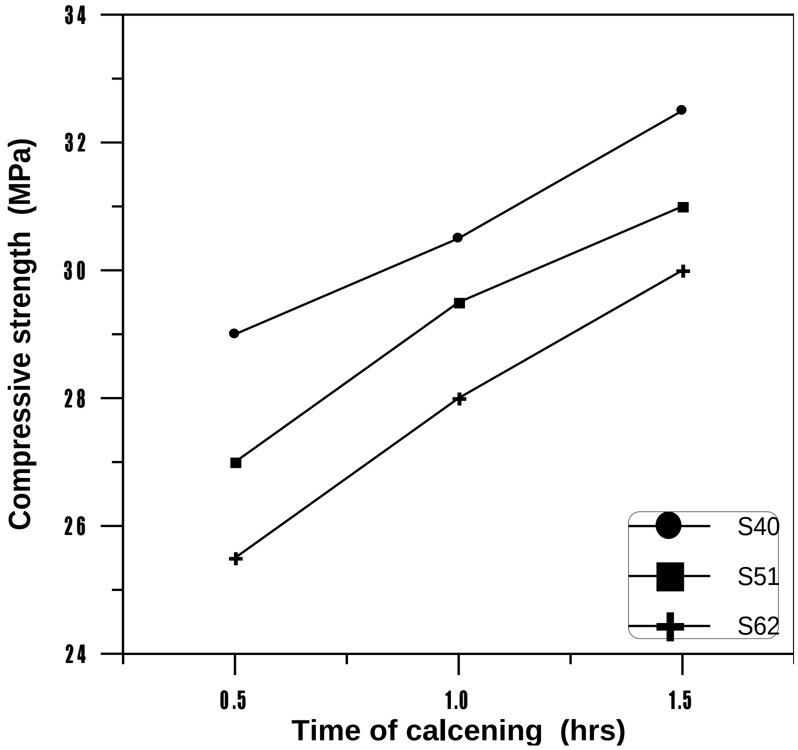



Figure (٤-٨): Relationship between compressive strength at ٧-days and time of calcining metakaolin.

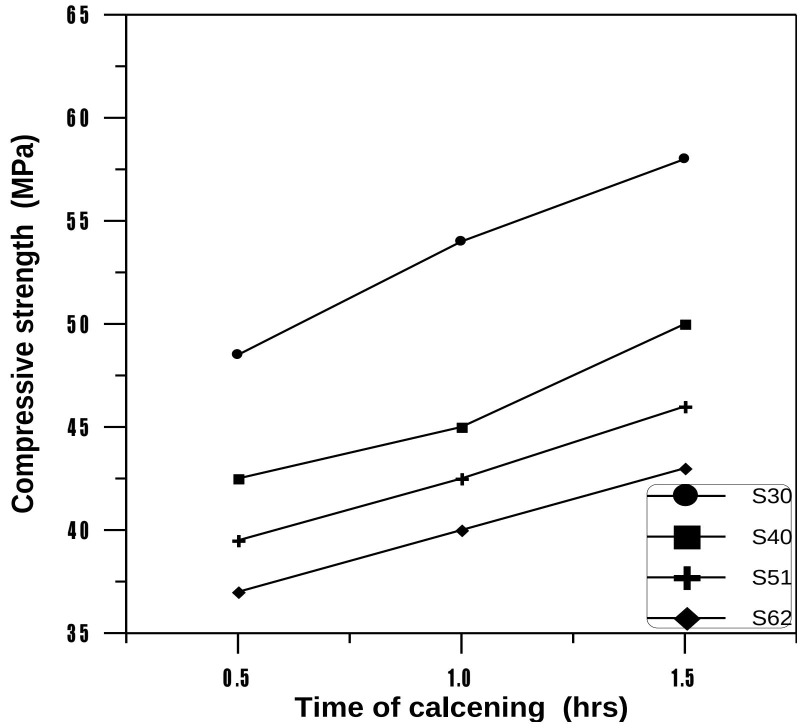



Figure (٤-٩): Relationship between compressive strength at ٢٨-days and time of calcining metakaolin.

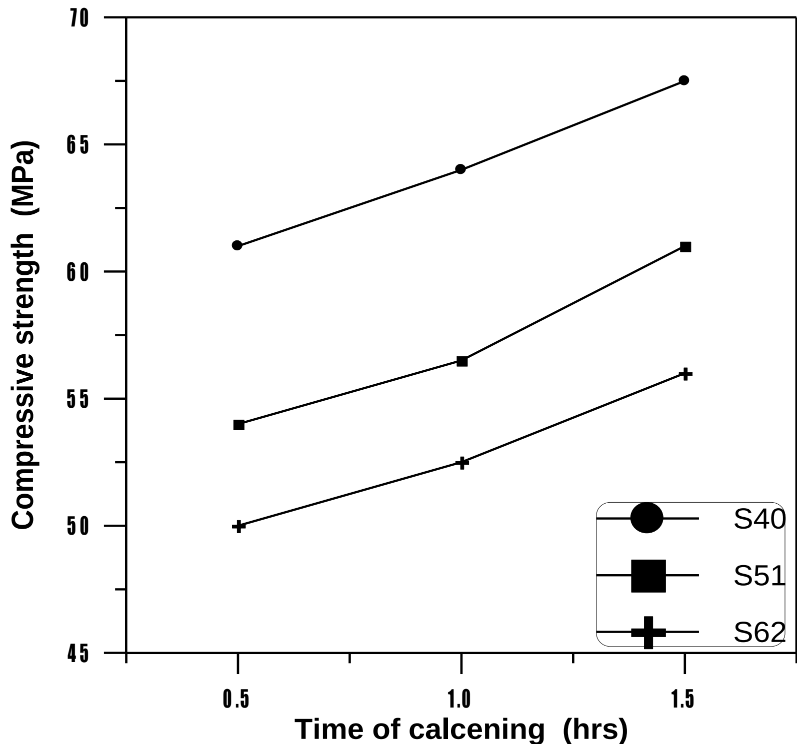


Figure (٤-١٠): Relationship between compressive strength at ٩٠-days and time of calcining metakaolin.

The surface of SCC tends to dry faster than NVC because; there is little or no bleed water at the surface due to using of ultra-fine materials and using low water to powder ratio. From the results shown in Figures (٤-١١) and (٤-١٢) it can be seen that sprinkle cured specimens improve compressive strength more than moist and air cured specimens by (١٠-١٢) %, (٢٣-٢٤) %, (١.٣-١.٦) %, (٢٨.٦-٣٠) %. (٠.٢-٢) % and (٢٩.٣-٣٢) % at ٧, ٢٨ and ٩٠ days for $\mathbf{S}_{٤٠}$ and $\mathbf{S}_{٥١}$ respectively, while moist cured specimens show larger compressive strength than sprinkle cured and air cured specimens by (٥.٥-١١.١) % and (٢٩.٥-٣٦) % for $\mathbf{S}_{٦٢}$ at ٢٨ and ٩٠ days respectively, as shown in Figure (٤-١٣).

Like normally vibrated concrete, the compressive strength for specimens with air curing is lower than that of the corresponding water cured and moist cured specimens. However, the extent of strength reduction was due to the insufficient curing for air cured specimens up to an age of ٩٠ days depends on water to powder ratio, (as the volume of voids increases when increasing the W/P) and the type of filler in the mix. It appears that the SCC mixes with calcined metakaolin type II are more affected by air curing compared to other types of curing conditions, (sprinkled and moist), as continued presence of water is required for the cement hydrates-pozzolana reaction to continue. Thus, the difference in the compressive strength between sprinkle and moist cured specimens can be attributed to the gel stiffining by drying for sprinkle curing, on the other hand it may be due to relaxtion in gel of filler type due to the presence of water by moist curing. This is in agreement with what was stated by Sonebi M.et al [٤٩].

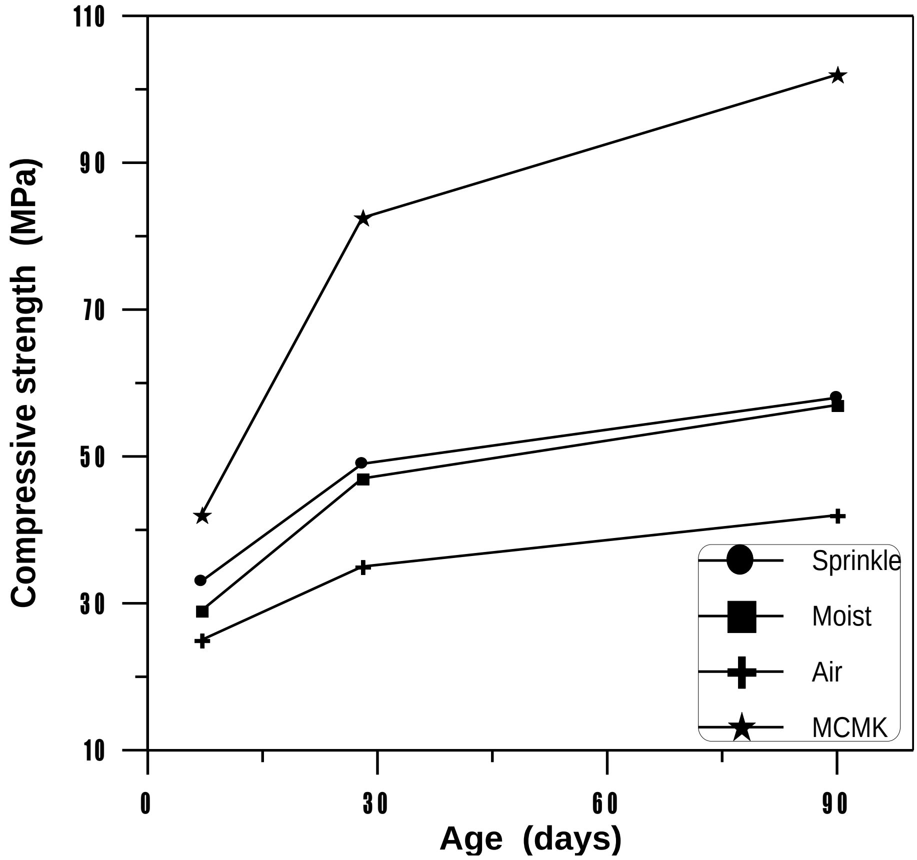



Figure (٤-١١): Relationship between compressive strength and age of II SCC with different curing conditions of W/P=٠.٤.

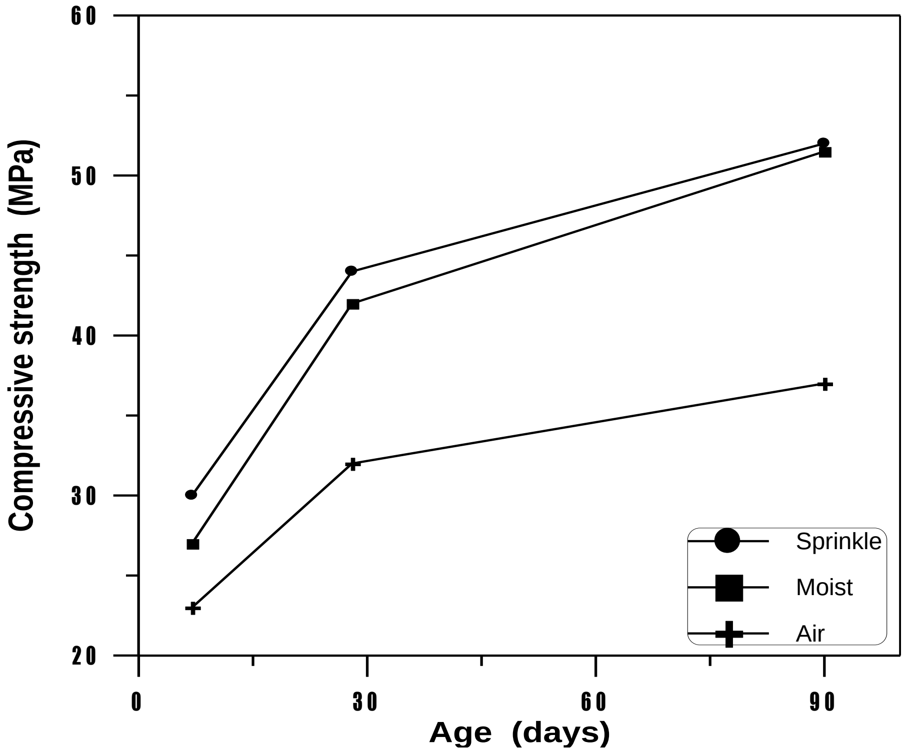



Figure (٤-١١): Relationship between compressive strength and age of II SCC with different curing conditions of W/P=٠.٥١.

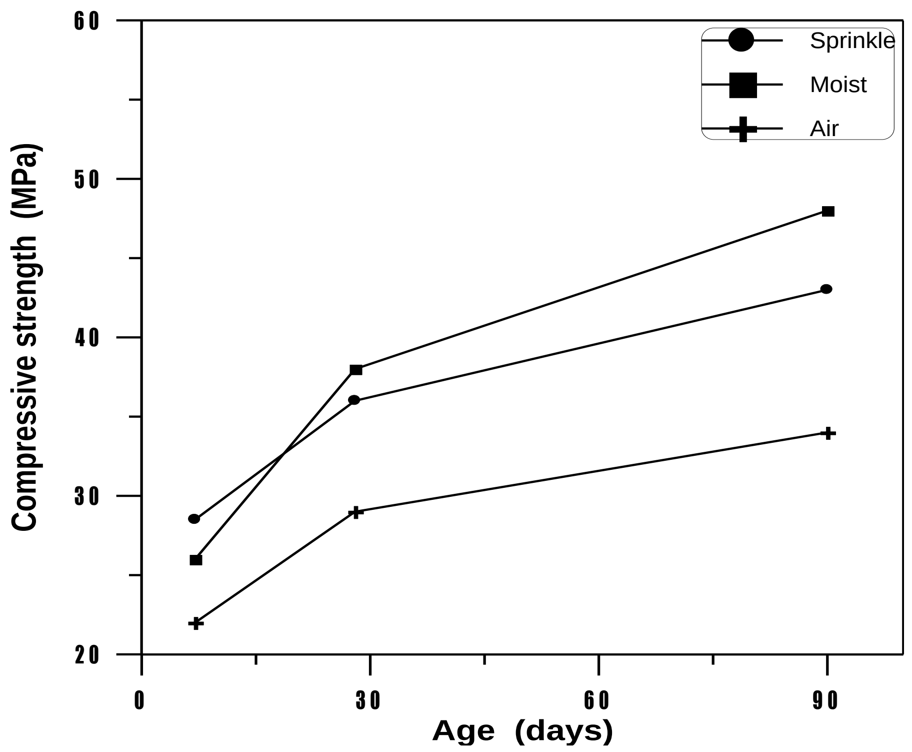



Figure (٤-١١): Relationship between compressive strength and age of II SCC with different curing conditions of W/P=٠.٦٢.

## ٤.٣.٢ Splitting tensile strength:

The results of splitting tensile strength for mixes with different (water to powder ratio, time of calcining metakaolin and curing conditions) are shown in Table (٤-٢) and Figures (٤-١٤) to (٤-١٩). Two cylinders of (١٠٠*٢٠٠) mm are tested t ٧, ٢٨ and ٩٠ days.

From the recorded results in Table (٤-٢) it can be seen that increasing the water to powder ratio from (٠.٤ to ٠.٥١) decreases the splitting tensile strength by (١-٣.٤) %, (١-٧.٩) %, and (٢.١-٨.٨) % at ٧, ٢٨ and ٩٠ days respectively, and increasing the W/P ratio from (٠.٤ to ٠.٦٢) % decreases the splitting tensile strength by (١٥.٩-١٩.٩) %, (٧.٤-١٧.٢) % and (١٣.٨-١٧.٦) % at ٧, ٢٨ and ٩٠ days respectively. This is due to the high initial volume of capillary voids in the mix. this increases when increasing the water content.

Table (٤-٢): Splitting tensile strength of SCC specimens.

| Mix Notation | Type of Filler | Splitting tensile strength (MPa) | | |
|---|---|---|---|---|
| | | ٧-days | ٢٨-days | ٩٠-days |
| **S٦٢** | Limestone | ٤.٣٠ | ٤.٨٦ | ٥.٢٥ |
| | Metakaolin type I | ٤.٥٠ | ٥.١٧ | ٥.٤١ |
| | Metakaolin type II | ٤.٦٢ | ٥.٣٤ | ٥.٨١ |
| **S٥١** | Limestone | ٥.١٨ | ٥.٤٠ | ٥.٨١ |
| | Metakaolin type I | ٥.٣٠ | ٥.٥١ | ٦.١٣ |
| | Metakaolin type II | ٥.٦٠ | ٥.٧٠ | ٦.٣٧ |
| | Metakaolin type III | ٥.٧٣ | ٦.١٠ | ٦.٨٥ |
| **S٤٠** | Limestone | ٥.٣٠ | ٥.٤٥ | ٦.٣٧ |
| | Metakaolin type I | ٥.٣٥ | ٥.٥٨ | ٦.٤٣ |
| | Metakaolin type II | ٥.٦٦ | ٥.٩٥ | ٦.٧٤ |
| | Metakaolin type III | ٥.٩٣ | ٦.٦٢ | ٧.٠٠ |
| RH According to Sonebi [٤٩] | Limestone powder | ----- | ٢.٤ | ----- |

Figures (٤-١٤) to (٤-١٦) show the splitting tensile strength development with age for different curing conditions. From these figures it can be seen that sprinkling cured specimens have higher splitting tensile strength than moist cured specimens by (٤.٨٤-٧.٣) %, (٣.٥-٦.٧) %, and (٢.٤٤-٥.٨) % at ٧, ٢٨ and ٩٠ days respectively, and sprinkling cured specimens have higher splitting tensile strength than air cured specimens by (٨.٦-١٧.٤) %, (١٣.١-١٥.٨) % and (١١.٩٣-٢٢.٣) % at ٧, ٢٨ and ٩٠ days respectively. This behavior can be explained by the stiffining process in the gel when drying or by relaxation in the gel when moist curing. Whereas for specimens with air curing, the insufficient curing leads to the insufficient of hydration products in concrete which minimizes the splitting tensile strength.

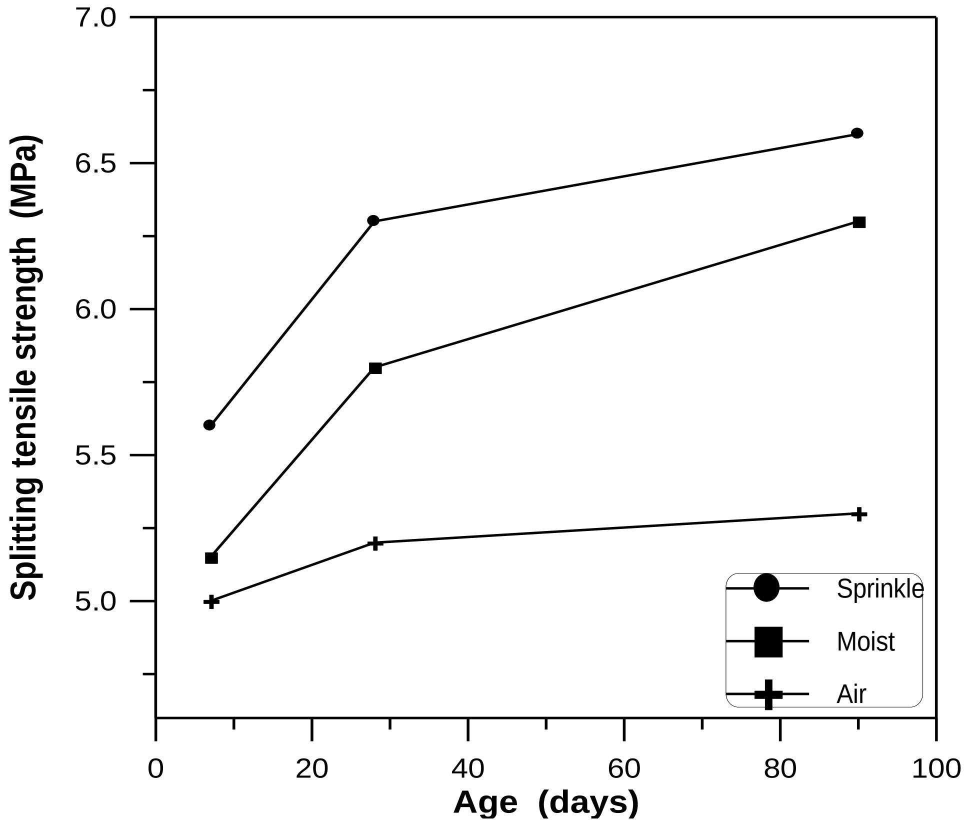



Figure (٤-١٤): Splitting tensile strength development of S٤٠ with age for different curing conditions.

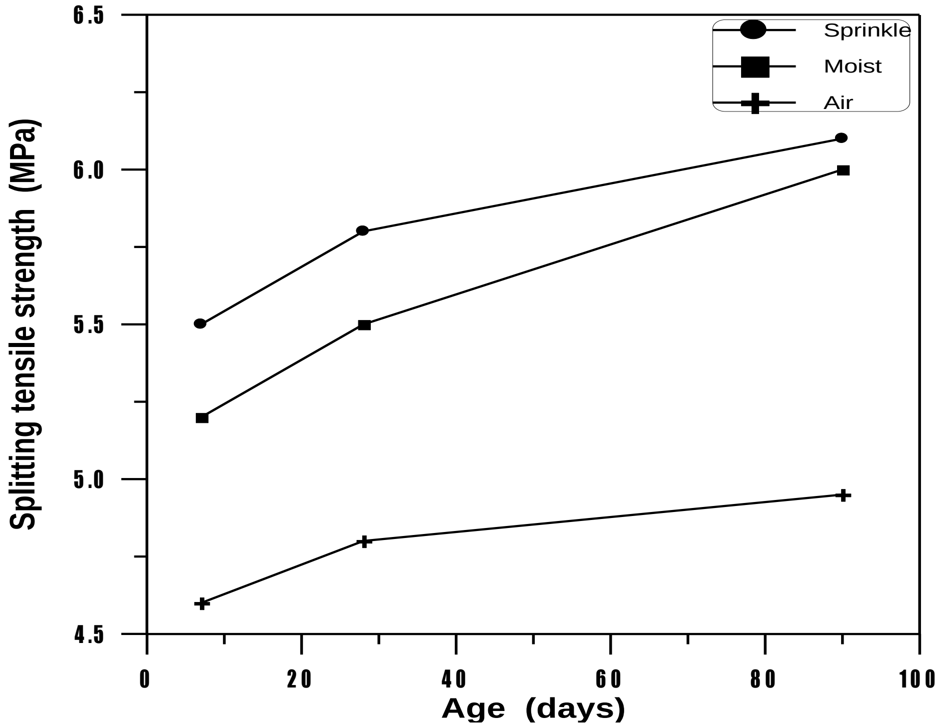



Figure (٤-١٥): Splitting tensile strength development of S٥١ with age for different curing conditions.

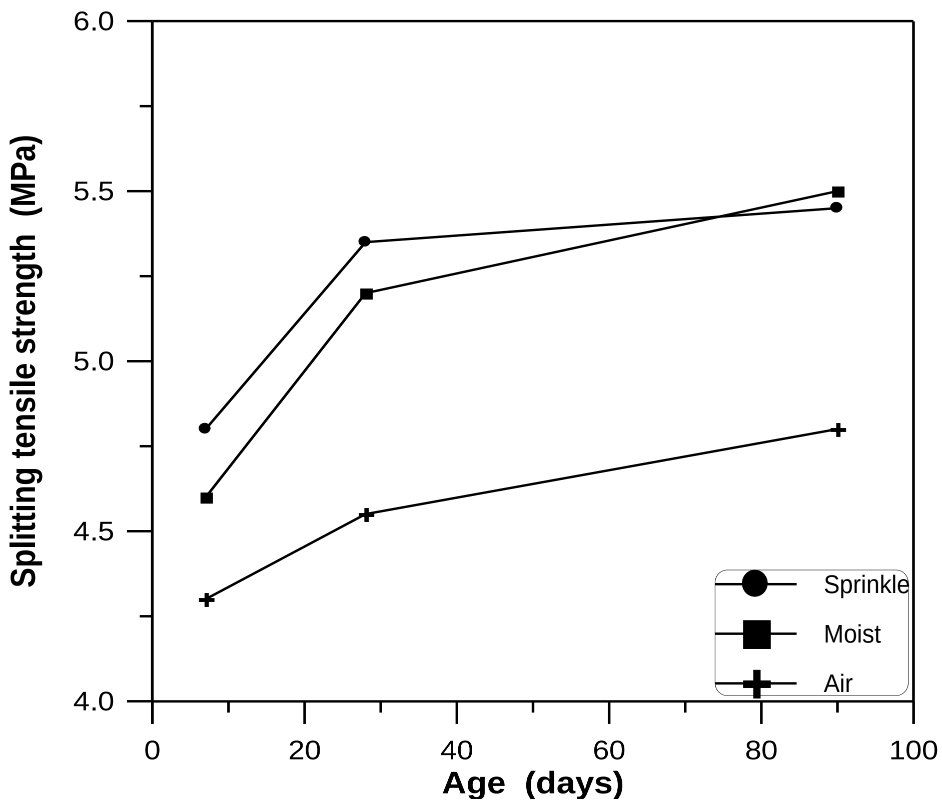



Figure (٤-١٦): Splitting tensile strength development of S٦٢ with age for different curing conditions.

The results shown in Figures (٤-١٧) to (٤-١٩) show that, when the time of calcining metakaolin increases from (٠.٥ to ١.٠) hr there is an increase in the splitting tensile strength by (٥.٣-٩.٨) %, (٥.٧-١٥.٧) %, and (٨.١٤-١٠.٥) % at ٧, ٢٨ and ٩٠ days respectively, and when the time of calcining metakaolin increases from (٠.٥ to ١.٥) hrs the splitting tensile strength increases by (٢.٣-٤.٨٤) %, (٢.٦-١٠.١٢) % and (٣.٥-٧.٠) % at ٧, ٢٨ and ٩٠ days respectively. At early ages, the higher splitting tensile strength is due to the better microstructure of the SCC, especially the smaller total porosity and more pore size distribution within the interfacial transition zone. While, at late ages, a pozzolanic reaction occurs with calcium hydroxide released from cement hydration and filling voids among and between cement particles. This trend is similar to what detected by Klaus and Yvette [٤٦].

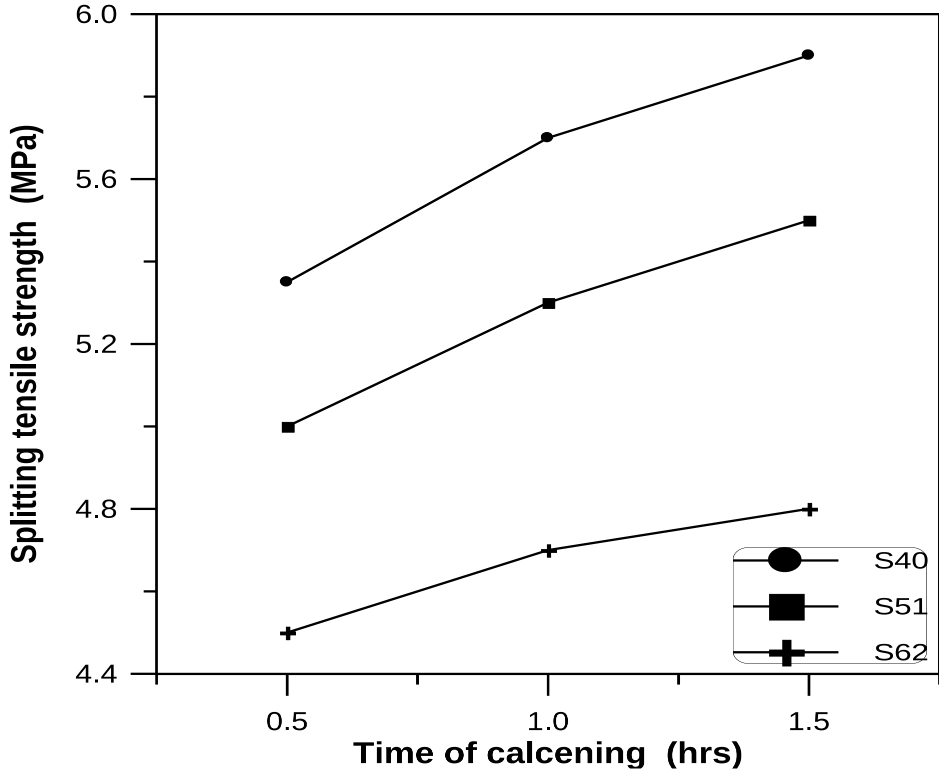



Figure (٤-١٧): Effect of time of calcining metakaolin on splitting tensile strength at ٧-days.

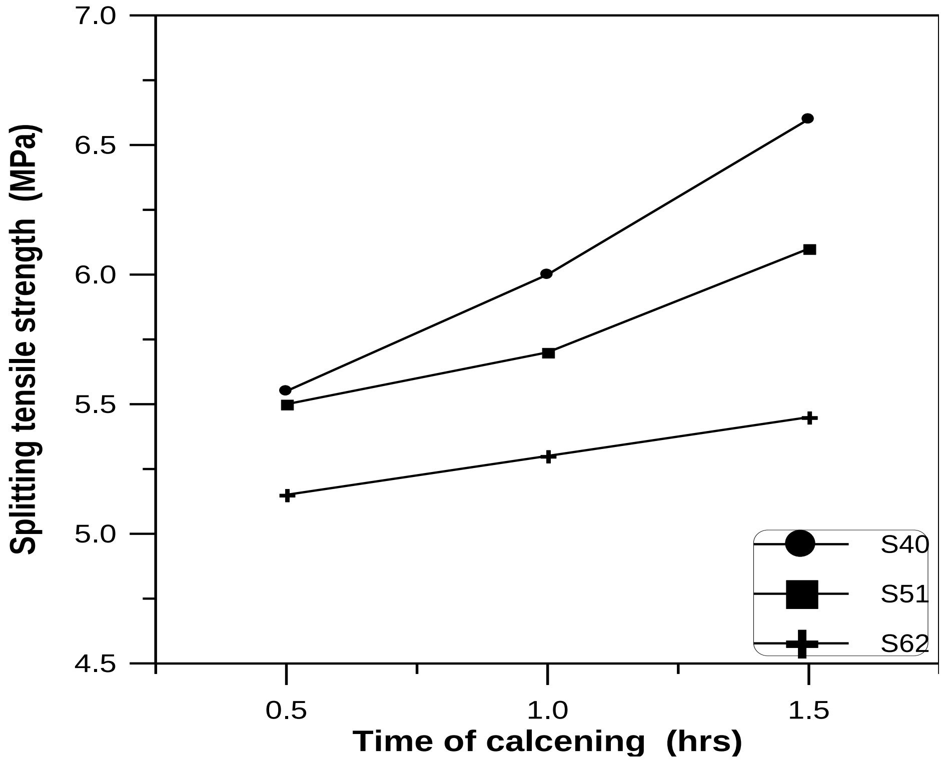



Figure (٤-١٨): Effect of time of calcining metakaolin on splitting tensile strength at ٢٨-days.

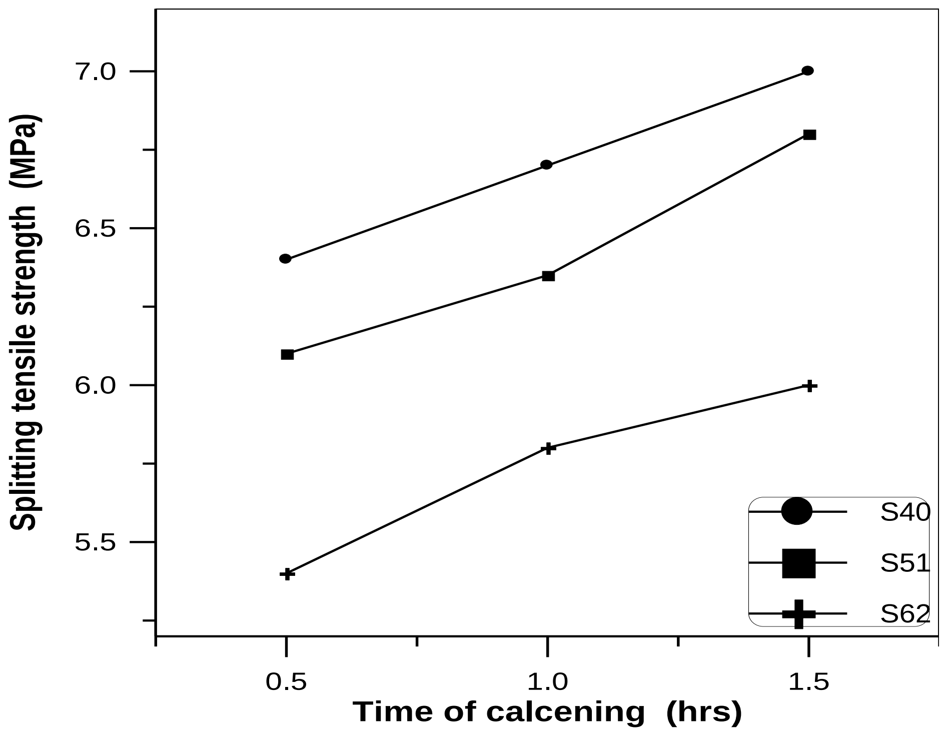


Figure (٤-١٩): Effect of time of calcining metakaolin on splitting tensile strength at ٩٠-days.

### ٤.٣.٣ Flexural strength:

The flexural strengh was measured by (١٠٠*٢٠٠*٤٠٠) mm self-compcting concrete prisms of different (water to powder ratio, filler type and curing conditions) as shown in Table (٤-٣) and Figures (٤-٢٠) to (٤-٢٥).

From the results in Table (٤-٣) it can be seen that **S٤٠** shows higher flexural strength than those of **S٥١** and **S٦٢**. Furthermore, increasing the water to powder ratio from (٠.٤ to ٠.٦٢) decreases the flexural strength by (١٧.٢-٤٦.٠) %, (١١.٢-٣٥.٧) % and (١٥.٤-٣٣.٧) % at ٧, ٢٨ and ٩٠ days respectively. This is due to the high early volume of capillary voids when using high water content in the mix. This observation was noticed by Victor et al [٤٨] and Malhotra [٧٠].

Table (٤-٣): The flexural strength of SCC specimens.

| Mix notation | Type of filler | Flexural strength (MPa) | | |
|---|---|---|---|---|
| | | ٧-days | ٢٨-days | ٩٠-days |

| | | | | |
|---|---|---|---|---|
| $S_{٦٢}$ | Limestone | ٢.٧٢ | ٣.٦٤ | ٤.١١ |
| | Metakaolin type I | ٣.٢٦ | ٣.٦٨ | ٤.٣٨ |
| | Metakaolin type II | ٤.٥٠ | ٥.٠٤ | ٥.٤٣ |
| $S_{٥١}$ | Limestone | ٣.١٠ | ٤.٢٧ | ٥.٠٤ |
| | Metakaolin type I | ٤.٠٧ | ٤.٥٨ | ٥.٢٠ |
| | Metakaolin type II | ٤.٦٥ | ٥.٢٢ | ٥.٩٠ |
| $S_{٤٠}$ | Limestone | ٥.٠٤ | ٥.٦٦ | ٦.٢٠ |
| | Metakaolin type I | ٥.٢٧ | ٥.٧٠ | ٦.٣٢ |
| | Metakaolin type II | ٥.٦٢ | ٦.٢٠ | ٦.٩٨ |
| **RH** According to Abed [٧٢] | Limestone powder | ---- | ٧.٥٠ | ٨.٣٠ |

Figures (٤-٢٠) to (٤-٢٢) show the flexural strength development with age for different curing conditions. From these figures, it is clear that all specimens are significantly affected by air curing due to the insufficient hydration products that fill all voids in concrete. Moreover, sprinkling cured specimens have higher flexural strength than that of moist cured specimens by (١.١-٢.٦٥) %, (١.٩-٢.٣) %, and (٠.٩-١.٠) % at ٧, ٢٨ and ٩٠ days respectively, and sprinkling cured specimens have higher flexural strength than that of air cured specimens by (٥.٥-٧) %, (٩.٢-١٣.٨) % and (١٤.٣-١٨.٥) % at ٧, ٢٨ and ٩٠ days respectively. This is due to the gel stiffining by drying for sprinkle cured specimens, while on the other hand it may be due to the presence of water by moist curing. When water to powder ratio is very high (٠.٦٢), moist cured specimens gain more flexural strength than sprinkle cured specimens by (٢-٣.٢) %. This behavior can be explained by the large volume of voids at early ages and the contineous moving of water providing the sufficient amount of water needed to complete all cement reactions.

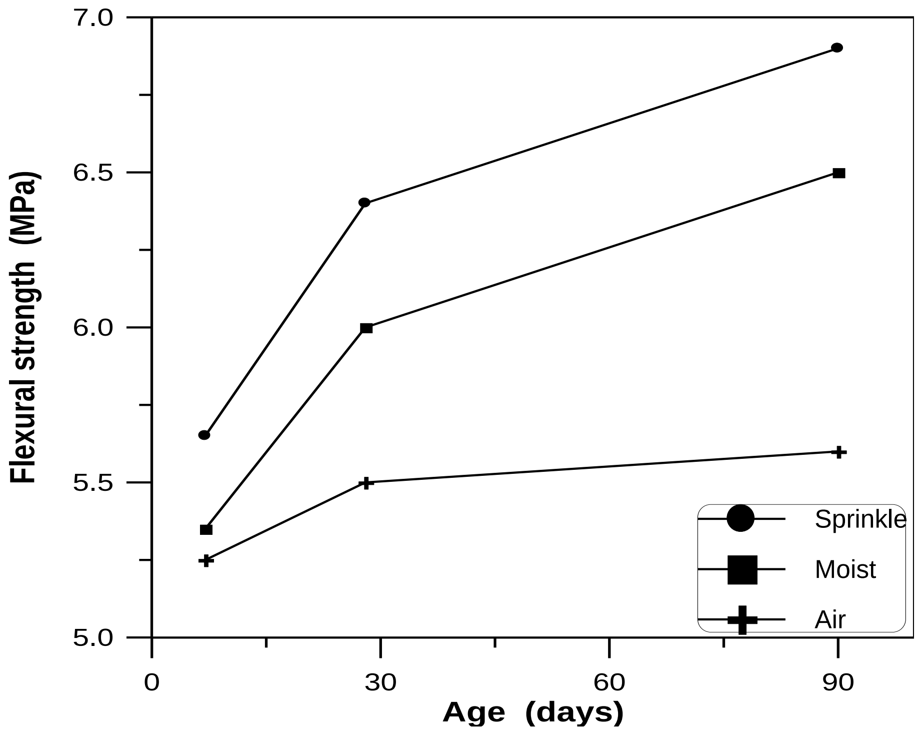



Figure (٤-٢٠): Effect of curing conditions on flexural strength of S٤٠ specimens with metakaolin type II filler.

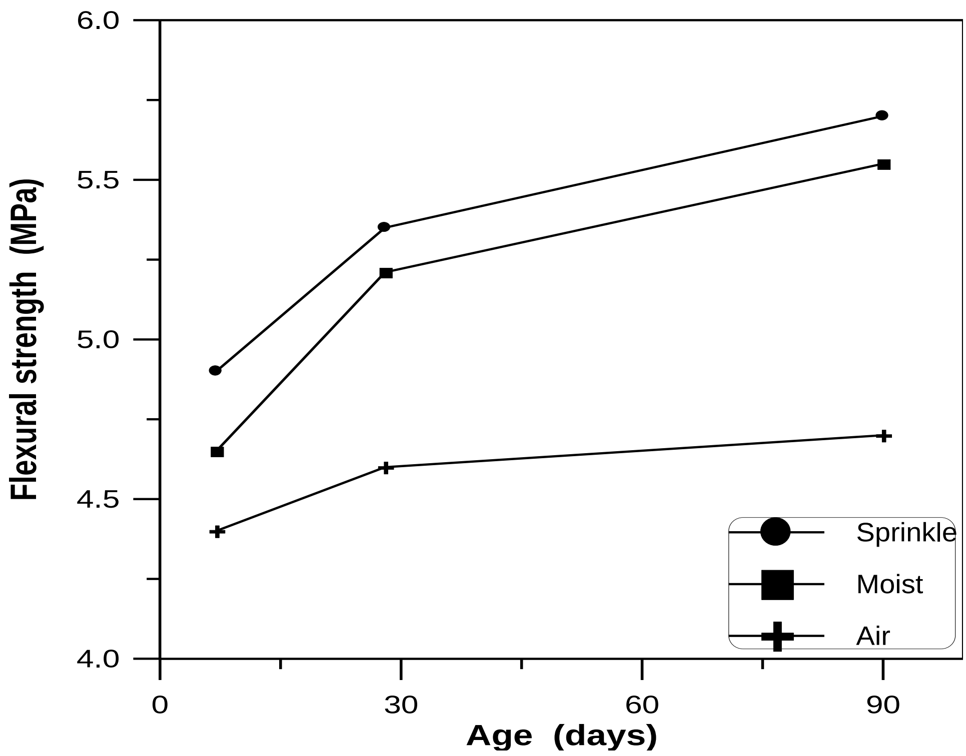



Figure (٤-٢١): Effect of curing conditions on flexural strength of S٥١ specimens with metakaolin type II filler.

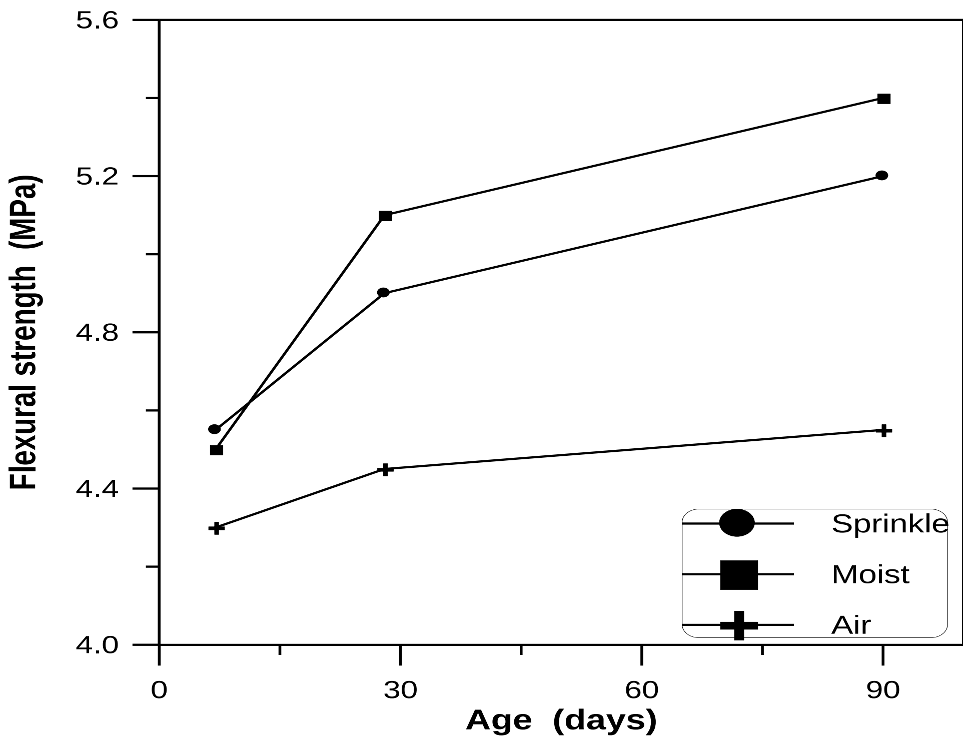



Figure (٤-٢٢): Effect of curing conditions on flexural strength of S٦٢ specimens with metakaolin type II filler.

From the results shown in Figures (٤-٢٣) to (٤-٢٥) it can be seen that increasing the time of calcining metakaolin from (٠.٥ to ١.٠) hr increases the flexural strength by (٨.٣-١٩.٥) %, (١٤.١-٢٤.١) %, and (٢٢.٢-٣٠.٧) % at ٧, ٢٨ and ٩٠ days respectively, and increasing this time from (٠.٥ to ١.٥) hrs increases the flexural strength by (٢٠.٥-٣٣.٦) %, (٢٦.٤-٣٧.٣) % and (٣٢.٩-٣٩.٢) % at ٧, ٢٨ and ٩٠ days respectively. This is caused by the better microstructure of the SCC, especially the smaller total porosity and the better pores distribution within the interfacial transition zone at early ages when increasing the time of calcining metakaolin as it becomes more soft and viscous. At later ages (٢٨ days and more), a pozzolanic reaction occurs between pozzolana in metakaolin and calcium hydroxide $Ca(OH)_٢$ released from cement hydration which fills voids among and between cement particles.

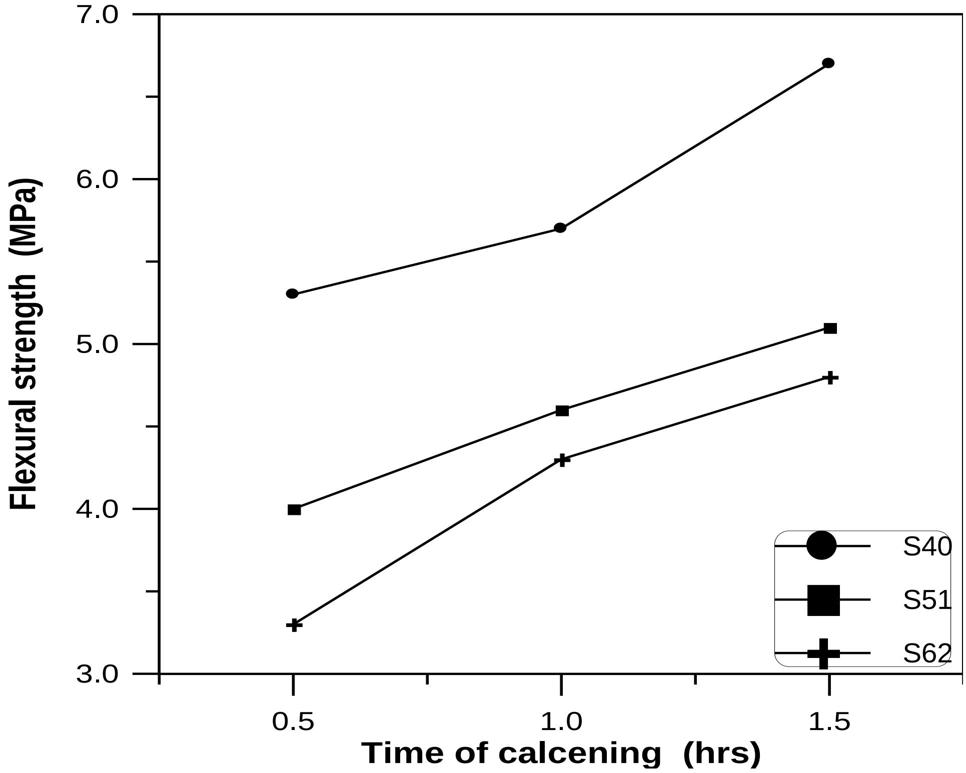



Figure (٤-٢٣): Effect of time of calcining metakaolin on flexural strength at ٧-days.

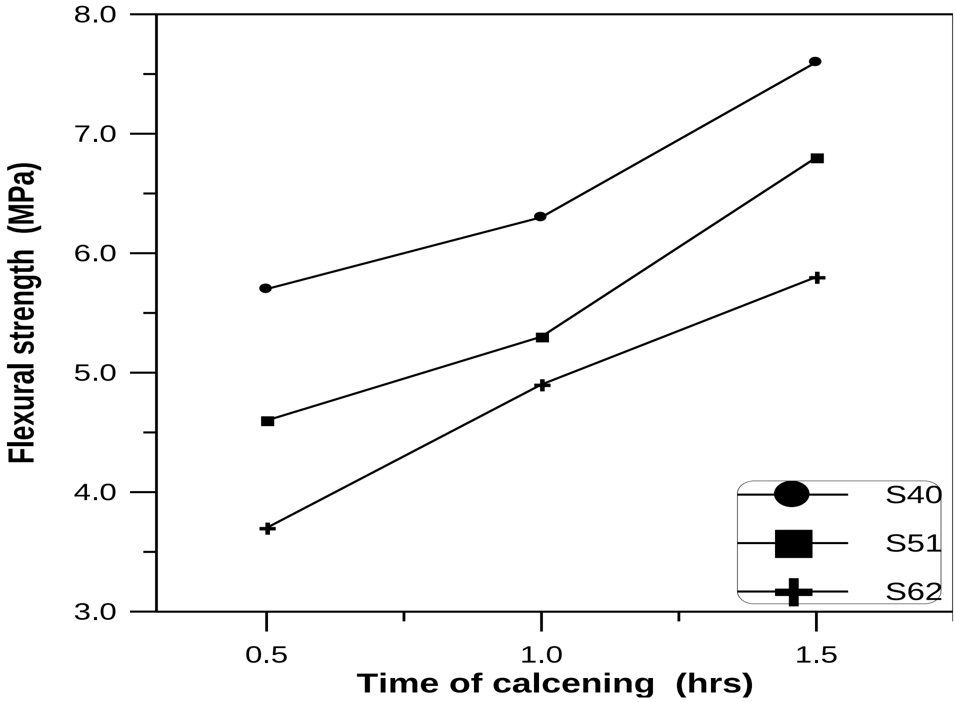



Figure (٤-٢٤): Effect of time of calcining metakaolin on flexural strength at ٢٨-days.

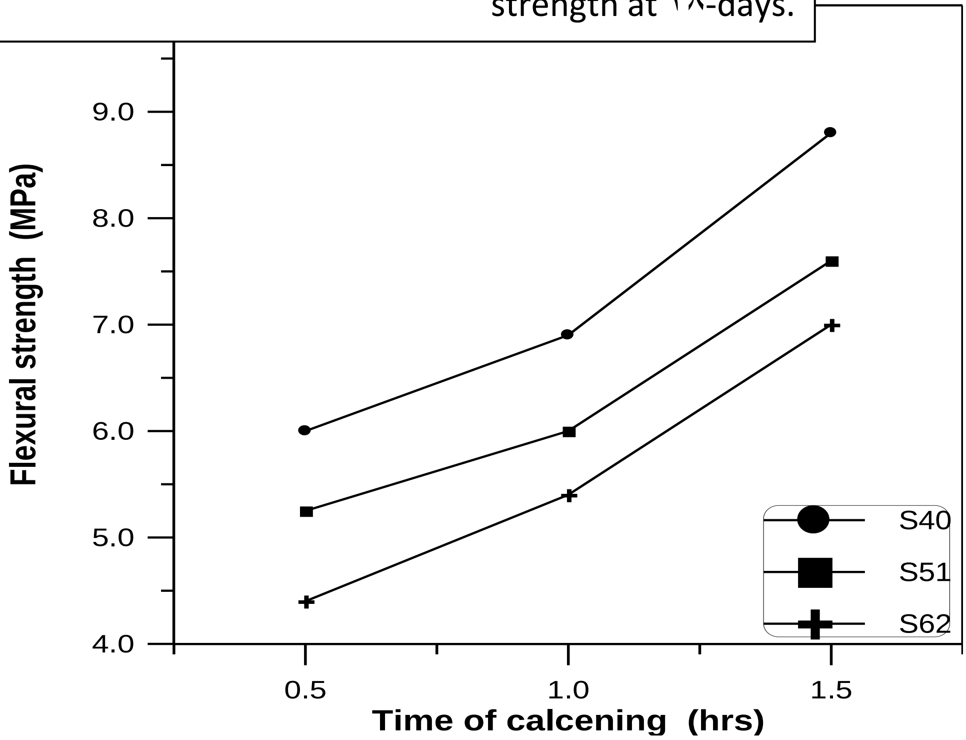



Figure (٤-٢٥): Effect of time of calcining metakaolin on flexural strength at ٩٠-days.

### ٤.٣.٤ Static modulus of elasticity:

The secant modulus of elasticity is defined as the slope of the chord of the uniaxial stree-strain curve between the point corresponding to ٤٠ percent of the maximum stress and the point corresponding to a strain of ٠.٠٠٠٠٥ (٧٢). Table (٤-٤) shows the results of the static modulus of elasticity for SCC specimens.

From the recorded results in Table (٤-٤) it can be seen that the ٢٨-days modulus of elasticity for concrete cylinders ranges between (٣٥.٧١-٤١.١٥) GPa for all the SCC specimens. However, increasing the water to powder ratio from (٠.٣ to ٠.٤) and (٠.٣ to ٠.٥١) leads to a reduction in the static modulus by (١.٧-٧.٥) % and (٥.٠-٩.٢) %. This behavior is due to the large early volume of voids in concrete in higher W/P ratios. On the other hand, the densifying effects of fillers reduce the pore size in low water to powder ratio. The inclusion of filler powders in the voids among and between cement particles makes strong, homogenous and dense interface zone between matrix and aggregate. However, the static modulus of elasticity for SCC specimens lies under the high strength concrete as shown in Table (٤-٤) because of the fact that the modulus of elasticity increases with the increase in compressive strength of concrete.

Table (٤-٤): Static modulus of elasticity of SCC at ٢٨-days (GPa).

| Mix Notation | Type of Filler | Ec (GPa) |
|---|---|---|

| | | |
|---|---|---|
| **S٥١** | Limestone | ٣٥.٧١ |
| | Metakaolin type I | ٣٦.٠٤ |
| | Metakaolin type II | ٣٧.١٨ |
| | Metakaolin type III | ٣٨.٣٤ |

Table (٤-٤): continue.

| | | |
|---|---|---|
| **S٤٠** | Limestone | ٣٦.٠٠ |
| | Metakaolin type I | ٣٧.٠٦ |
| | Metakaolin type II | ٣٨.٩٠ |
| | Metakaolin type III | ٤٠.٠٠ |
| **S٣٠** | Limestone | ٣٧.٢٥ |
| | Metakaolin type I | ٣٩.٤٣ |
| | Metakaolin type II | ٣٩.٧٦ |
| | Metakaolin type III | ٤١.١٥ |
| **SCCC** According to Sonebi (٤٩) | Limestone powder | ٤١.٩٠ |

Figure (٤-٢٦) shows the relationship between the time of calcining metakaolin and the static modulus of elasticity at ٢٨-days. It can be seen that increasing the calcining time from (٠.٥ to ١.٠) hr and (٠.٥ to ١.٥) hrs results to increase the static modulus of elasticity by (٠.٦-٤.٢) % and (٤.٨-٩.٨) %

respectively. This is due to both, increasing the softness of metakaolin by calcining at early ages and to the pozzolanic reaction at later ages.

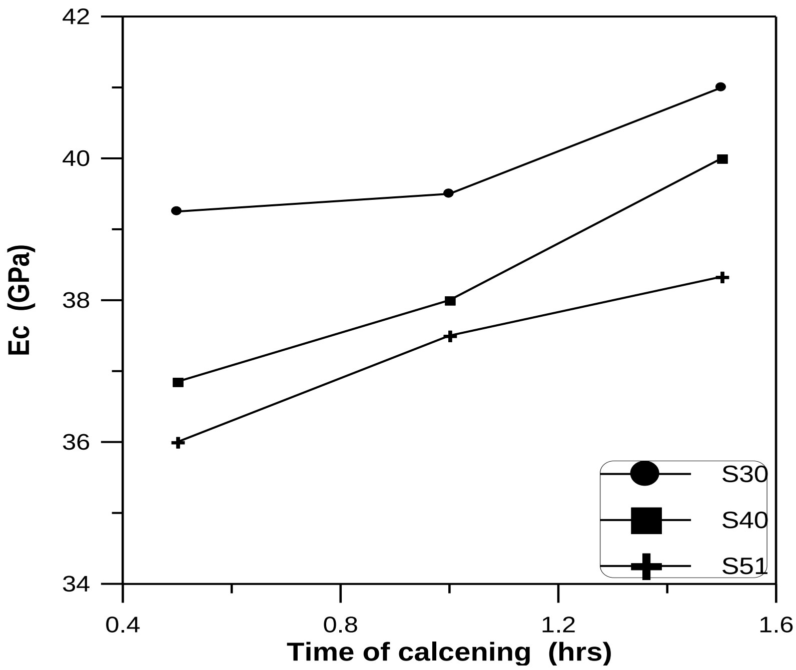



Figure (٤-٢٦): Effect of time of calcining metakaolin on static modulus of elasticity at ٢٨-days.

From the results shown in Figures (٤-٢٧) to (٤-٣٠) it is clear that the ascendig part of the stress-strain curves for all the concrete specimens becomes more linear and steeper when the water content decreases. This behavior is similar to that reported by Mohammed [٧٢].

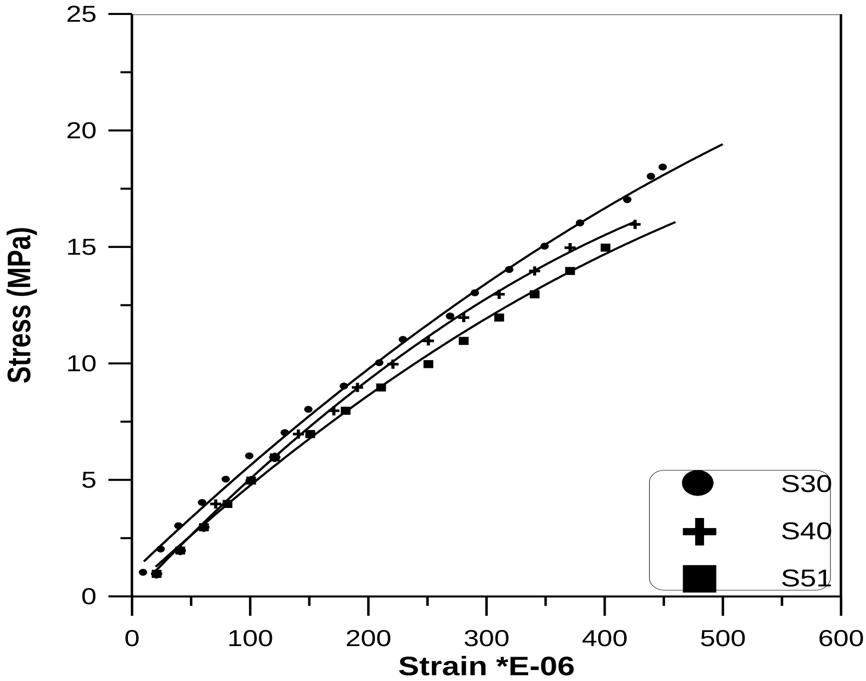



Figure (٤-٢٧): Effect of W/P ratio on stress-strain behavior of specimens containing limestone powder.

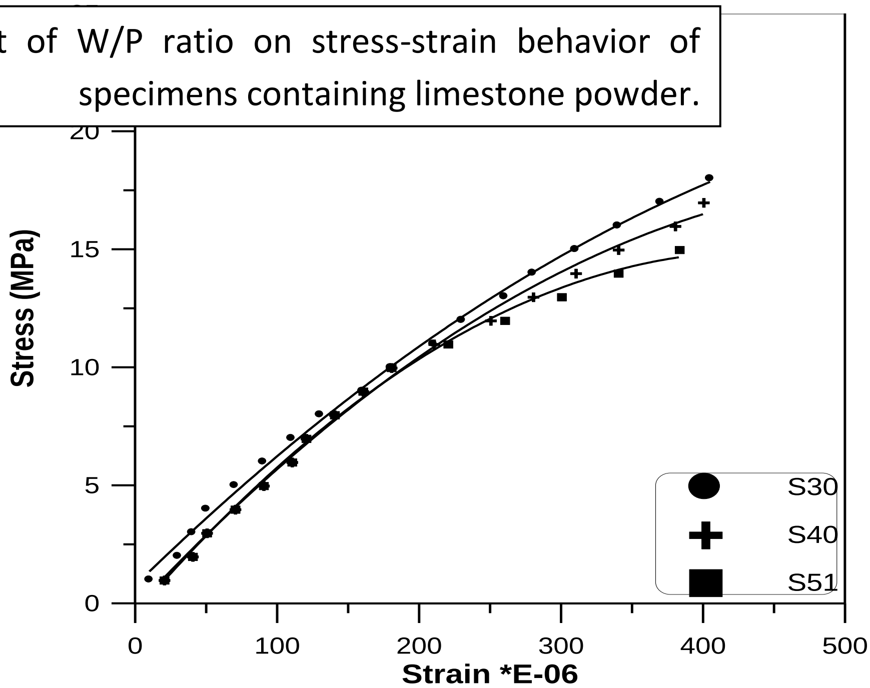



Figure (٤-٢٨): Effect of W/P ratio on stress-strain behavior of specimens containing metakaolin type I powder.

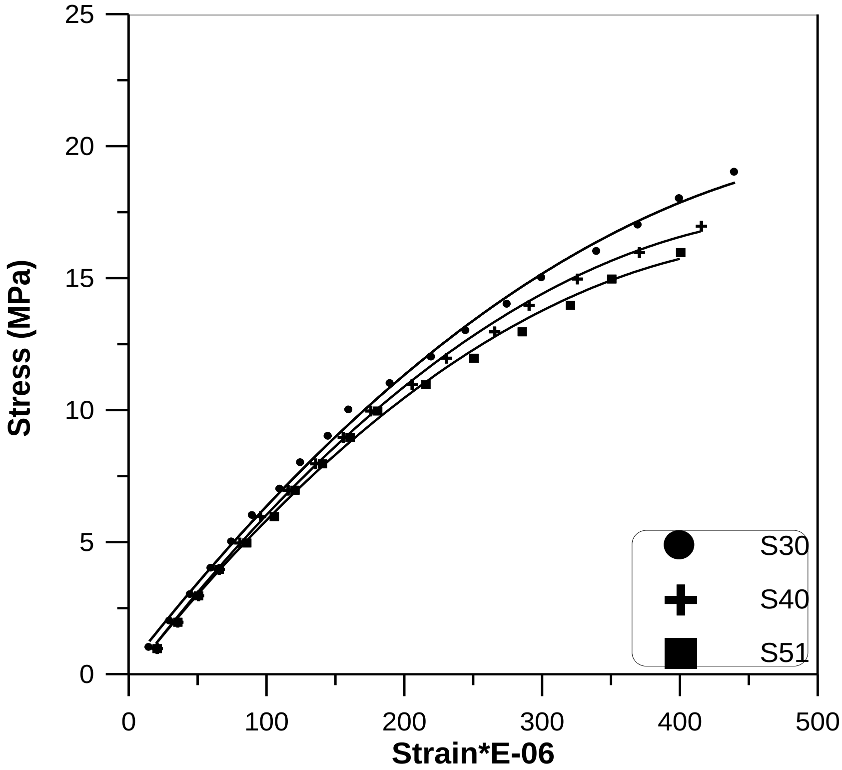



Figure (٤-٢٩): Effect of W/P ratio on stress-strain behavior of specimens containing metakaolin type II powder.

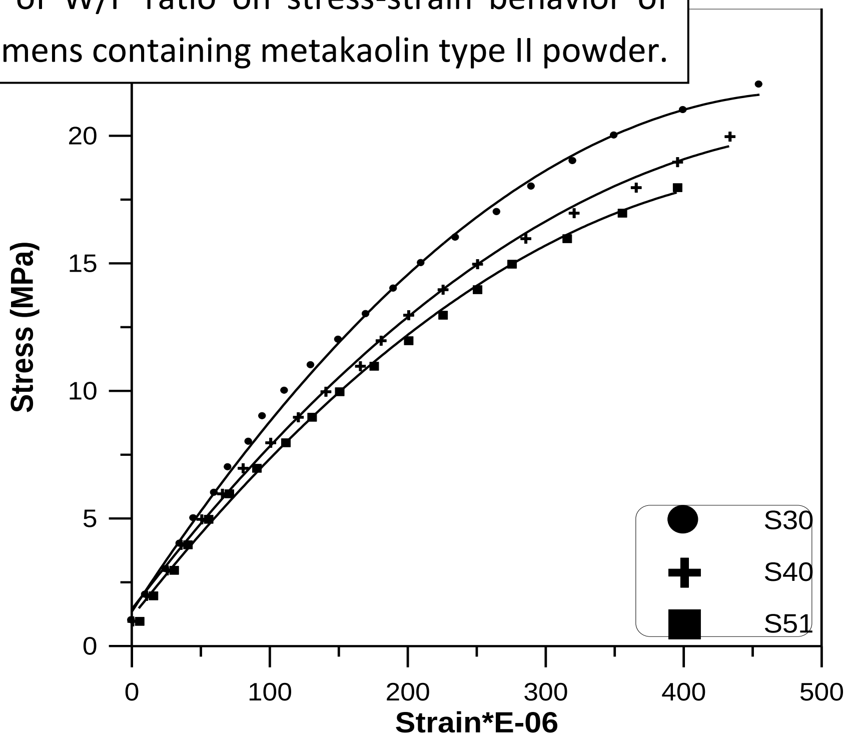



Figure (٤-٣٠): Effect of W/P ratio on stress-strain behavior of specimens containing metakaolin type III powder.

## ٤.٤ Non-Destructive results:

### ٤.٤.١ Ultra-sonic pulse velocity:

The results of U.P.V. measured on ١٠٠ mm cubes with different (water to powder ratios and time of calcining metakaolin) are plotted in Figures (٤- ٣١) to (٤-٣٦).

From the results shown in Figures (٤-٣١) to (٤-٣٣) it can be seen that increasing the W/P ratio from (٠.٤ to ٠.٥١) decreases the pulse velocity by (٢.٣-٥.٧) %, (٠.٦-٨.٢) %, and (٢.٠-٧.٠) % at ٧, ٢٨ and ٩٠ days respectively, and increasing the W/P ratio from (٠.٤ to ٠.٦٢) decreases the pulse velocity by (٤.٨-٩.٦) %, (١.٩-١٢.٦) % and (٣.٨-٩.٧) % at ٧, ٢٨ and ٩٠ days respectively. This reduction in U.P.V. with the increase in W/P ratio is due to the large early volume of voids in concrete body, which obstructs the pulse transition and prolongs the transit time.

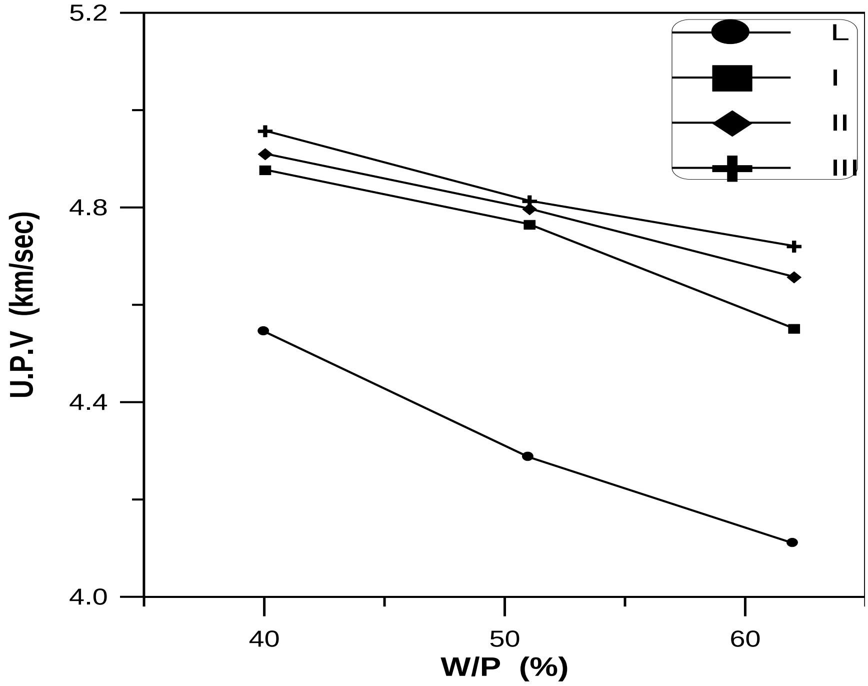



Figure (٤-٣١): Relationship between U.P.V and W/P ratio at ٧-days.

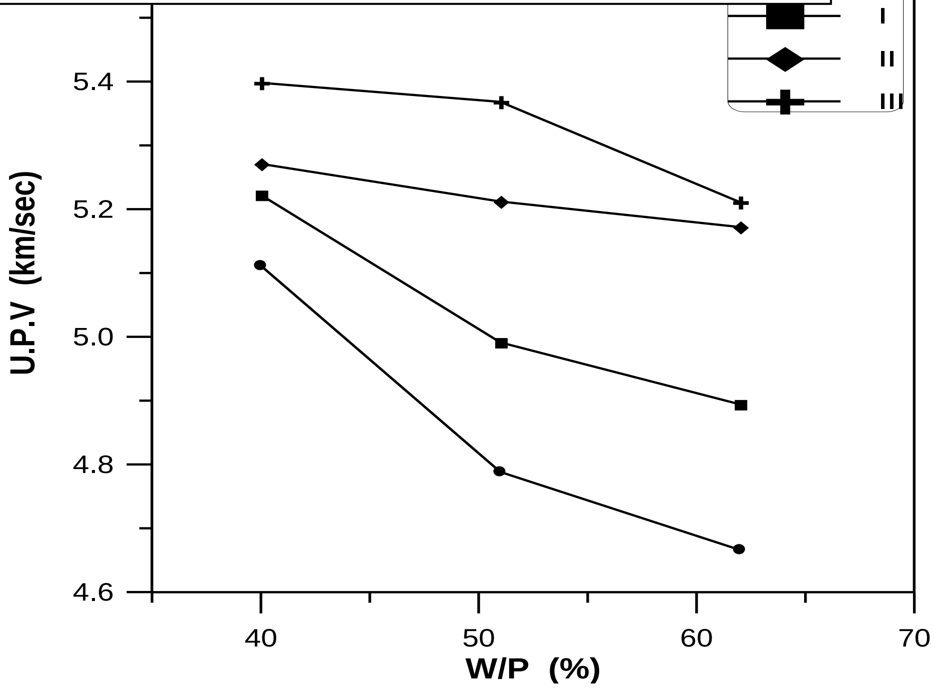



Figure (٤-٣٢): Relationship between U.P.V and W/P ratio at ٢٨-days.

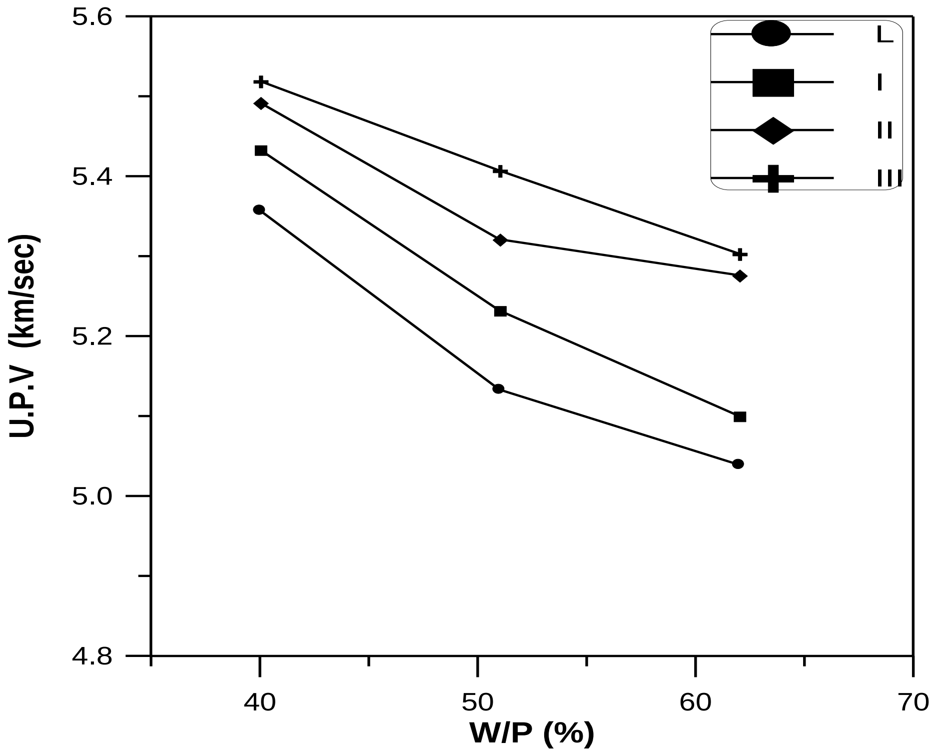



Figure (٤-٣٣): Relationship between U.P.V and W/P ratio at ٩٠-days.

Figures (٤-٣٤) to (٤-٣٦) show that increasing the time of calcining metakaolin from (٠.٥ to ١.٠) hr and (٠.٥ to ١.٥) hrs leads to increase the pulse velocity by (٠.٧-٢.٣) %, (١.٠-٣.٧) %, (١.٠-٥.٧) %, (٣.٤-٧.٦) %, (١.١-٣.٩) % and (١.٦-٥.٦) % at ٧, ٢٨ and ٩٠ days respectively. This is caused by the more softness of metakaolin by calcining at early ages, and to the pozzolanic reaction with calicum hydroxidate at later ages. It is clear that different types of filler help to improve the structure of the mortar aggregate interface, to get high density as that of the bulk mortar due to the continued hydration and dissolution of different filler particles and then increases the density of the SCC specimens. This behavior is similar to what is reported by Mohammed [٧٢].

U.P.V (km/sec)

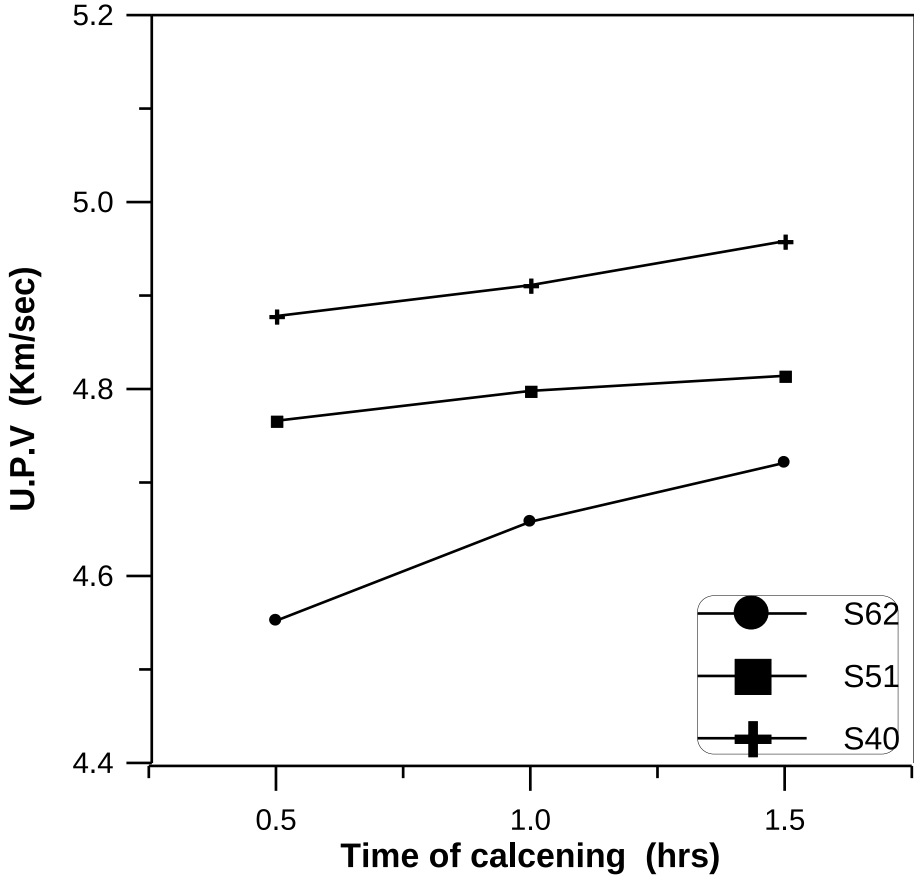



Figure (٤-٣٤): Effect of time of calcining metakaolin on U.P.V at ٧-days.

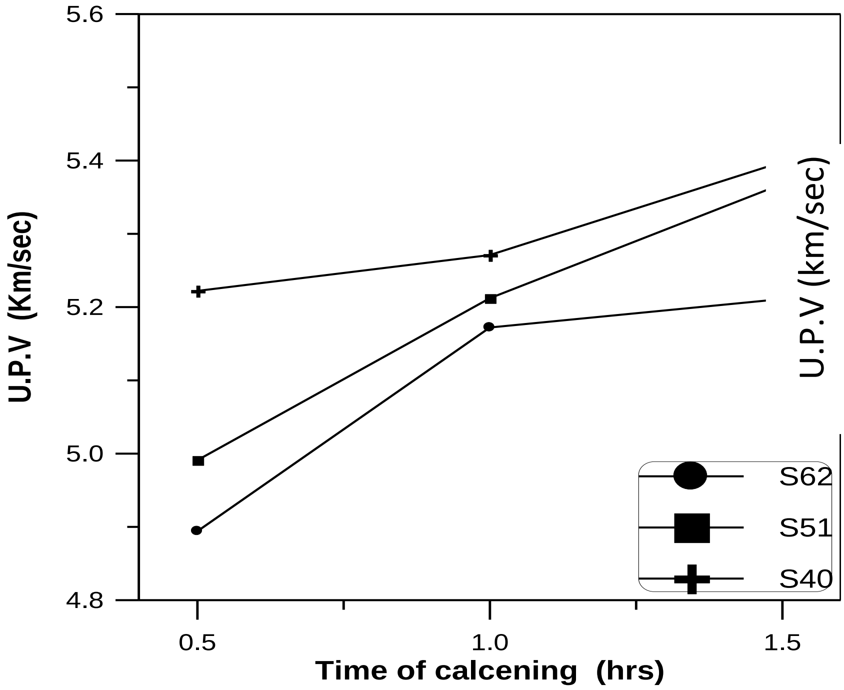
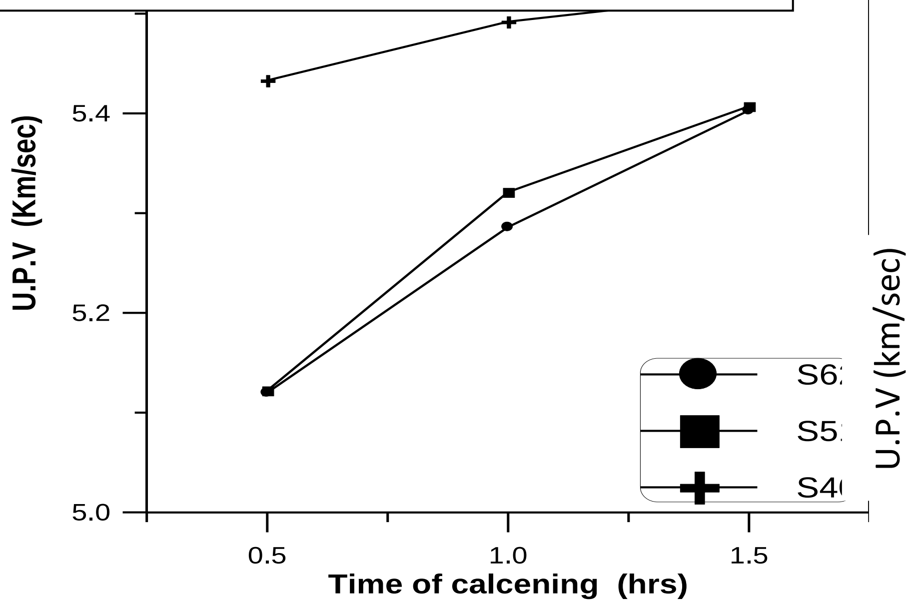



Figure (٤-٣٥): Effect of time of calcining metakaolin on U.P.V at ٢٨-days.




## ٤.٤.٢ Rebound hammer results:

Figure (٤-٣٦): Effect of time of calcining metakaolin on U.P.V at ٩٠-days.

The surface hardness of the ١٠٠ mm SCC cubes is assessed by the, "Schmidt rebound hammer test", according to the BS ١٨٨١: part ٢٠١; ١٩٨٦. The results of the rebound number for the concrete specimens of the three series of water to powder ratio are shown in Table (٤-٥). While, Figures (٤-٣٧) to (٤-٣٩) show the relationship between rebound number and time of calcining metakaolin powder.

From the recorded results in Table (٤-٥) it can be seen that the rebound number for the SCC specimens ranges between (٣٠-٤٠), (٣٣-٤٢.٥) and (٣٦-٤٤) at ٧, ٢٨ and ٩٠ days respectively. On the other hand, increasing the water to powder ratio from (٠.٤ to ٠.٥١) and (٠.٤ to ٠.٦٢) results in a reduction in the rebound number by (٥.٧-١٠) %, (١٤.٣-١٥.٨) %, (٤.٧-٧.٩) %, (٧.٥-١٠.٥) %, (٢.٤-٦.٨) % and (٣.٦-٦.٨) % at ٧, ٢٨ and ٩٠ days respectively. This behavior can be explained by increasing the volume of voids in the concrete structure and to the use of ultra-fine particles in the mix. The estimated compressive strength from rebound number is less than that measured on cubes by (١٠-٣٠) %. This is due to using high amount of fine materials and decreasing the size and amount of coarse aggregate used in the mix. This is why the Schmidt hammer test is not favorable to this kind of concrete, "Self-Compacting Concrete"

From the results shown in Figures (٤-٣٧) to (٤-٣٩) it is clear that increasing the time of calcining metakaolin from (٠.٥ to ١.٠) hr and (٠.٥ to ١.٥) hrs increases the rebound number by (٦.١-٨.٦) %, (٩.١-١٤.٣) %, (٥.٣-٨.٨) %, (١١.٨-١٥.٧) %, (٥.١-٥.٣) % and (٦.٥-١١.٤) % at ٧, ٢٨ and ٩٠ days respectively. This is due to the densifying effect of metakaolin which increses by increasing the duration of firing process on metakaolin at fresh state, on the other hand, at later ages the pozzolanic reaction with calicum hydroxidate and filling effect of voids among and between cement particles. This is in agreement with

Sonebi [٤٩] and Mohammed [٧٢]. Figure (٤-٤٠) shows the relationship between compressive strength and rebound number with a coefficient of determination of (٨٣, ٩٥ and ٨٢.٥) % at ٧, ٢٨ and ٩٠ days respectively.

Table (٤-٥): Rebound number values of SCC.

| Mix notation | Type of Filler | Rebound number | | |
|---|---|---|---|---|
| | | ٧-days | ٢٨-days | ٩٠-days |
| S٦٢ | Limestone | n.a | ٣٣ | ٣٦ |
| | Metakaolin type I | ٣٠ | ٣٤ | ٣٨ |
| | Metakaolin type II | ٣٢ | ٣٧ | ٤٠ |
| | Metakaolin type III | ٣٤ | ٣٩ | ٤١ |
| S٥١ | Limestone | n.a | ٣٤ | ٣٧ |
| | Metakaolin type I | ٣٣ | ٣٥ | ٣٨.٥ |
| | Metakaolin type II | ٣٥ | ٣٨ | ٤٠.٥ |
| | Metakaolin type III | ٣٦ | ٤٠.٥ | ٤١ |
| S٤٠ | Limestone | n.a | ٣٦ | ٣٨ |
| | Metakaolin type I | ٣٥ | ٣٨ | ٣٩.٥ |
| | Metakaolin typeII | ٣٨ | ٤٠ | ٤١.٥ |
| | Metakaolin typeIII | ٤٠ | ٤٢.٥ | ٤٤ |

| | | | | |
|---|---|---|---|---|
| **RH** by Sonebi[٤٩] | Limestone powder | --- | ٤٠.٨ | --- |

Where:

n.a= not allowable.

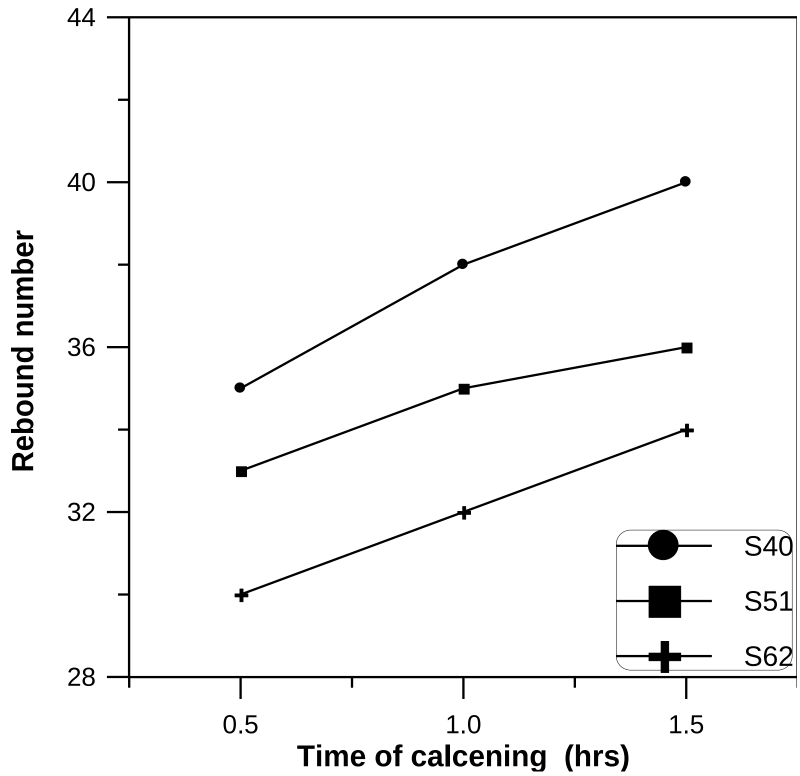



Figure (٤-٣٧): Effect of time of calcining metakaolin on rebound number at ٧-days.

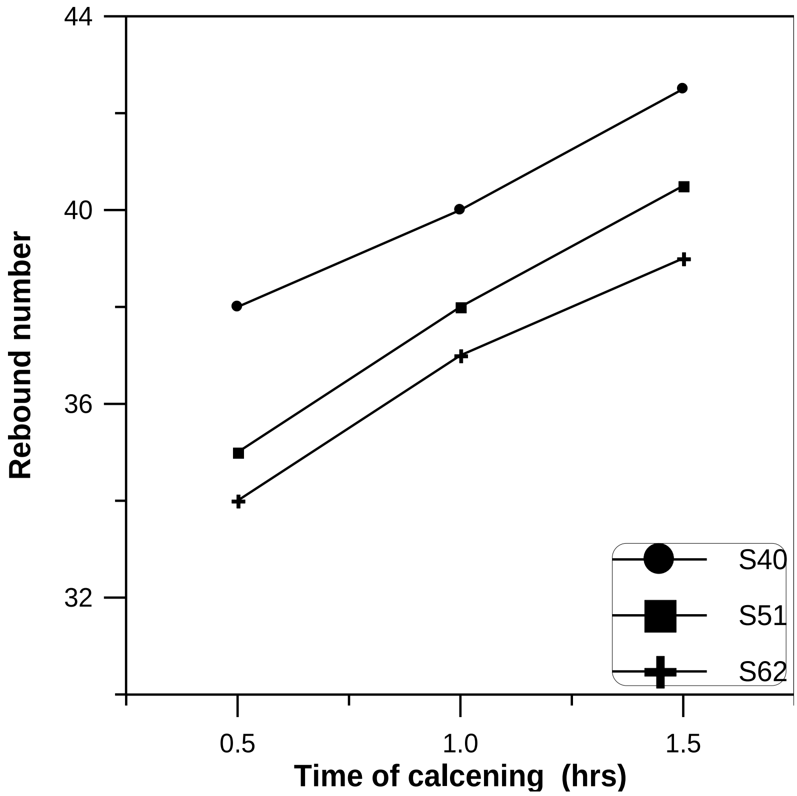



Figure (٤-٣٨): Effect of time of calcining metakaolin on rebound number at ٢٨-days

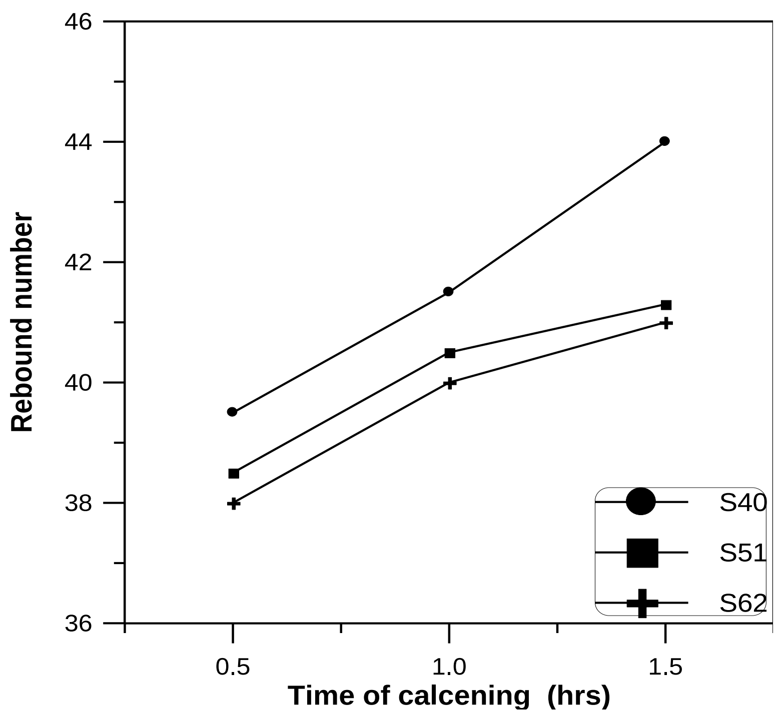



Figure (٤-٣٩): Effect of time of calcining metakaolin on rebound number at ٩٠-days

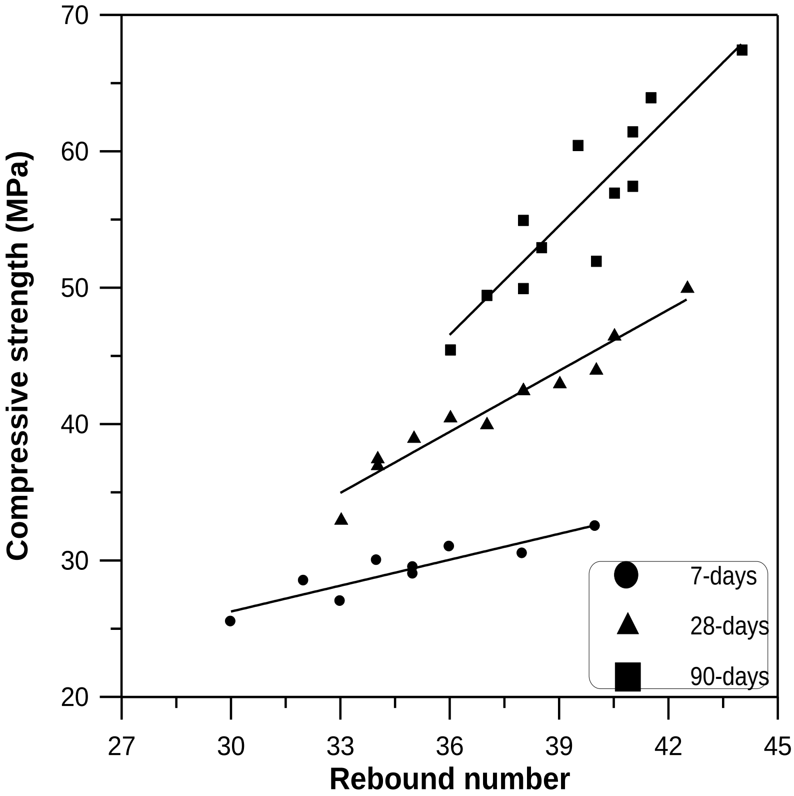



Figure (٤-٤٠): Relation between compressive strength and rebound number at different ages.

## ٤.٥ Mathematical m

In order to obtain a useful mathematical relationship, that gives the best predicted values for compressive strength, linear multiple variables regression of statistica ٥ program is used. This makes it possible to choose the best combination of variables to be introduced into the regression.

The standard error and the coefficient of correlation were also determined for each regression to check its statistical significance. The exponential equation used was of the following general form:

$$Y = a_0 * x_1^{a1} * x_2^{a2} * x_3^{a3} \ldots\ldots\ldots x_n^{an}$$ --------------------(٤-١)

where:

Y=Dependent variable.

$x_1, x_2, x_3 \ldots\ldots x_n$=Independent variables.

$a_0, a_1, a_2, a_3 \ldots\ldots a_n$=Constants.

The regression for prediction of **Fc** can be writen as follows:

**$Fc = a_0 * (Rn)^{a1} * (T)^{a2} * (W/P)^{a3} * (UPV)^{a4} * (A)^{a5} *$** -----(٤-٢)

Where:

**Fc**= compressive strength in MPa.

**Rn**= rebound number.

**T** = time of calcining metakaolin in hrs.

**W/P**= water to powder ratio.

**U.P.V**= ultrasonic pulse velocity in km/sec.

**A** = age of concrete specimens in days.

Table (٤-٦) gives the values of the constants **($a_0, a_1, a_2, a_3 \ldots a_n$)** for the regressions for **Fc**. This Table also gives the values of coefficient of correlation and the standard errors. From the values of coefficient of correlation obtained, it can be concluded that these regressions are statistically significant. The size of the investigated data is of ٣٦, each with ٥ independent variables. From this

Table the following equations could be used to estimate the corresponding values with good coefficient correlation and less variables introduce in it and it could be estimated that eq. **(٤-٥)** is the best for practical work:

**Fc= ٥.٣٠*(Rn)$^{-.٠٦}$*(T)$^{.٠٩}$*(W/P)$^{-.٠٥}$*(U.P.V)$^{.٤٤٦}$*(A)$^{.٦٤}$……………..(٤-٣)**

**Fc= ٤.٣١*(T)$^{.٠٨٧}$*(W/P)$^{-.٠٦}$*(U.P.V)$^{.٣٩٣}$*(A)$^{.٦٤٨}$…………………….(٤-٤)**

**Fc= ٣.٣٢*(W/P)$^{.٠٥٢}$*(U.P.V)$^{.٤٦٢}$*(A)$^{.٦٠٥}$…………………………..(٤-٥)**

**Fc= ٢.٣٣*(U.P.V)$^{.٥٠٦}$ *(A)$^{.٥٧٧}$……………………………………..(٤-٦)**

Table (٤-٦): Coefficient of exponential regressions for the prediction of **Fc**:

| **Regr. No.** | **$a_٠$** | **$a_١$ Rn** | **$a_٢$ T** | **$a_٣$ W/P** | **$a_٤$ U.P.V** | **$a_٥$ A** | **C.C** | **S.E** |
|---|---|---|---|---|---|---|---|---|
| ١ | ٦.٢٩ | -.٠٥ | .٠٧٤ | -.٠٤ | .٤٤٤ | .٦٤٠ | .٩٥٦ | ٢.٦٤٦ |
| ٢ | ٥.٣٠ | -.٠٦ | .٠٩٠ | -.٠٥ | .٤٤٦ | .٦٤٠ | .٩٥٧ | ٢.٦٠٤ |
| ٣ | ٤.٣١ | ---- | .٠٨٧ | -.٠٦ | .٣٩٣ | .٦٤٨ | .٩٥٧ | ٢.٥٩٩ |
| ٤ | ٣.٣٢ | ---- | ---- | .٠٥٢ | .٤٦٢ | .٦٠٥ | .٩٥٦ | ٢.٦٤٢ |
| ٥ | ٢.٣٣ | ---- | ---- | ---- | .٥٠٦ | .٥٧٧ | .٩٥٥ | ٢.٦٥١ |

Where:

**C.C**=coefficient of correlation.

**S.E**=standard error.

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## ٥.١ Conclusions:

Based on the tests results of the present study on the influence of water to powder ratio, time of calcening metakaolin and curing conditions on some mechanical properties of SCC, the following conclusions can be drawn:-

١. With the carefull in proportioning and mixing, SCC can be produced with locally availble materials without any inner or outer vibration in order to fill all the concrete body.

٢. The water to powder ratio has a small effect on the workability. It can be seen that increasing the W/P ratio from (٣٠ to ٦٢) % increases the slump-flow by ١٢ % and decrease the T٥٠ cm by ٤٠ %.

٣. The limestone powder SCC have higher flowability compared to metakaolin type (I, II and III) SCC by (٠.٨-٢.٨) %, (١.٢-٣.٩) % and (١.٨-٥.٠) %, and lower T٥٠ cm by (٢-٩) %, (١٢.٧-١٦) % and (٢٠-٣٠) % respectively.

٤. When the time of calcining metakaolin increases from (٠.٥-١.٥) hrs the slump-flow decreases insignificantly by (٠.٥-٣) % while T٥٠ cm increases by (٣-٢٧.٥) %.

٥. The filling height for the SCC ($U_{١}$-$U_{٢}$) is between (٠-١.٥) cm for all the mixes and it decreases by ٦٠ % while increasing the W/P ratio from ٣٠ % to ٦٢ %.

٦. The blocking ratio ($H_٢/H_١$) ranges between (٠.٨-٠.٩) as measured by L-box test.

٧. The V-funnel time is (٦-١٢.٤) sec. Increasing the W/P ratio by ٣٢ % results to decrease the V-time by ٤٠ %.

٨. All the SCC tests in the fresh state can be done in the laboratory or at job site.

٩. Increasing the W/P ratio from (٠.٤ to ٠.٦٢) results to decrease the compressive strength by (١١.١, ٢٢.٧ and ٢٧) % at ٧, ٢٨ and ٩٠ days respectively.

١٠. Increasing the time of calcining metakaolin from (٠.٥-١.٥) hrs increases the compressive strength by (٧, ١٤.٣ and ١٠.٦) % at ٧, ٢٨ and ٩٠ days respectively.

١١. SCC is more affected by air curing compared to other curing conditions.

١٢. Sprinkle curing is more favorable at low W/P ratio (٠.٥١ and less). The increaments in the compressive strength for specimens with sprinkle curing range (١٠-١٢) %, (٢٣-٢٤) %, (١.٣-١.٦) %, (٢٨.٦-٣٠) %, (٠.٢-٢) % and (٢٩.٣-٣٢) % at ٧, ٢٨ and ٩٠ days respectively as compared to moist and air curing.

١٣. The values of splitting tensile strength range (٤.٣-٥.٩٣) MPa, (٤.٨٦-٦.٦٢) MPa, and (٥.٢٥-٧.٠٠) MPa at ٧, ٢٨ and ٩٠ days respectively.

١٤. The values of flexural strength of the SCC range (٢.٧٢-٦.٩٨) MPa, (٣.٦٤-٧.٧٥) MPa and (٤.٩١-١٠.٠٥) MPa at ٧, ٢٨ and ٩٠ days respectively.

١٥. Specimens in flexure and splitting show similar behavior to those in compressive.

١٦. The ٢٨-days Ec ranges (٣٥.٧١-٤١.١٥) GPa. Increasing the W/P ratio from (٠.٣ to ٠.٤) decreases the Ec by (١.٧-٧.٥) %, while from (٠.٣ to ٠.٥١) decreases the Ec by (٥.٠-٩.٢) %.

١٧. Increasing the time of calcining metakaolin from (٠.٥-١.٥) hrs increases the Ec by (٠.٦-٩.٨) %.

١٨. When the W/P ratio increases from (٠.٤-٠.٦٢) the U.P.V decreases by (٢.٣-٩.٦) %, (٠.٦-١٢.٦) % and (٢-٩.٧) % at ٧, ٢٨ and ٩٠ days respectively.

١٩. The Schmidt rebound hammer test is not favorable to SCC at early ages because of the high softness of the surface.

## ***٥.٢ Recommendations for further researchers:***

١. Further work is required to investigate the use of other reactive filler types rather than that used in this study like rise hask ash, to produce SCC.

٢. Further research projects are rquired to interpret the influence on the hardened properties of SCC more precise as the cement type, aggregate size and bond between matrix and aggregate.

٣. Admixtures where the time for concrete strength grouth can be determined and controlled, especially in hot weather, need to be developed.

٤. Further development of production methods and equipment suitable for handling, treatment and curing of SCC.

٥.

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# RELEVANT STANDARDS

١. **IQS No.٥/١٩٨٤**" Specification for Portland Cements".

٢. **BS ٨٨٢:١٩٩٢**" Specification for Aggregates from Natural Sources for Concrete".

٣. **BS ٨١٢:١٩٩٠**" Methods for Determinaion of Physical Properties".

٤. **ASTM C٤٩٤-٩٢**" Specification for Chemical Admixtures for Concrete".

٥. **BS ٥٣٢٨:٤:٩٠**" Specification for the Procedures to be Used in Sampling, Testing and Assessing Compliance of Concrete".

٦. **BS ٨٥٠٠:٢:٤.٤**" Additional Requirements For Limestone Powder and Metakaolin Powder For Concrete".

٧. **BS ١٨٨١:١١٦:٨٣**" Method for Determination of Compressive Strength of Concrete Cubes".

٨. **BS ١٨٨١:١١٧:٨٣**" Method for Determination of Tensile Splitting Strength ".

٩. **BS ١٨٨١:١١٨:٨٣**" Method for Determination of Flexural Strength ".

١٠. **BS ١٨٨١:١٢١:٨٣**" Method for Determination of the Static Modulus of Elasticity in Compression".

١١. **BS ١٨٨١:٢٠٢:٨٦**" Recommendations for Surface Hardness Testing By Rebound Hammer".

١٢. **BS** ١٨٨١:٢٠٣:٨٦" Recommendations for Measurement of Velocity of Ultra-sonic Pulse of Concrete".