

# **IMPACT AND ABRASION RESISTANCE OF FLAX AND STEEL FIBER REINFORCED CONCRETE**

*A Thesis*

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of the University of Babylon in Partial  
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# مقاومة الصدم والتآكل السطحي للخرسانة المسلحة بألياف الكتان والحديد

مرسالة

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

من قبل

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## الخلاصة

يتضمن هذا البحث دراسة مختبرية حول مقاومة الصدم ومقاومة التآكل السطحي للخرسانة المسلحة بالالياف الحديدية واخرى مسلحة بمخلفات الياف الكتان. تم قياس مقاومة الصدم باستعمال فحص عملي موصى به من قبل لجنة معهد الخرسانة الامريكي المرقمة ٥٤٤ . تم ايجاد مقاومة التآكل السطحي باتباع الطريقة المبسطة والقياسية المشار اليها في المواصفة الالمانية DIN ٥٢١٠٨. ويتناول البحث ايضا دراسة الخواص الميكانيكية الاخرى والمتضمنة مقاومة الانضغاط ومقاومة الشد الانشطاري ومعايير التصدع. المتغيرات التي اعتمدت في هذه الدراسة هي نوع الالياف وكمية الالياف ومقاومة الانضغاط للخرسانة وعمر النماذج. اضيفت الالياف الحديدية ومخلفات الياف الكتان بنسب حجمية مختلفة وصلت إلى ١% و ٤% على التوالي.

اشارت نتائج الفحوصات بأن زيادة النسبة الحجمية لكلا النوعين من الالياف يؤدي إلى زيادة في مقاومة التآكل السطحي للخرسانة. إن إضافة ١% من الالياف الحديدية المتعرجة و ٤% من مخلفات الياف الكتان يؤدي إلى تحسن مقاومة التآكل السطحي بمقدار أقصاه ٣٦.٤% و ١٧.٤% على التوالي. تتناسب مقاومة السطح للتآكل المقاسة بواسطة عمق التآكل للخرسانة المسلحة بالالياف مع الخواص الميكانيكية الاخرى (مقاومة الانضغاط ومقاومة الشد الانشطاري ومعايير التصدع).

اظهرت الخرسانة المسلحة بالالياف التي تم تناولها في هذا البحث مقاومة صدم متفوقة مقارنة بالخرسانة العادية. تزداد هذه الخاصية بزيادة كمية الالياف المضافة. عند مقارنة القيم الفعلية تم التوصل إلى ان مقاومة الصدم للخرسانة الحاوية على نسبة ٤% من مخلفات الياف الكتان هي مقاربة أو أعلى منها لتلك الحاوية على ١% من الالياف الحديدية المتعرجة. تزداد مقاومة الصدم بزيادة مقاومة الانضغاط للمادة المألثة لنفس النسبة الحجمية من الالياف الحديدية وإلى حد معين ثم تبدأ بعده بالنقصان. تزداد قابلية امتصاص طاقة الصدم للخرسانة المسلحة بمخلفات الياف الكتان عند زيادة كل من مقاومة انضغاط المادة المألثة والعمر.

لقد بين تحليل نتائج الفحوصات المختبرية بأن مقاومة الانضغاط ومقاومة الشد الانشطاري ومعايير التصدع تتحسن بوجود الالياف الحديدية المتعرجة ولكنها لا تتأثر كثيرا بإضافة مخلفات الياف الكتان.

ز

رَفَعُ دَرَجَاتٍ مِّنْ شَاءُ وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ

صدق الله العظيم

سورة يوسف ، الآية ٧٦

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٢٠٠٢

# A BSTRACT

An experimental study was conducted to investigate the impact and surface abrasion resistance of concrete reinforced with steel fibers (SFRC) and waste flax fibers (WFFRC). The impact strength was measured by using a simple, portable and practical drop-weight test recommended by the ACI Committee 083. The abrasion resistance was determined according to a simple and standard test procedure outlined in DIN 02108. Other mechanical properties including compressive strength, splitting tensile strength and modulus of rupture were also examined. Variables incorporated in this research were fiber type, fiber content, compressive strength and age of testing. Steel fibers and waste flax fibers were added to concrete in various volume fractions of up to 1 and 3% respectively.

Test results indicate that increasing the percentage of both types of fibers leads to increase abrasion resistance of concrete. Addition of 1% crimped steel fibers and 3% waste flax fibers increase the abrasion resistance by a maximum of 36.3 and 17.3% respectively. The surface property (depth of wear) of fiber reinforced concrete is directly related to the bulk characteristics (compressive strength, splitting tensile strength and modulus of rupture).

The fiber reinforced concrete (FRC) investigated is superior in impact strength to the plain control concrete. This property increases as the amount of fibers addition is increased. When the observed values are compared, the 3% volume fraction of waste flax fibers can produce impact strength comparable or higher than that obtained at 1% crimped steel fibers. For a given steel fiber content, the impact strength increases with matrix

compressive strength up to a certain limit beyond which it starts to decrease. The capacity of WFFRC to absorb impact energy enhances as the compressive strength of the matrix and the age increase.

The analysis of the test results also shows that compressive strength, splitting tensile strength and modulus of rupture are improved by including crimped steel fibers, but insignificantly influenced by waste flax fibers.



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## **L**IST OF NOTATIONS

<b>SYMBOL</b>	<b>DESCRIPTION</b>
$A$	Contact surface area of the specimen.
$A_{s, max}$	Maximum aspect ratio of the fiber.
$A_{s, min}$	Minimum aspect ratio of the fiber.
$c$	A factor represents the effect of Poisson's ratio of fiber and matrix on the laws of mixtures.
$DOW$	Depth of wear.
$d$	Diameter of fiber.
$E_c, E_f, E_m$	Elastic modulus of composite, fiber, matrix.
$E_{CT}$	Compression toughness energy.
$E_{FT}$	Flexural toughness energy.
$E_I$	Impact energy.
$E_{, .}$	Impact energy of plain concrete.
$F_{cu}$	Compressive strength.

$F_{cus}, F_{cuw}$	Compressive strength of steel fiber reinforced concrete, waste flax fiber reinforced concrete.
$F_r$	Modulus of rupture.
$F_{rs}, F_{rw}$	Modulus of rupture of steel fiber reinforced concrete, waste flax fiber reinforced concrete.
$F_{sp}$	Splitting tensile strength.
$F_{sps}, F_{spw}$	Splitting tensile strength of steel fiber reinforced concrete, waste flax fiber reinforced concrete.
$FRC$	Fiber reinforced concrete.
$I_{fs}, I_{fw}$	Impact resistance at failure of steel fiber reinforced concrete, waste flax fiber reinforced concrete.
$I_{vs}, I_{vw}$	Impact resistance at first visible crack of steel fiber reinforced concrete, waste flax fiber reinforced concrete.

<b>SYMBOL</b>	<b>DESCRIPTION</b>
---------------	--------------------

$l$	Length of fiber.
$l_c$	Critical length of fiber.
$M$	Mass of the drop hammer.
$N$	Number of blows to produce failure.
$p$	Percent reinforcement.
$s$	Average fiber spacing.
$SFRC$	Steel fiber reinforced concrete.
$V_f, V_m$	Volume fraction of fiber, matrix.
$V_f(crit)$	Critical fiber volume.
$V_{fs}, V_{fw}$	Volume fraction of steel fiber, waste flax fiber.
$V_I$	Impact speed.
$WFFRC$	Waste flax fiber reinforced concrete.
$\Delta_m$	Reduction in mass after 12 min. abrasion period.
$\epsilon_c, \epsilon_f, \epsilon_m$	Strain in composite, fiber, matrix.
$\epsilon_{mu}$	Matrix cracking strain.

$\eta_1$	Orientation efficiency factor.
$\eta_2$	Length efficiency factor.
$\rho$	Density of the specimen.
$\sigma_c, \sigma_f, \sigma_m$	Stress in composite, fiber, matrix.
$\sigma_{fu}$	Matrix failure stress of fully bonded fibers, or pull out stress of debonded fibers.
$\sigma_{mu}$	Matrix cracking stress.
$\sigma_t$	Tensile strength of the composite.
$\tau$	Average sliding friction bond stress between fiber and matrix.

*Note: Other symbols are defined as they appear in the text.*

# CERTIFICATION

We certify that we have read this thesis, titled (**Impact and Abrasion Resistance of Flax and Steel Fiber Reinforced Concrete**), and as examining committee examined the student **Ali Hassoon Nahhab Al-Khafaji** in its contents and in what is connected with it, and that in our opinion it meets the standard of thesis for the Degree of Master of Science in Civil Engineering (Construction Materials).

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# APPENDIX



**Table (A.1): Physical properties of the cement**

Physical Properties	Test results	IOS ٥: ١٩٨٤ <sup>(٧٤)</sup> Limits
Fineness, Blaine, cm <sup>٣</sup> /gm	٣٠٦٠	≥ ٢٣٠٠
Setting time, Vicat's method		
Initial hrs: min.	١:٥٤	≥ ١:٠٠
Final hrs: min.	٣:٣٥	≤ ١:٠٠
Compressive strength of ٧٠.٧ mm cube, MPa		
٣ days	٢٢	≥ ١٥
٧ days	٢٨	≥ ٢٣

Table (A.۲): Chemical composition of the cement

Oxide	(%)	IOS ۵: ۱۹۸۴ <sup>(۷۴)</sup> Limits
CaO	۶۱.۲۶	
SiO <sub>۲</sub>	۲۰.۸۰	
Fe <sub>۲</sub> O <sub>۳</sub>	۳.۲۰	
Al <sub>۲</sub> O <sub>۳</sub>	۶.۱۲	
MgO	۴.۴۰	≤ ۵.۰
SO <sub>۳</sub>	۲.۳۳	≤ ۲.۸
Free lime	۰.۷۶	
L.O.I.	۱.۷۵	
I.R.	۰.۶۱	≤ ۴.۰
		≤ ۱.۵
Compound composition	(%)	IOS ۵: ۱۹۸۴ <sup>(۷۴)</sup> Limits
C <sub>۳</sub> S	۳۵.۸۸	
C <sub>۲</sub> S	۳۲.۵۶	
C <sub>۳</sub> A	۱۰.۸۰	
C <sub>۴</sub> AF	۹.۷۳	
L.S.F.	۰.۸۸	۰.۶۶-۱.۰۲

Table (A.۳): Properties of the sand

Sieve size (mm)	Percent passing	IOS $\xi_0$ : ۱۹۸۴ <sup>(۷۰)</sup> Limits, Zone ۳
۹.۵	۱۰۰	۱۰۰
۴.۷۵	۹۵	۹۰-۱۰۰
۲.۳۶	۹۳	۸۵-۱۰۰
۱.۱۸	۷۹	۷۵-۱۰۰
۰.۶	۶۱	۶۰-۷۹
۰.۳	۲۸	۱۲-۴۰
۰.۱۵	.	۰-۱۰
Properties	Test results	IOS $\xi_0$ : ۱۹۸۴ <sup>(۷۰)</sup> Limits
Sulphate content, SO <sub>r</sub> (%)	۰.۲۷	$\leq ۰.۵$
Specific gravity	۲.۶۰	
Absorption (%)	۱.۶	

**Table (A.4):** Properties of the gravel

Sieve size (mm)	Percent passing	IOS εο : 198ε <sup>(%)</sup> Limits
14.0	100	100
9.0	100	80-100
4.75	16	0-20
2.36	0.9	0-5
Properties	Test results	IOS εο : 198ε <sup>(%)</sup> Limits
Sulphate content, SO <sub>r</sub> (%)	0.08	≤ 0.1
Specific gravity	2.64	
Absorption (%)	0.8	

**Table (A.5):** Technical description of superplasticizer (Melment L10)

Main action	Concrete superplasticizer
Subsidiary effect	Hardening accelerator
Appearance	Clear to slightly milky
Solids in aqueous solution	Approximately 20%
Density	1.1 g/cm <sup>3</sup>
Chloride content	Less than 0.005 %
Sugar content	None
pH value	7-9
Storage life	At least two years

## **CERTIFICATION**

We certify that this thesis titled “**Impact and Abrasion Resistance of Flax and Steel Fiber Reinforced Concrete**”, was prepared by “**Ali Hassoon Nahhab Al-Khafaji**” under our supervision at Babylon University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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# CHAPTER 1

## INTRODUCTION

Concrete is an inherently brittle material with a relatively low tensile strength compared to compressive strength. Reinforcing by randomly distributed short fibers presents an effective approach to the stabilization of the crack system and improving the ductility and tensile strength of concrete. A variety of fibers, including steel, polypropylene, glass and natural fibers have been applied to concrete.

Fiber reinforcement of concrete is one of the most effective ways for improving its resistance to impact, blast, explosion and other forms of short duration dynamic loads. While the toughening mechanism is well understood in this composite under statically applied loads, unfortunately in the case of impact and other dynamic loads, our understanding is far from adequate and continued research is clearly needed<sup>(1,2)</sup>. The root cause of this lack of understanding is the absence of a standardized test technique for conducting impact tests on fiber reinforced concrete (FRC)<sup>(3)</sup>.

A wide range of impact loading tests that are mostly complicated and expensive have been used in practice. However, the results arised from them are not comparable because the test method, specimen size and support conditions used in these tests are arbitrary.

Information about abrasion resistance of FRC is still very limited and contradictory. Also, testing surface abrasion resistance of FRC is extremely difficult with existing methods such as ASTM Test for Abrasion Resistance of Concrete by Sandblasting (C1148) and ASTM Test for Abrasion Resistance of Horizontal Concrete Surfaces (C1191), if realistic and practical results are desired<sup>(r)</sup>. Therefore, this property of FRC need to be measured simply and accurately.

Fiber reinforced concrete can be an alternative for the use in slabs on grade, overlays, pavements and other such applications<sup>(s)</sup>. These applications require the concrete to be more resistant to impact and abrasion. In such an environment the concrete is subjected to impact from falling objects, aircraft, or from motor vehicles. It suffers from the abrasive action of pedestrian traffic, loaded steel or rubber wheeled trolleys, and sliding of objects.

The present work was conducted in two phases. In the first phase, the impact and abrasion properties of steel fiber reinforced concrete were investigated and measured by simplified and practical methods. In the second phase, the use of waste flax fibers as a reinforcement in concrete was studied. In both phases a total of 100 specimens were prepared and tested under impact, abrasion, splitting tension, flexure and compression. To undertake the experiments of impact strength, a portable and economical test recommended by ACI Committee 544<sup>(r)</sup> was adopted and used. To perform abrasion resistance tests, the German DIN 52108 standard test method was adopted and used.

Four parameters were taken into account: mix proportion and hence compressive strength, type of fibers, namely, crimped steel fibers and waste flax fibers, volume fraction of fibers, and age of the specimens at test. The following reasons led to propose waste flax fibers in this investigation: (i)

they are a type of natural fibers and can be used in applications where impact damage is likely <sup>(i)</sup>, (ii) they are locally available during reclaiming process of rubber tires, and (iii) they are disposable and thus, no additional cost will be added for concrete construction, in addition to environmental advantages.

The research work presented in this study is given through five chapters. This introduction represents Chapter One.

Chapter Two presents a literature review on the impact and abrasion resistance of concrete. Also it involves fiber reinforcement mechanism and the effect of fibers on some of static and dynamic properties of concrete.

Chapter Three contains the properties of materials used, experimental procedure, specimens preparation and the tests carried out.

Chapter Four includes the results of the experimental work and their discussion.

Chapter Five is devoted to the main conclusions and suggestions for further research.

# CHAPTER 2

## REVIEW OF LITERATURE

### 2.1 Introduction

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

1. Composite material concept.
2. Factors influencing the mechanical properties of FRC.
3. The behavior of plain concrete in impact and abrasion.
4. The influence of fibers on impact resistance, abrasion resistance, compressive strength, splitting tensile strength and flexural strength of concrete.

### 2.2 Composite Material Concept

The term “composite material” refers to the product made by combining two or more components of different physical characteristics in order to obtain a material having certain desired properties not available in either of the components alone <sup>(1)</sup>.

FRC is a composite material made of hydraulic cements, fine and coarse aggregates and a dispersion of small fibers. It may also contain pozzolans and admixtures commonly used with conventional concrete <sup>(v)</sup>.

The strength and the elastic modulus of the composite can be theoretically obtained by using a simple elastic theory which can be applied to determine the stress of FRC for uncracked section <sup>(A)</sup>. This theory is commonly called “Laws of Mixtures” and it is based on the following assumptions:

1. The fibers are unidirectionally oriented in the direction of stress.
2. The fibers are fully bonded to the matrix, i.e., equal strains in matrix and fiber.
3. Poisson’s ratio in matrix and fiber is equal to zero.

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad \text{..... (2.1a)}$$

Let volume of composite,  $V_c = 1$

$$\sigma_c = \sigma_f V_f + \sigma_m (1 - V_f) \quad \text{..... (2.1b)}$$

where

$\sigma_c, \sigma_f, \sigma_m$  : stress in composite, fiber, matrix.

$V_f, V_m$  : volume fraction of fiber, matrix.

Since  $\varepsilon_c = \varepsilon_f = \varepsilon_m$

$$\therefore E_c = E_f V_f + E_m V_m \quad \text{..... (2.2a)}$$

$$E_c = E_f V_f + E_m (1 - V_f) \quad \text{..... (2.2b)}$$

where

$\varepsilon_c, \varepsilon_f, \varepsilon_m$  : strain in composite, fiber, matrix.

$E_c, E_f, E_m$  : elastic modulus of composite, fiber, matrix.

The assumptions of the elastic theory are not likely to be real in practice, therefore the Equations (2.1b) and (2.2b) become:

$$\sigma_c = \eta_1 \eta_2 \sigma_f V_f + \sigma_m (1 - V_f) + c \quad \dots\dots\dots (2.3)$$

$$E_c = \eta_1 \eta_2 E_f V_f + E_m (1 - V_f) + c \quad \dots\dots\dots (2.4)$$

where

$\eta_1$  : orientation efficiency factor.

$\eta_2$  : length efficiency factor.

$c$  : a factor represents the effect of Poisson's ratio of fiber and matrix on the laws of mixtures.

## 2.3 Factors Influencing the Mechanical Properties of FRC

The behavior of FRC is affected by many factors including mix design, method of compaction, fiber volume fraction, aspect ratio, spacing, orientation and the critical length of fiber.

### 2.3.1 Mix Design

The mixture of FRC needs no much coarse aggregate to prevent the segregation or balling of fibers. Coarse aggregate larger than 19 mm is not recommended and 9.5 mm is preferable.

Compared to conventional concrete, fiber concrete mixes are generally characterized by higher cement content, higher fine aggregate content and smaller sized coarse aggregate. Thus, conventional procedures of mix design is not likely to be completely applicable and some adjustments may be required<sup>(v)</sup>.

### 2.3.2 Method of Compaction

FRC should be prepared by using external vibration whenever possible. Internal vibration is not desirable and rodding is not acceptable because these methods of compaction probably produce nonuniform distribution of fibers<sup>(ε)</sup>.

**Shaaban and Gesund** <sup>(9)</sup> studied the influence of compaction method of SFRC cylinders on splitting tensile strength. They concluded that external vibration increased the splitting tensile strength by about ۲۰ percent beyond that of rodded specimens. While, they did not notice significant differences in compressive strengths for both concretes.

### ۲.۳.۳ Fiber Volume Fraction

The term “volume fraction” of fibers refers to a ratio of fiber volume to the volume of composite. It is usually expressed as a percentage.

The mechanical properties of the composite material will be improved as the volume fraction of fibers increases. However, when too many fibers are added to a matrix, fibers balling will occur and thus, there is a limit to the volume of fibers beyond which the performance of FRC decreases.

The critical fiber volume can be defined as the minimum volume of fibers which will carry the load after matrix cracking. It can be characterized by the following equations <sup>(۱۰)</sup>:

$$V_f(crit) = \frac{\sigma_{mu}}{\sigma_{fu} - \varepsilon_{mu} E_f + \sigma_{mu}} \quad \dots\dots\dots (۲.۵)$$

where

$V_f(crit)$  : critical fiber volume.

$\sigma_{mu}$  : matrix cracking stress.

$\sigma_{fu}$  : maximum failure stress of fully bonded fibers, or pull out stress of debonded fibers.

$\varepsilon_{mu}$  : matrix cracking strain.

Equation (۲.۵) can also be expressed as:

$$V_f(crit) = \frac{E_c \varepsilon_{mu}}{\sigma_{fu}} \quad \dots\dots\dots (2.6)$$

where

$E_c$  : elastic modulus of composite (defined by Equation (2.2b)).

Critical fiber volume can also be graphically obtained as shown in Fig.(2.1).

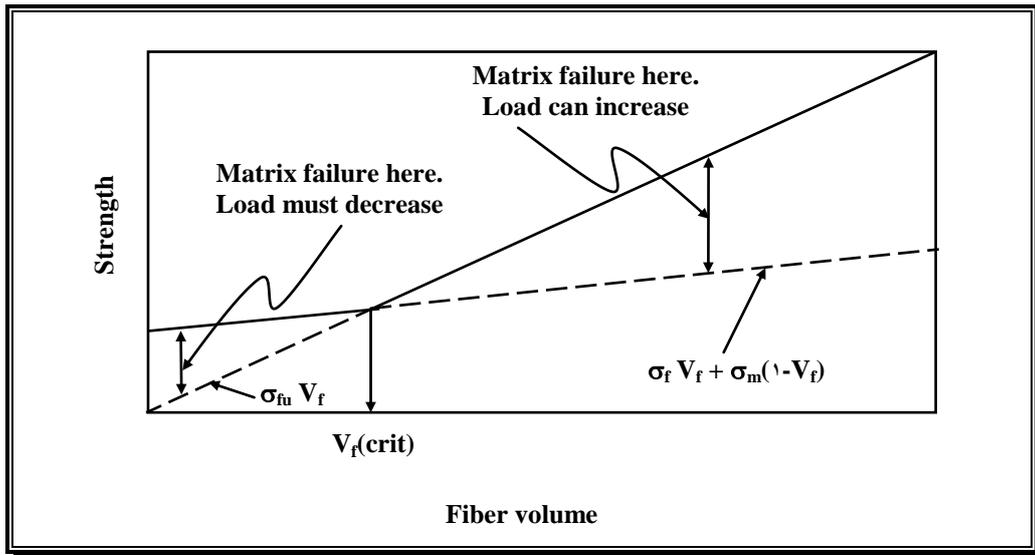


Fig.(2.1): Graphical representation of Equation (2.1b) and the position of critical fiber volume <sup>(4)</sup>

When the volume fraction of fibers is below  $V_f(crit)$ , single fracture of matrix will be expected. While multiple fracture will occur when the volume fraction of fibers exceeds  $V_f(crit)$ .

### 2.3.4 Aspect Ratio of Fiber

Aspect ratio is defined as the fiber length divided by an equivalent diameter. Typical aspect ratios range from about 30 to 100 for length dimensions of 1.5 to 16 mm <sup>(5)</sup>. It is one of the most important parameters governing the behavior of FRC both in fresh and hardened state.

The maximum aspect ratio is that ratio at which the fiber will be fractured instead of being pulled out from the matrix at the instant of

failure<sup>(11)</sup>. It can be obtained by equating the force required to fracture the fiber to that required to pull out it from the matrix.

$$\frac{\pi d^2}{4} \sigma_{fu} = \pi d \tau \frac{l}{4}$$

$$\frac{l}{d} = \frac{\sigma_{fu}}{\tau} = A_{s,max} \quad \dots\dots\dots (2.7)$$

where

- $\sigma_{fu}$  : fracture strength of fiber.
- $\tau$  : average sliding friction bond stress between fiber and matrix.
- $l, d$  : fiber length, fiber diameter.
- $l/\xi$  : average pull out length.
- $A_{s,max}$ : maximum aspect ratio of the fiber.

On the other hand, the minimum aspect ratio is an important parameter for strengthening a flexural member in order to show a post-cracking behavior.

**Hannant**<sup>(11)</sup> reaches to a suitable shape of stress block in flexural member and an expression for the minimum aspect ratio ( $A_{s,min}$ ) for constant volume fraction of fibers ( $V_f$ ) in plane and space orientation.

For plane orientation,

$$A_{s,min} = \frac{8\pi}{39} \cdot \frac{\sigma_t}{\tau} \cdot \frac{1}{V_f} \quad \dots\dots\dots (2.8)$$

For space orientation

$$A_{s,min} = \frac{32}{39} \cdot \frac{\sigma_t}{\tau} \cdot \frac{1}{V_f} \quad \dots\dots\dots (2.9)$$

where

- $A_{s,min}$  : minimum aspect ratio of the fiber.
- $\sigma_t$  : tensile strength of the composite.

### ۲.۳.۵ Fiber Spacing

The average fiber spacing may be obtained either from the number of fibers crossing a unit area of a given plane section through the material or from the distance between the centroids of individual fibers <sup>(۱۲, ۱۳)</sup>.

**Romualdi and Baston** <sup>(۱۴)</sup> noticed a significant improvement in the tensile strength of mortar by using closely spaced fibers as crack arresters.

**Romualdi and Mandel** <sup>(۱۵)</sup> found an expression to determine the average fiber spacing for randomly distributed fibers:

$$s = 13.8d \sqrt{\frac{1}{p}} \quad \dots\dots\dots (۲.۱۰)$$

where

$s$  : average fiber spacing.

$d$  : diameter of fiber.

$p$  : percent reinforcement by volume.

### ۲.۳.۶ Critical Fiber Length

Critical fiber length ( $l_c$ ) is the length at which the tensile stress of fiber reaches to the ultimate value.  $l_c$ , therefore is a function of bond between the fiber and matrix. When the length of fiber ( $l$ ) is below its critical length ( $l_c$ ), the failure of the composite happens due to the fiber pulling out. While in the case of long fibers ( $l > l_c$ ), the failure of FRC is due to the fiber yielding.

The critical fiber length can be determined from the following equation <sup>(۱۶)</sup>:

$$l_c = \frac{\sigma_{fu} \cdot d}{2 \tau} \quad \dots\dots\dots (۲.۱۱)$$

where

$\sigma_{fu}$  : fracture strength of fiber.

$d$  : diameter of fiber.

$\tau$  : average sliding friction bond stress between fiber and matrix.

### 2.3.7 Orientation of Fiber

The effectiveness of fibers incorporated in concrete depends also upon the orientation of fibers in relation to the direction of stress. Many factors may affect the orientation of fibers such as length and diameter of fiber, mixing, placing and compaction.

The fibers contribution to the strength of composite depend on the orientation efficiency factor,  $\eta_1$ .

The value of  $\eta_1$  depends on the method of analysis used. Some typical values of this factor are given in Table (2.1).

**Table (2.1):** Orientation efficiency factors for a given fiber orientation relative to the direction of stress <sup>(\*)</sup>

Fiber orientation	$\eta_1$ according to	
	Cox	Krenchel
1- D aligned	1	1
2- D random in plane	1/3	3/8
3-D random	1/6	1/5

From Table (2.1), it can be expected that the fibers oriented in the direction of stress exhibit the most efficiency in strengthening the FRC.

**Romualdi and Mandel** <sup>(10)</sup> suggested that only 41 percent of the total amount of randomly oriented fiber reinforcement is effective in crack control and post-cracking behavior.

## ۲.۴ Compressive Strength of FRC

**Johanston** <sup>(۱۶)</sup> noticed that the increase in the compressive strength was ۲۰% when ۶% by weight of steel fibers were added. **Ramakrishnan et al.** <sup>(۱۷)</sup> reported the same improvement but with ۱% steel fibers by volume.

**Abdul – Hameed** <sup>(۱۸)</sup> found that as the aspect ratio was increased from ۶۲.۵ to ۱۰۰, the compressive strength decreased for the same volume fraction of steel fibers. He related this to the increase in fiber spacing only. While the presence of fibers balling at a high aspect ratio may be the main cause of such behavior <sup>(۱۹)</sup>.

**Al-Imam** <sup>(۱۹)</sup> reported an increase in compressive strength of about ۲۰% using ۱.۵% crimped steel fibers. On the other hand, **Ali and Al-Shamma** <sup>(۲۰)</sup> noticed that the ۲۸ days compressive strength for ۱% steel fiber content was varied from +۶.۸ to -۷.۹% with respect to plain concrete strength.

**Mansur and Aziz** <sup>(۲۱)</sup> stated that there was no indication of the effect of either the volume fraction or the length of jute fibers on compressive strength of the composite.

## ۲.۵ Flexural Strength of FRC

The increase in modulus of rupture of SFRC over that of ordinary concrete has been established by several investigations.

**Synder and Lankard** <sup>(۲۲)</sup> found that the flexural strength of steel fibrous mortars was influenced by many factors. These included fiber length, fiber diameter, fiber volume, W/C ratio, workability and the degree of consolidation. They reported that the first crack flexural strength of mortars could be increased by three times and ultimate flexural strength by

four times through the use of short (6.4 to 63.0mm), small diameter (0.10 to 0.79mm), steel fibers.

**Al-Ausi** <sup>(22)</sup> found an increase in first crack flexural strength of 6 and 30% with 0.7 and 1% steel fibers respectively and an increase in ultimate strength of 37 and 69% respectively. **Matar** <sup>(24)</sup> reported an increase in ultimate flexural strength at 28 days ranging from 18.7 and 30.6% due to the addition of 0.70 and 1.0% steel fibers respectively.

**Soroushian et al.** <sup>(20)</sup> observed that the inclusion of cellulose fibers in matrices improved the flexural strength of the specimens.

## 2.6 Splitting Tensile Strength of FRC

The test results generated from **Shaaban** and **Gesund** <sup>(9)</sup> indicated that the split-cylinder tensile strength of SFRC was proportional to the amount of fibers up to the investigated limit ( $V_f=2.4\%$ ).

**Rasheed** <sup>(26)</sup> observed that the splitting tensile strength of concrete was increased by 01.0 and 81.6% with the addition of 1% duoform steel fibers of aspect ratios 133 and 100 respectively.

## 2.7 Abrasion Resistance of Plain Concrete and FRC

The abrasion resistance of concrete is defined by the ACI Committee 201 <sup>(27)</sup> as the ability of surface to resist being worn away by rubbing and friction. Concrete may suffer from the abrasive action of: (1) foot traffic and skidding, scraping and sliding of objects (2) heavy trucking and cars (3) abrasive materials carried by waters and cavitation forces.

Abrasion resistance is not a bulk property such as strength but is a surface property that depends mainly on surface layer characteristics.

There are several types of standard abrasion test methods published by the American Society of Testing and Materials (ASTM). They include:

1. ASTM C418, “Standard Test Method for Abrasion Resistance of Concrete by Sand Blasting”; which simulates the wear condition in hydraulic structures subjected to abrasive materials<sup>(21)</sup>;
2. ASTM C779, “Standard for Assessing the Abrasion Resistance of Horizontal concrete Surface, Procedure A, Revolving Disks”; which imitates rubbing, grinding, scuffing and sliding wear mechanisms<sup>(22)</sup>;
3. ASTM C779, “Standard for Assessing the Abrasion Resistance of Horizontal Concrete Surface, Procedure B, Dressing Wheel” ; with testing apparatus producing high – impact stress by rolling, impact and cutting action prevalent in heavy industrial environments<sup>(23)</sup>;
4. ASTM C779, “Standard for Assessing the Abrasion Resistance of Horizontal Concrete Surface, Procedure C, Ball Bearing”; Simulating very severe conditions of wear such as steel-wheeled trolleys and actual traffic load in pavement applications<sup>(24)</sup>; and
5. ASTM C944, “Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating Cutter Method”; intended to imitate cutting, sliding and impact wear mechanism<sup>(25)</sup>.

Testing abrasion resistance of FRC with the above ASTM standards is extremely difficult, if realistic and practical results are desired<sup>(26)</sup>.

**Nanni**<sup>(27)</sup> concluded that the selected ball bearing abrasion test (ASTM C779) did not indicate any significant difference between plain concrete and steel or synthetic FRC. The researcher attributed this to that the performed test affected a small area and a small depth.

Currently three versions of abrasion resistance testing techniques are available in England which are slightly different from those listed above<sup>(28, 29)</sup>:

- (a) Aston abrasion tester (AT).
- (b) Cement and Concrete Association abrasion tester (BCAT).
- (c) Chaplin abrasion tester (CT).

Aston abrasion tester consists, basically, of a rotating plate carrying three case-hardened steel wheels. The plate is connected to a shaft, driven by electric motor so that the wheels abrade a circular path over the concrete surface. This path is 20 mm wide, and its depth is measured with a depth gauge after a standardized test period of 10 minutes, to determine the extent of abrasion. A dead load of 40 kg is placed around the machine as a lead collar. The other two abrasion testers are very similar to the Aston abrasion tester.

In Germany, a standard test method (DIN 52108), “Testing the Abrasive Wear of Inorganic Non-Metallic Materials Using the Böhme Disk Abrader”, is available<sup>(34)</sup>. This method was adopted in the present investigation.

It is generally agreed that the abrasion test methods are used for evaluations of relative quality and are not intended for the measurement of expected life of a particular surface<sup>(35)</sup>.

### 2.2.1 Abrasion Resistance of Plain Concrete

It has been recognized that cement content, W/C ratio, type of finish and curing affect the properties of concrete surface layer. Since these parameters also influence the concrete compressive strength, there is a tendency to accept concrete strength as a guide for abrasion resistance evaluation. Unfortunately, however, it has been shown that variations in surface finish (**Ytterberg**)<sup>(36)</sup>, curing method (**Nanni**)<sup>(37)</sup>, or in testing conditions, i.e., air – dry versus wet (**Ghafoori and Sukandar**)<sup>(38)</sup>, have a much greater influence on surface resistance than strength.

**Carrasquillo** <sup>(38)</sup> stated that the resistance to abrasion of concrete containing class C fly ash was greater than that of concrete containing class F fly ash or no fly ash.

Abrasion resistance of plain concrete has been studied also by various other investigators. Their results can be summarized as follows:

- Abrasion resistance of concrete increases with the increase in cement content, compressive strength, unit weight and the decrease in W/C ratio (**Liu** <sup>(39)</sup>, **Sadegzadeh et al.** <sup>(40)</sup>, **Ozturan** and **Kocataskin** <sup>(41)</sup>, **Gjørv et al.** <sup>(42)</sup>).
- Concrete becomes more resistant to abrasion as the aggregate used is harder, better abraded and more resistant to abrasion (**Liu** <sup>(39)</sup>, **Pedersen** <sup>(43)</sup>).
- Surface hardeners, liquid or dry – shake, are found to improve the resistance of concrete to abrasive action (**Ytterberg** <sup>(36)</sup>, **Sadegzadeh** and **Kettle** <sup>(44)</sup>).

### 2.2.2 Abrasion Resistance of FRC

Published data is rare and recent for abrasion resistance of FRC<sup>(45,46,47)</sup>.

**Liu** and **McDonald** <sup>(48)</sup> developed testing method to evaluate the resistance of concrete to the abrasive action of water borne particles in stilling basin. The apparatus consisted of essentially a drill press, agitation paddle, a cylindrical steel container that houses a disk-shaped concrete specimens, and 10 steel grinding balls of various sizes. The water in the container was circulated by immersed agitation paddle that was powered by the drill press rotating at approximately 1200 rpm. The circulating water, in turn, moved the abrasive charges (steel grinding balls) on the surface of the concrete specimen (298 mm diameter × 102 mm high),

producing the desired abrasion effects. They reported that the average 48-hour abrasion –erosion loss of SFRC was approximately 22% higher than that of concrete not containing fibers. The investigators attributed this behavior to two factors:

- (i) FRC has less coarse aggregate content per unit volume than that of the plain concrete.
- (ii) The deterioration of concrete around the fibers was due to the vibration of exposed fibers caused by the water flow and the movement of the abrasive charges in the test environment.

**Eren *et al.*** <sup>(46)</sup> developed abrasion testing machine from a concrete drilling machine. The abrasive action was achieved by using a stone of 12 mm in diameter and 4 mm thick which was glued at the edge of the machine cylinder. At the beginning of the test, the abrasive stone was brought into contact with the surface of the specimen (100 mm diameter × 10 mm thick). The motor was then started and abrasion continued for 40 seconds which was found to be sufficient to produce a significant wear (2mm) of the concrete surface.

Three different parameters, namely, silica fume of two different percentages (0 and 10% by weight of cement), three different types of hooked-end bundles of steel fibers having aspect ratios of 60, 70 and 83 and three different percentages of steel fibers (0.0, 1 and 2% by volume of concrete) were used. It was found that the addition of 2% steel fibers increased abrasion resistance by a maximum of 40, 40 and 47% at 0, 0 and 10% silica fume respectively. The results indicated that the abrasion resistance of concrete increased with the increase in volume fraction of steel fibers.

**Vassou** <sup>(47)</sup> used the Aston abrasion tester to investigate the influence of steel fibers and polypropylene fibers on abrasion resistance of concrete.

Steel fiber content was varied from 0.5% to 3% by volume of the matrix. Polypropylene fiber content was 0.1% by volume. The length of steel fiber was varied from 40 mm to 60 mm to investigate the effect of steel fiber length on abrasion resistance. It was noticed that the fibers generally improved the abrasion resistance. The maximum increase in abrasion resistance was 70 and 86% due to the inclusion of 0.5% steel fibers and 0.1% polypropylene fibers respectively. It was also noticed that the longer steel fibers increased the depth of wear.

## 2.8 Impact Resistance of Plain Concrete and FRC

Impact may be defined as a collision between two bodies which occurs in a short interval of time during which the two bodies exert on each other relatively large forces, called impact loads, which depends on velocity, mass, shape, elastic and plastic properties of the collided bodies<sup>(4)</sup>. Some examples of impact loading are missile and projectile impact, ship collision and pile during driven.

Various techniques have been used to measure the impact resistance of concrete, such as:

1. Free fall drop weight tests (single or repeated impact);
2. Charpy / Izod tests;
3. Explosive tests; and
4. Fracture mechanics tests.

In all of the above test methods there was an attempt to quantify the energy required to achieve failure. However, because both the failure criteria and the physical processes by which failure occurs vary from test to test, comparisons between any of the above tests are very difficult<sup>(4)</sup>.

### 2.1.1 Impact Resistance of Plain Concrete

**Sandhu** <sup>(51)</sup> tested 152 mm concrete cubes under repeated impact by dropping about 44 kg steel hammer from a height of about 91 cm. It was found that the strength of concrete under the impact loading increased with the increase in compressive strength, tensile strength and age of curing. It was also noticed that the resistance to impact reduced significantly with the increase in water content.

**Green** <sup>(51)</sup>, **Hughes** and **Gregory** <sup>(52)</sup> used the ballistic pendulum to study the impact strength of concrete. The test was performed on 100 mm concrete cubes. They observed that the impact strength increased with increasing cement content and compressive strength for concrete made with ordinary portland cement or supersulphate cement.

A drop hammer test had been used by **Hughes** and **Watson** <sup>(52)</sup> to measure the compressive strength, ultimate strain, energy absorption and the modulus of elasticity of 152 mm concrete cubes under the impact loading. Results have shown that the compressive strength of the specimens tested at a rate of strain less than  $\wedge$  / sec. was almost the same as that obtained in static tests. The improvement in strength and modulus of elasticity was clear for higher strain rates.

**Senbetta** <sup>(54)</sup> developed a test to measure the impact resistance of industrial floor materials. He used 5 cm cubes as test specimens and the Los Angeles Machine, traditionally used for testing aggregates, as the test equipment. After each 500 cycles of the drum turning, the mass of each specimen was taken. The test was continued until the drum rotated for a total of 2000 revolutions. The natural log of the mass of material after the given number of cycles was then plotted against the number of cycles. The investigator suggested that the inverse of the slope of a straight line could represent the impact resistance.

**Biscoff and Perry** <sup>(50)</sup> loaded plain concrete cylinders, 100 mm in diameter and 200 mm length in compression at both a slow static rate and higher impact rate. They reported that the compressive strength increased by 50-60% and the energy absorption capacity by 64-118% under the impact loading.

**Banthia et al.** <sup>(49)</sup> suggested the following explanation of the higher impact strength and higher fracture energy at higher stressing rate. It was based on fracture mechanics concepts. The phenomenon of strain rate sensitivity can be explained by combining the classical Griffith theory with the concept of sub-critical crack growth. According to the Griffith theory, failure in brittle materials occurs when a flaw exceeds the critical flaw size for a given stress. According to the concept of sub-critical crack growth, under sustained load a sub-critical flaw may grow until it reaches the critical flaw size and failure will then occur. Thus, if the load is applied very slowly, the sub-critical flaws have time to grow and thus the failure occurs at a lower value of load. However, if the load is applied at a very high rate, there is little or no time available for the growth of sub-critical flaws, and a higher load can be reached by the structural element before failure occurs.

### 2.8.2 Impact Resistance of FRC

One of the major advantages of concrete reinforced with randomly distributed fibers is the improved resistance to impact loads. Unfortunately, however, this property of FRC seems to be the least understood. The main cause of this lack of understanding is the absence of a standard technique for testing FRC under impact loads <sup>(1,2)</sup>.

A number of investigators <sup>(13, 56, 57, 58)</sup> used the drop weight test developed by **Schrader** <sup>(59)</sup> and published by the ACI Committee 544 <sup>(2)</sup> to measure the impact resistance of fiber reinforced cement composites.

Standard equipment used for testing compaction of soil has been used. The  $\phi 100 \times 64$  mm cylindrical specimens were used. The number of blows to first visible crack as well as to failure were recorded.

From the drop weight test results, **Ramakrishnan et al.** <sup>(17)</sup> found that the concrete reinforced with 1.8% hooked steel fibers was 100 and 100% stronger than concrete reinforced with 1% straight steel fibers and plain concrete respectively. **Ramakrishnan et al.** <sup>(16)</sup> also stated that the hooked steel fibers have good ability to absorb impact load, but for shotcrete.

**Morgan** <sup>(15)</sup> reported that the number of blows to first crack at age of 28 days of plain shotcrete and 1% steel fiber shotcrete was ranging from 39 to 111 blows respectively. The number of blows to failure was 41 and 111 blows.

**Swamy and Jojagha** <sup>(14)</sup> found that the impact strength of steel fiber reinforced lightweight concrete increased with the fiber length and aspect ratio. They also noticed that the impact strength of plain concrete and SFRC increased with increasing the compressive strength. They found, however, a limit for plain concrete strength (40 MPa) beyond which the impact resistance had decreased.

**Clifton and Knab** <sup>(11)</sup> suggested a test to determine the impact resistance of concrete subjected to high velocity small projectiles. The depth of the projectile penetration into the concrete made by a special gun was used as a measure of the resistance of concrete to projectile penetration. They found that the type of reinforcement (fibers, expanded metal and rebar grid), did not appear to affect the projectile penetration. They also found that increases in the compressive strength values generally resulted in decreases in the projectile penetration values.

**Suaris** and **Shah** <sup>(11)</sup> used the instrumented impact test to measure some mechanical properties of concrete under the impact loading. The instrumented impact system was of the drop weight type with the hammer and the striker (tup) assembly weighing 1.0 kN. The striker was instrumented with two strain gages which enabled the measurement of the compressive-load interaction between the tup and the specimen during the impact event. A dynamic load cell was used to provide records of the load and energy absorption histories. The energy absorption trace was produced by the integration of the load time trace multiplied by the velocity at impact. The test was applied on the mortar beam specimens of dimensions 38.1 mm wide  $\times$  36.2 mm deep  $\times$  457.2 mm long. The results indicated that the modulus of rupture of mortars and the deflection at peak load increased at high rate of strain. The investigators found that the tensile strength of concrete was more sensitive to strain rate than to its compressive strength. The energy absorbed by concrete reinforced with steel, polypropylene and glass fibers under the impact loading was found to be about 100, 31 and 9 times respectively, that for plain concrete.

**Gopalaratnam** and **Shah** <sup>(12)</sup>, **Naaman** and **Gopalaratnam** <sup>(13)</sup> tests led to similar conclusions in respect of modulus of rupture, energy absorbed and compressive strength of steel fiber reinforced mortar.

**Fattuhi** <sup>(14)</sup> tested concrete slabs (300  $\times$  300  $\times$  60 mm) reinforced with different types of fibers under repeated impact by dropping a 9.1 kg steel ball at the center of the slab. The deflection, which was used as the impact resistance criterion, was measured after different number of blows. He found that the residual deflection of hooked steel fiber reinforced slabs was less than that for polypropylene fiber reinforced slabs.

**Rostasy** and **Hartwich** <sup>(15)</sup>, testing (100  $\times$  100 mm) cylinders in uniaxial compression, observed that the deformation energy of concrete

increased strongly with the amount of steel fiber addition and with the rate of strain.

**Ali et al.** <sup>(16)</sup> tested simply supported concrete slabs (830 × 830 × 70 mm) under the impact load by repeated falling of 9 kg steel ball from a height of 290 cm on the slab center. The number of blows to initial scabbing and to penetrate all the slab thickness were recorded. They reported an increase in the impact resistance of about 46.0 percent at 70 mm slab thickness penetration and 0.0 percent at initial scabbing stage due to the addition of 1% steel fibers.

**Banthia et al.** <sup>(17, 18)</sup> used the instrumented drop weight impact machine to study the impact resistance of fiber reinforced shotcrete. A 63.0 kg hammer was dropped from a height of 0.40 m on a beam (100 × 100 × 300 mm). The contact load developed between the hammer and the shotcrete specimen was measured by a dynamic load cell mounted on the striking end of the hammer, and the beam itself was instrumented with accelerometers to measure its response during the impact event. The contact load time pulse and the accelerometer data were further analyzed to perform a complete dynamic analysis of the event. The output of the test was plotted as impact load-displacement plot and hence the fracture energy was the area under the plot.

In other investigations **Banthia et al.** <sup>(19, 20)</sup> used a similar machine to that described above to study the impact resistance of shotcrete, but the test specimen was a plate (300 × 300 × 100 mm) instead of the beam. The results showed that the fiber reinforced shotcrete was highly sensitive to the rate of loading for beam and plate test specimens. Both flexural strength and fracture energy were enhanced under impact load. A superior performance of steel fibers over the lower modulus polypropylene, polymeric fibers was presented.

**Marar et al.** <sup>(v1)</sup> suggested a repeated impact drop-weight test which was performed on 100 mm (diameter)×100 mm (length) concrete cylinders. The weight of the drop hammer was 13.0 kg and the height of the drop was 0.3 m. It was aimed to produce a relationship between compression toughness and impact energy of high strength SFRC. Toughness was determined from the area under the stress-strain curve in compression. Hooked – end bundles steel fibers with three different  $l/d$  ratio of 60, 75 and 83 were used. The fiber content was varied from 0.5 to 2% by volume. The investigators found that as the fiber content and aspect ratio were increased, both the compression toughness energy and the impact energy increased. They reported the following relationship between compression toughness energy and impact energy for aspect ratios of 60, 75 and 83 respectively:

$$E_{CT}(60) = 1392.8 \ln\left(\frac{E_I}{E_{I0}}\right) + 1185.2 \quad \dots\dots\dots(2.12)$$

$$E_{CT}(75) = 1706.4 \ln\left(\frac{E_I}{E_{I0}}\right) + 1132.2 \quad \dots\dots\dots(2.13)$$

$$E_{CT}(83) = 1735.6 \ln\left(\frac{E_I}{E_{I0}}\right) + 1293.0 \quad \dots\dots\dots(2.14)$$

where

$E_{CT}$  : compression toughness energy (N.m).

$E_I$  : impact energy (N.m).

$E_{I0}$  : impact energy of plain concrete (N.m).

In another research **Marar et al.** <sup>(v2)</sup> used the same impact test summarized above and the same type of fibers to produce a relationship between flexural toughness and impact energy of high strength SFRC. Flexural toughness was calculated as the area under the load-deflection plot. For fiber aspect ratios of 60, 75 and 83, regression analysis was found

to be provided a logarithmic relationship between flexural toughness energy and impact energy as shown below respectively:

$$E_{FT}(60) = 23.748 \ln \left( \frac{E_I}{E_{10}} \right) \quad \dots\dots\dots (2.15)$$

$$E_{FT}(75) = 25.653 \ln \left( \frac{E_I}{E_{10}} \right) \quad \dots\dots\dots (2.16)$$

$$E_{FT}(83) = 29.405 \ln \left( \frac{E_I}{E_{10}} \right) \quad \dots\dots\dots (2.17)$$

where  $E_{FT}$  is flexural toughness energy (N.m).

**Aziz et al.** <sup>(6)</sup> found that the inclusion of jute fibers which are a type of natural fibers (fiber length = 20mm and volume fraction=3%) in a cement paste improved the impact strength by 40%. Similar finding was reported by **Siraskar** and **Kumar** <sup>(7)</sup> in their research work on the impact resistance of coconut and jute fiber reinforced cement composites (Table(2.2)).

**Table(2.2):** Impact strength of various natural fiber reinforced cement composites<sup>(7)</sup>

Concrete type	Impact strength (N.cm/m <sup>3</sup> )		
	7 days	21 days	90 days
Plain concrete	130	2.3	6.8
3% coconut fiber reinforced	473	1148	2.93
3% jute fiber reinforced	270	473	2.20

# CHAPTER 3

## EXPERIMENTAL WORK

### 3.1 Introduction

This chapter is concerned with the properties of materials used, experimental procedure, specimens preparation and the tests carried out.

### 3.2 Materials

#### 3.2.1 Cement

Ordinary portland cement manufactured by the New Cement Plant of Kufa was used throughout this study which was conformed with IOS ١٩٨٤<sup>(٧٤)</sup>. The physical properties and chemical composition of the cement are given in Tables (A.١) and (A.٢).

#### 3.2.2 Fine Aggregate

Al-Akhaidhur well graded natural sand was used. The physical and chemical properties of the sand are listed in Table (A.٣). Its grading conformed with IOS ٤٥: ١٩٨٤<sup>(٧٥)</sup>, Zone ٣.

### 3.2.3 Coarse Aggregate

The gravel used was brought from Al-Nebae area. it was sieved on 9.5 mm sieve to exclude the large size particles in order to obtain good workability and uniform dispersion of fibers throughout the composite. Table (A.4) shows the physical and chemical properties of the gravel. The table also includes the limits specified by IOS 45: 1984<sup>(v)</sup>.

### 3.2.4 Water

Tap water was used in this work for both making and curing the specimens.

### 3.2.5 Superplasticizer

The high – range water – reducing admixtures or superplasticizers available are relatively a new category of chemical admixtures and of considerably higher efficiency than those within the range of normal plasticizers.

In the present work, a commercially marketed superplasticizer Iraqi-admixture known as Melment L10 was used; chemically is sulphonated melamine formaldehyde condensate composition (Type F according to ASTM C494<sup>(v)</sup>). It was used to reduce the water content of some mixes while maintaining workability in order to produce concrete with high compressive strength. The technical description of this admixture is shown in Table (A.5).

### 3.2.6 Fibers

Two types of fibers were used: crimped steel fibers and waste flax fibers. The later fibers were disposable during reclaiming process of rubber tires. The properties of fibers investigated are presented in Table (3.1).

Table (٣.١): Properties of the fibers

Fiber type	Density (kg/m <sup>٣</sup> )	Tensile strength (MPa)	Length (mm)	Diameter (mm)	Aspect ratio
Crimped steel	٧٨٠٠	١٠٠٠	٣٠	٠.٤	٧٥
Waste flax	٨٢٥	٢٦٠-٣٢٠	٢٠-٧٠	٠.٨-١.٠	٢٠.٠-٨٧.٥

### ٣.٣ Mix Proportions

The mix design of FRC is a matter of trial and error and there is no standard procedure which has been agreed upon so far <sup>(٦, ٧٧)</sup>. In addition, the fiber mixes require higher cement and sand contents comparing to the plain mixes and so conventional procedure of mix design is not directly applicable <sup>(٤, ٧)</sup>. Accordingly, the proportioning of mixes was based mainly on previous works <sup>(٧٧, ٧٨)</sup>.

Two basic mixes were used in the experimental work of the present study. The proportions by weight were ١: ٢: ٢ and ١: ١: ٢ (cement: sand: gravel). Superplasticizer was also added to the second mix to produce a third one with less W/C ratio and same workability.

### ٣.٤ Experimental Procedure

#### ٣.٤.١ Optimum Dosage of Superplasticizer

The use of superplasticizer requires a very high degree of control to be exercised over the batching of concrete. Trial mixes were found to be necessary to fix the superplasticizer dosage to the optimum. A concrete mix ١: ١: ٢: ٠.٣٩ (cement: sand: gravel: water by weight) with ٧٠ mm slump was used to examine this dosage. Fig.(٣.١) shows the effect of superplasticizer

content on the reduction in water requirement to produce the same mix workability. It can be seen from this figure that 4% by weight of cement dosage of the admixture is the optimum with the reduction in W/C ratio of 10.4%.

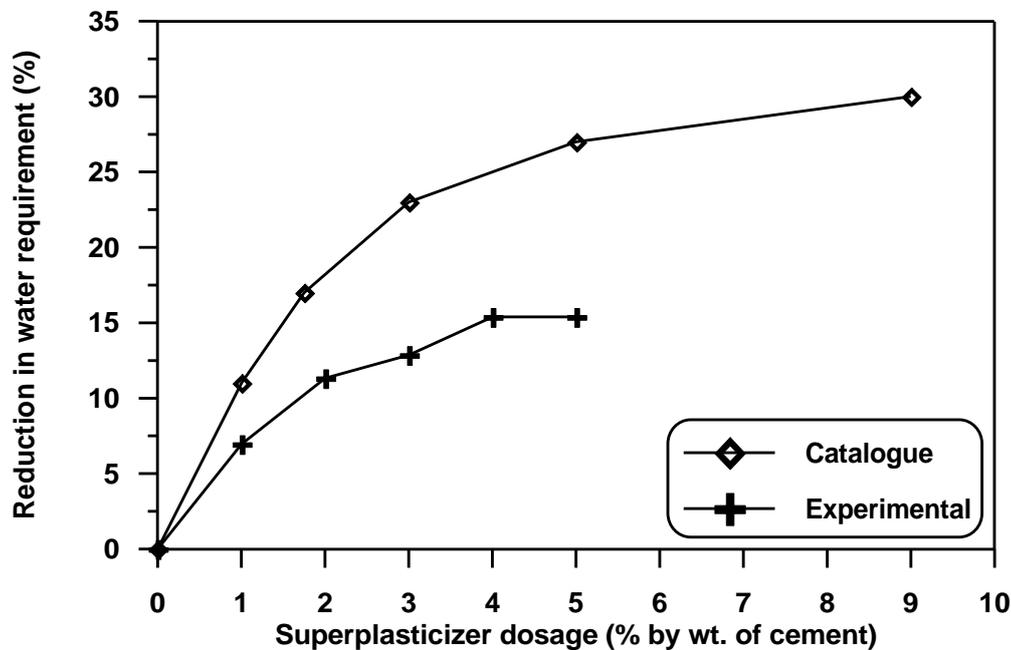


Fig.(3.1): Relation between reduction in water requirement and superplasticizer dosage

### 3.4.2 Concrete Mixes

Normal – strength and medium – strength plain concrete and FRC were investigated. Superplasticizer was also added to the medium – strength mixes in a dosage of 4% to attain the desired water reduction and hence further strength development. The details of the mixes are given in Table (3.2). Concrete mixes, therefore, can be divided into six series according to the strength level and type of fiber.

Twelve crimped steel fiber mixes were made using different fiber concentrations, 0.3, 0.5, 0.7 and 1.0% by volume. Twelve mixes were made with waste flax fiber of 1, 2, 3 and 4% volume percentages. To compare the properties of FRC with plain concrete, six plain concrete mixes were also prepared using the basic mix proportions.

Table (۳.۲): Details of plain concrete and FRC mixes

Series	Mix proportions cement: sand: gravel (by wt.)	W/C (by wt.)	Superplasticizer dosage (% by wt. of cement)	Fiber type	V <sub>f</sub> (%)
ASF	۱:۲:۲	۰.۵۲	۰	No-fiber	۰.۰
				Steel	۰.۳ ۰.۵ ۰.۷ ۱.۰
BSF	۱:۱:۲	۰.۳۹	۰	No-fiber	۰.۰
				Steel	۰.۳ ۰.۵ ۰.۷ ۱.۰
CSFS	۱:۱:۲	۰.۳۳	ε	No-fiber	۰.۰
				Steel	۰.۳ ۰.۵ ۰.۷ ۱.۰
DWF	۱:۲:۲	۰.۵۷	۰	No-fiber	۰.۰
				Waste flax	۱.۰ ۲.۰ ۳.۰ ۴.۰
EWF	۱:۱:۲	۰.۴۳	۰	No-fiber	۰.۰
				Waste flax	۱.۰ ۲.۰ ۳.۰ ۴.۰
FWFS	۱:۱:۲	۰.۳۶	ε	No-fiber	۰.۰
				Waste flax	۱.۰ ۲.۰ ۳.۰ ۴.۰

## ۳.۵ Specimens Preparation

### ۳.۵.۱ Mixing

Conventional and steel fiber concretes were mixed in a horizontal pan-type mixer of ۰.۱ m<sup>۳</sup> capacity. The interior surface of the mixer was cleaned and moistened before it was used. The aggregate and cement were

first mixed dry for 10 sec., then the water or the water with superplasticizer was added and mixed for another 10 sec. The steel fibers were then fed continuously to the mixer for a period of 1 to 1.5 min. depending upon the fiber content, using a 100 mm steel sieve to separate and prevent fiber clumps from entering the mixer.

Attempts of mixing the waste flax fiber concretes in the mixer were failed due to the phenomenon of fibers balling when the fiber content is high, and thus they were manually mixed. The aggregate and cement were first mixed dry. Then the water or the water with superplasticizer was added and mixed until a homogeneous mix was obtained. The waste flax fibers were then added and mixed until a uniform distribution of fibers within the mixture was achieved.

### 3.5.2 Casting

After mixing, the concrete was poured into the moulds and compacted using a vibrating table. The specimens were left for about 10 min. before they were leveled by hand trowelling.

### 3.5.3 Curing and Age of Testing

The moulds of concrete specimens were covered with polyethylene sheets and left in the laboratory for 24 hrs. The specimens were then demoulded carefully and stored in a water tank until 3 days before testing date. The specimens of series ASF, BSF, CSFS and FWFS mixes were tested at ages 28 and 90 days apart from abrasion ones which were tested at ages 30 and 92 days. Series DWF and EWF tests were performed at only 28 days, or 30 days in the case of abrasion tests.

## 3.6 Testing Fresh and Hardened Concrete

### 3.6.1 Slump Test

The slump of fresh mixes was measured according to ASTM C143<sup>(v)</sup> test method.

### 3.6.2 Compressive Strength Test

Compressive strength tests were carried out according to B.S. 1881: Part 116<sup>(vi)</sup>, using a digital testing machine of 2000 kN maximum capacity. Three cubes (150 mm) were tested for each mix at each age for determination of compressive strength. The load was applied without shock and increased continuously at a constant rate.

### 3.6.3 Modulus of Rupture Test

Three points flexure tests were performed on three (100×100×400 mm) prisms with a span of 300 mm using the machine meeting the requirement of ASTM C293<sup>(vii)</sup>.

### 3.6.4 Splitting Tensile Strength Test

The splitting tensile strength was determined according to the procedure outlined in ASTM C496<sup>(viii)</sup>, using (100×200 mm) cylinders. Each strength value is the average of strength of three specimens.

### 3.6.5 Abrasion Resistance Test

The abrasion resistance was determined according to the German DIN 52108<sup>(ix)</sup> standard test method which was applied on 50 mm cubes. The apparatus required for this test are the Böhme disk abrader and the abrasive materials.

The Böhme disk abrader consists mainly of three parts ( Plate (۳.۱)).

۱. An approximately ۷۵ mm diameter rotating disk positioned horizontally with the speed of  $(۳ \pm ۱)$  revolution / min.
۲. A U frame about ۴ mm thickness and ۷۱ mm length of each side to hold the test specimen.
۳. A loading device.

The artificial silica sand was used as the abrasive material. During the abrasion event the sand was allowed to be in contact between the specimen and the rotating disk in order to produce appreciable loss of the specimen thickness.

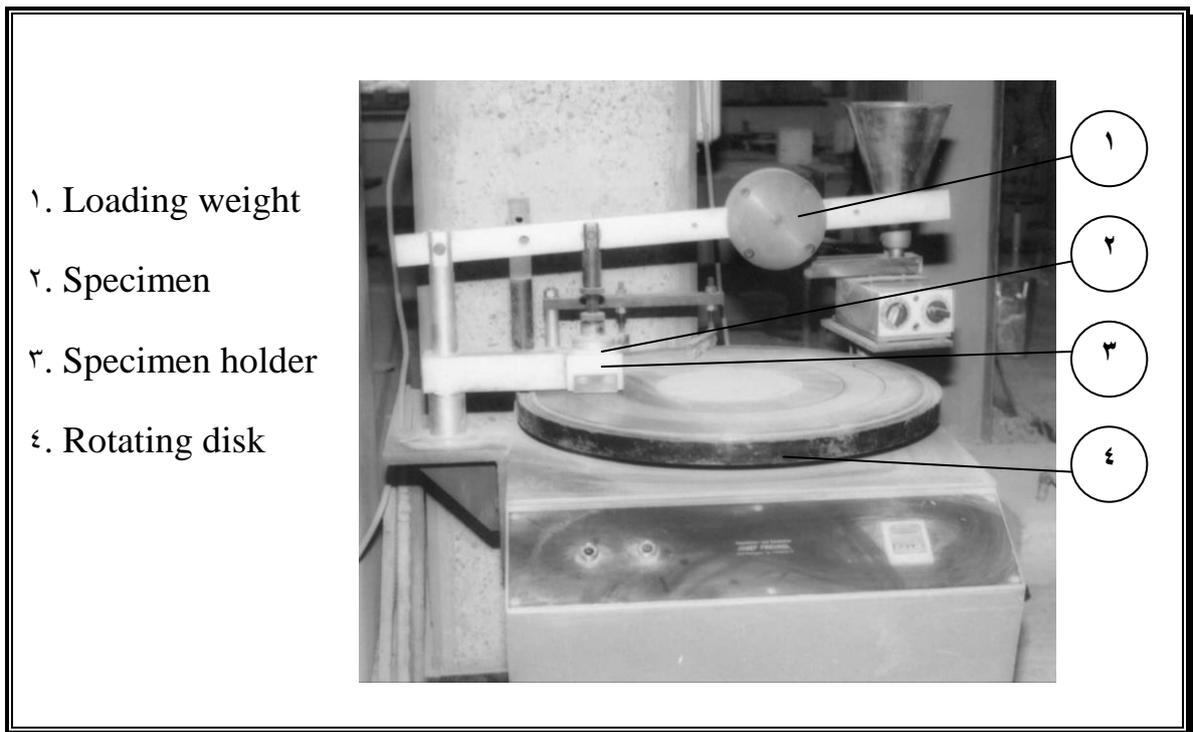


Plate (۳.۱): Abrasion resistance testing machine

### 3.6.5.1 Testing Procedure

Prior to each test, the specimen was weighed to the nearest 0.01 g and measured to the nearest 0.1 mm. It was then placed in the holder and subjected to a standard abrasive load of 294 N. The disk was then rotated and the sand was dropped on the disk taking care that the sand remained evenly distributed over the area which is defined by a width of the specimen. At the end of each 30 sec. abrasion period both the disk and contact face were cleaned. The test was continued for a standard 12 min. period of abrasion. The specimen was then weighed at accuracy of 0.01 g.

The depth of wear was considered as the mean reduction in the specimen thickness, using the following equation:

$$DOW = \frac{\Delta m}{\rho \cdot A} \quad \dots\dots\dots(3.1)$$

where

DOW : depth of wear.

$\Delta m$  : reduction in mass after 12 min. abrasion period.

$\rho$  : density of the specimen.

A : contact surface area of the specimen.

Each value of abrasion or wear depth is the average of test results of three cubes.

### 3.6.6 Impact Resistance Test

A portable and economical impact test published by the ACI Committee 543 (7) was used.

Referring to Plate (۳.۲) and Fig.(۳.۲), the equipment for the drop-weight test consists of three main components:

- i) A ۴.۵۴ kg standard, manually operated compacting hammer with a ۴۵۷ mm drop (ASTM D۱۵۵۷)<sup>(۸۳)</sup>.
- ii) A ۶۳.۵ mm hardened steel ball.
- iii) A manufactured flat base plate with four positioning lugs and a bracket to position the steel ball on top of the test specimen.

Cylindrical steel moulds having the inside dimensions of  $۱۵۰ \phi \times ۶۴$  mm were made to cast the disk specimens.

#### ۳.۶.۶.۱ Testing Procedure

Prior testing, the thickness of the specimen was recorded. The samples were then coated on the bottom with a heavy grease and placed on the base plate within the positioning lugs with the finished face up. The bracket with the cylindrical sleeve was bolted in place and the hardened steel ball placed on the top of the specimen within the bracket. The drop hammer was then placed with its base upon the steel ball and held vertically. The hammer was then dropped repeatedly, and the number of blows required for the first visible crack to form at the top surface and for ultimate failure was recorded. Ultimate failure is defined by the ACI Committee ۵۴۴ in terms of the number of blows required to open the cracks in the specimen sufficiently to enable the fractured pieces to touch three of the four positioning lugs on the base plate.

To carry out the test satisfactorily, the base plate was held rigidly by securing it firmly on about (۶۰۰×۶۰۰×۴۵۰ mm) concrete block. The stage of ultimate failure is clearly recognized by the fractured specimen butting against the lugs on the base plate as shown in Plate (۳.۳).

Three test samples were used for each variable.

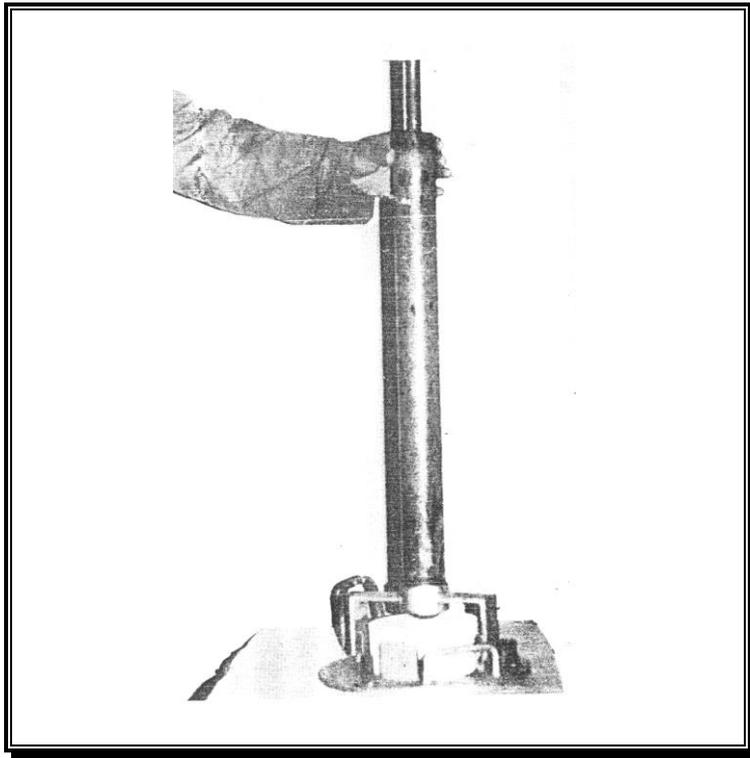


Plate (۳.۲): Impact resistance testing device

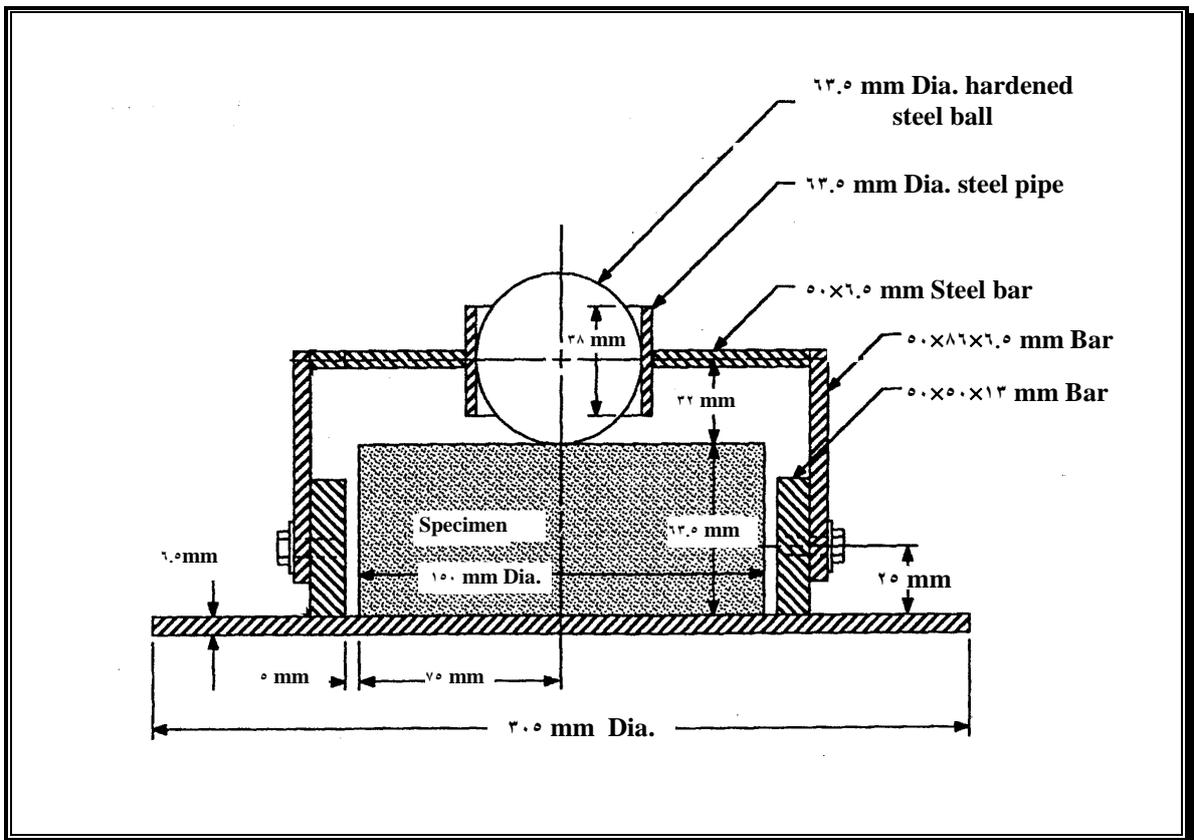
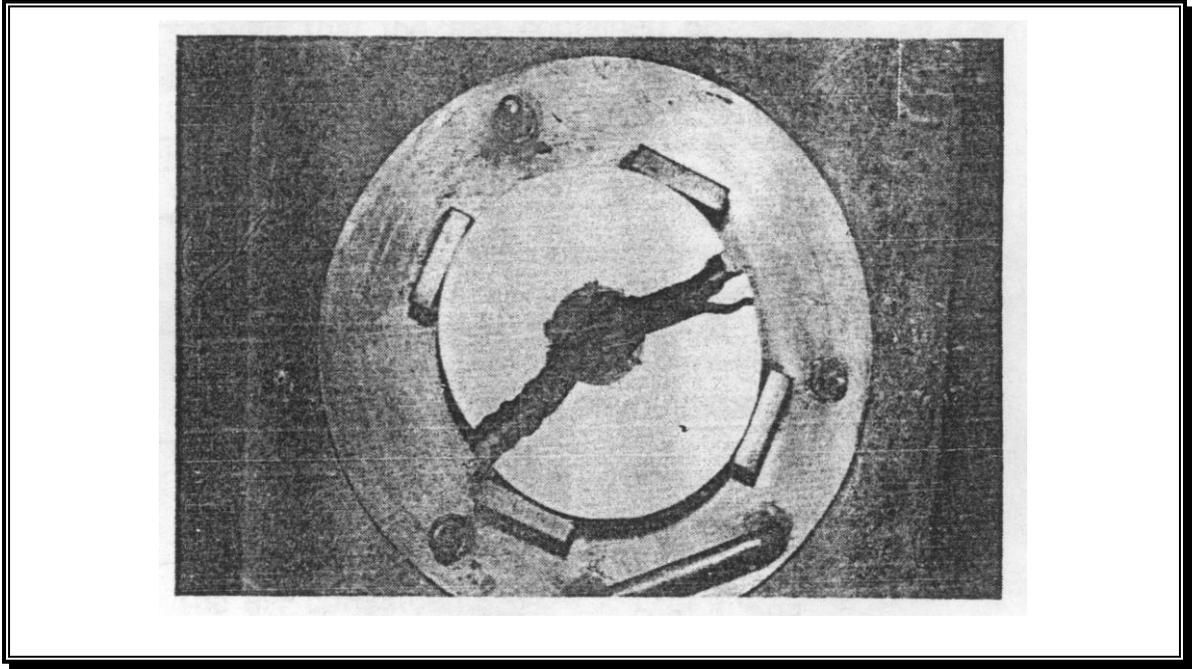


Fig.(۳.۲): Section through test equipment for impact resistance



**Plate (۳.۳):** The fractured test specimen on the base plate

# CHAPTER 4

## RESULTS AND DISCUSSION

### ٤.١ Introduction

This chapter presents the results of the experimental work which was carried out according to the testing program. To condense the data, only the average values are provided in form of tables and figures and then discussed.

### ٤.٢ Slump Test Results

Table (٤.١) summarizes the measured values of slump of plain and fiber concrete mixes. It is obvious from the table that the fresh mix workability is appreciably lowered with increasing the fiber content. This could be related to the large surface area of fibers and also the interparticle friction of fibers and fibers and aggregate.

### ٤.٣ Compressive Strength Test Results

The failure mechanism under compression loading in FRC and the role of fibers in this mechanism is not well understood<sup>(٢٣, ٢٤)</sup>. Compressive strength of concrete is strongly related to density and presence of voids and FRC mixes may have more voids and less density than plain concrete mixes if they are not properly compacted. The compressive strength results of plain concrete and FRC mixes are summarized in Table (٤.٢).

Table (٤.١): Slump of plain and fiber concrete mixes

Series	Mix proportions cement : sand : gravel (by wt.)	W/C (by wt.)	Superplasticizer dosage (% by wt. of cement)	Fiber type	V <sub>f</sub> (%)	Slump (mm)
ASF	١:٢:٢	٠.٥٢	.	No-fiber	٠.٠	٧٠
				Steel	٠.٣	٦٥
					٠.٥	٥٥
					٠.٧	٤٥
					١.٠	٢٠
BSF	١:١:٢	٠.٣٩	.	No-fiber	٠.٠	٦٥
				Steel	٠.٣	٦٠
					٠.٥	٥٠
					٠.٧	٣٥
					١.٠	١٠
CSFS	١:١:٢	٠.٣٣	٤	No-fiber	٠.٠	٧٠
				Steel	٠.٣	٦٥
					٠.٥	٥٠
					٠.٧	٣٥
					١.٠	١٥
DWF	١:٢:٢	٠.٥٧	.	No-fiber	٠.٠	١٦٠
				Waste flax	١.٠	٩٠
					٢.٠	٥٥
					٣.٠	٢٠
					٤.٠	٥
EWF	١:١:٢	٠.٤٣	.	No-fiber	٠.٠	١٦٥
				Waste flax	١.٠	٨٠
					٢.٠	٥٥
					٣.٠	٣٥
					٤.٠	١٠
FWFS	١:١:٢	٠.٣٦	٤	No-fiber	٠.٠	١٦٥
				Waste flax	١.٠	٧٠
					٢.٠	٤٥
					٣.٠	٢٠
					٤.٠	٠

Table (٤.٢): Compressive strength test results

Series	Fiber type	V <sub>f</sub> (%)	Compressive strength (MPa)		Increase in compressive strength (%)	
			٢٨ days	٩٠ days	٢٨ days	٩٠ days
ASF	No-fiber	٠.٠	٢٨.٤	٣٦.٥	-	-
	Steel	٠.٣	٣٠.٥	٣٨.٣	٧.٤	٤.٩
		٠.٥	٣٢.٨	٤٢.٠	١٥.٥	١٥.١
		٠.٧	٣٤.٢	٤٥.٢	٢٠.٤	٢٣.٨
		١.٠	٣٣.٩	٤١.٨	١٩.٤	١٤.٥
BSF	No-fiber	٠.٠	٤٤.٨	٤٩.٦	-	-
	Steel	٠.٣	٤٨.٣	٥١.١	٧.٨	٣.٠
		٠.٥	٤٩.٥	٥٢.٧	١٠.٥	٦.٣
		٠.٧	٥٠.٣	٥٣.٠	١٢.٣	٦.٩
		١.٠	٤٩.٣	٥١.٩	١٠.٠	٤.٦
CSFS	No-fiber	٠.٠	٥٣.١	٥٨.٢	-	-
	Steel	٠.٣	٥٣.٩	٥٩.٧	١.٥	٢.٦
		٠.٥	٥٦.٠	٦١.٣	٥.٥	٥.٣
		٠.٧	٥٧.٦	٦٢.٠	٨.٥	٦.٥
		١.٠	٥٦.٣	٦١.٩	٦.٠	٦.٤
DWF	No-fiber	٠.٠	٢٤.٢	-	-	-
	Waste flax	١.٠	٢٥.٤	-	٥.٠	-
		٢.٠	٢٥.٣	-	٤.٥	-
		٣.٠	٢٤.٩	-	٢.٩	-
		٤.٠	٢٤.٢	-	٠.٠	-
EWF	No-fiber	٠.٠	٣٨.٤	-	-	-
	Waste flax	١.٠	٣٩.٧	-	٣.٤	-
		٢.٠	٣٨.٦	-	٠.٥	-
		٣.٠	٣٨.٢	-	-٠.٥	-
		٤.٠	٣٥.٦	-	-٧.٣	-
FWFS	No-fiber	٠.٠	٤٦.٦	٥٦.٤	-	-
	Waste flax	١.٠	٤٧.١	٥٦.٦	١.١	٠.٤
		٢.٠	٤٧.٠	٥٧.٩	٠.٩	٢.٧
		٣.٠	٤٦.٣	٥٣.٦	-٠.٦	-٥.٠
		٤.٠	٤٥.١	٥١.٩	-٣.٢	-٨.٠

Figs.(4.1) and (4.2) show the variation of compressive strength with volume percentage of steel fibers, for ages 28 and 90 days respectively. It is clear from the figures that the compressive strength increases due to the inclusion of crimped steel fibers, and as the fiber content is increased the compressive strength increases up to a limit beyond which the improvement achieved in strength goes down. This limit is 0.7% volume fraction of fibers for all SFRC mixes. The enhancement in compressive strength of concrete caused by incorporating steel fibers was also previously reported by **Johanston** <sup>(16)</sup>, **Ramakrishnan et al.** <sup>(17)</sup>, **Abdul-Hameed** <sup>(18)</sup> and **Al-Imam** <sup>(19)</sup>.

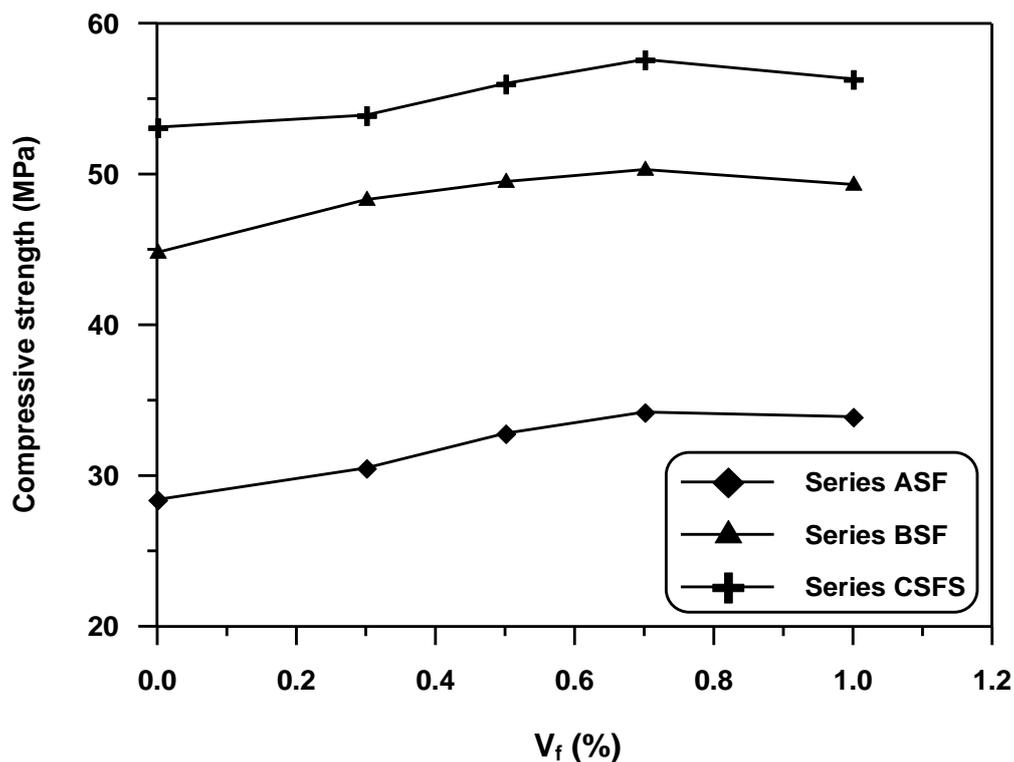


Fig.(4.1): Variation of the 28 days cube compressive strength with volume fraction of steel fibers for different series

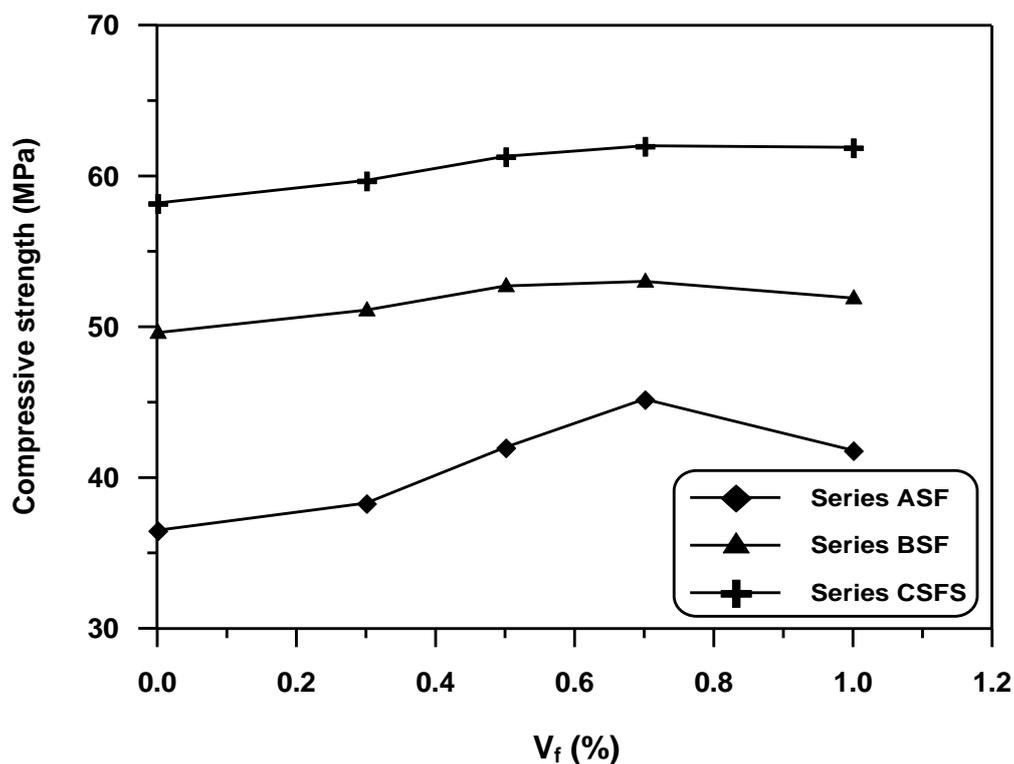


Fig.(4.2): Variation of the 90 days cube compressive strength with volume fraction of steel fibers for different series

The relation between compressive strength and waste flax fiber content is presented in Figs.(4.3) and (4.4). It can be seen that the waste flax fibers do not affect the concrete strength appreciably. The fair reduction in strength at high fiber content mixes is attributed to the reduction in workability of these mixes and the presence of fibers balling during mixing which lead to incomplete compaction and more voids.

It is evident from the results that the effect of using a superplasticizer results in an increase in the strength of plain concrete and FRC with the decrease in W/C ratio.

The presence of steel and waste flax fibers enabled the cubes to keep their integrity even after failure, while plain concrete cubes disintegrated after the maximum load was reached.

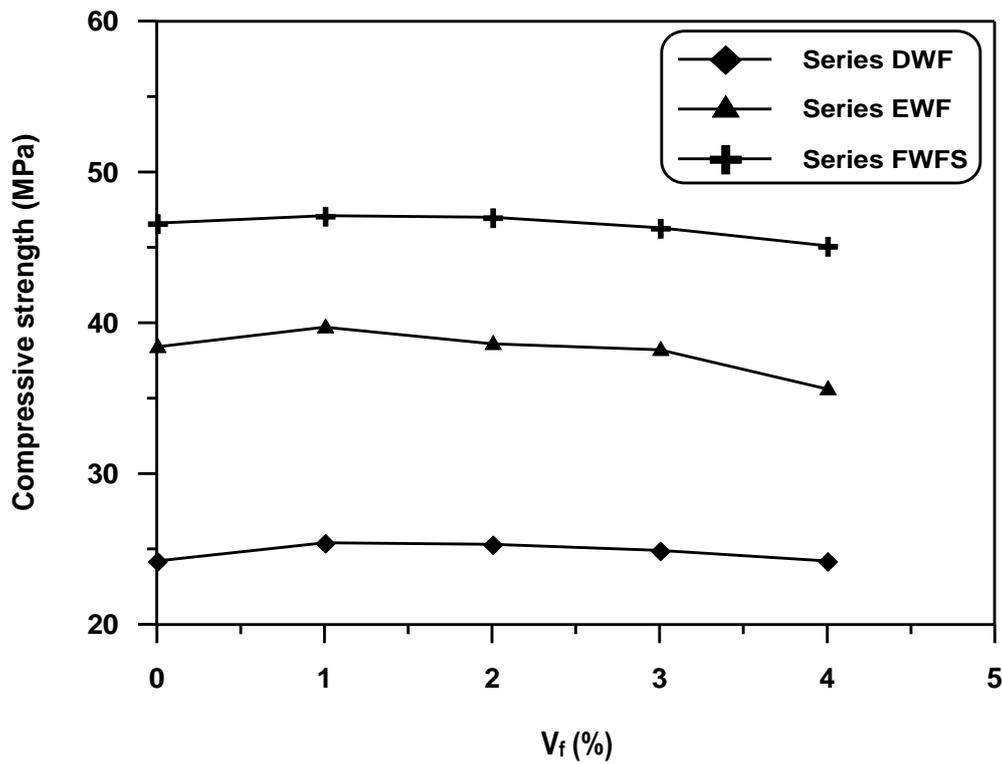


Fig.(4.3): Variation of the 28 days cube compressive strength versus volume percentage of waste flax fibers for different series

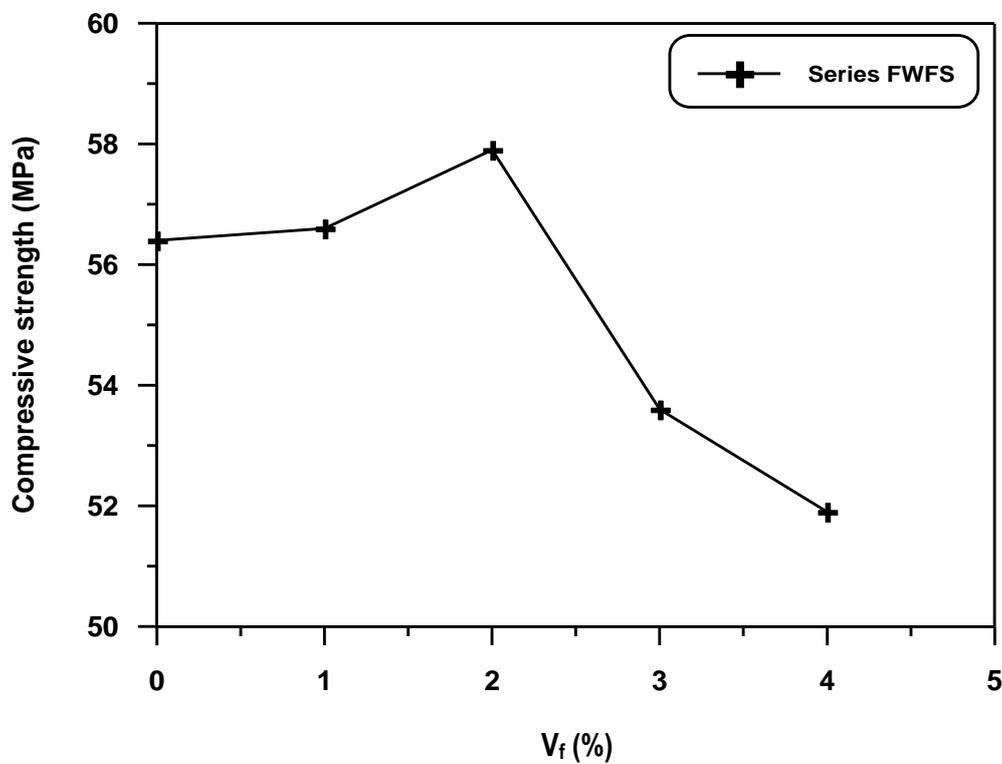


Fig.(4.4): Variation of the 90 days cube compressive strength with volume percentage of waste flax fibers

### ٤.٤ Splitting Tensile Strength Test Results

The values of splitting tensile strength of the specimens considered in the present investigation are abstracted in Table (٤.٣).

**Table (٤.٣):** Splitting tensile strength test results

Series	Fiber type	V <sub>f</sub> (%)	Splitting tensile strength (MPa)		Increase in splitting tensile strength (%)	
			٢٨ days	٩٠ days	٢٨ days	٩٠ days
ASF	No-fiber	٠.٠	٢.٣٢	٢.٨٦	-	-
	Steel	٠.٣	٢.٥٨	٣.٢٠	١١.٢	١١.٩
		٠.٥	٣.٤٦	٣.٨٥	٤٩.١	٣٤.٦
		٠.٧	٣.٨٣	٤.٣٨	٦٥.١	٥٣.١
		١.٠	٤.٠٥	٥.٢١	٧٤.٦	٨٢.٢
BSF	No-fiber	٠.٠	٣.٧٥	٤.٢٠	-	-
	Steel	٠.٣	٤.٣٣	٤.٤١	١٥.٥	٥.٠
		٠.٥	٥.٢٨	٥.٥٦	٤٠.٨	٣٢.٤
		٠.٧	٥.٨٨	٦.١٣	٥٦.٨	٤٦.٠
		١.٠	٦.١٢	٦.٤٦	٦٣.٢	٥٣.٨
CSFS	No-fiber	٠.٠	٤.٤٣	٥.٢١	-	-
	Steel	٠.٣	٤.٨٦	٥.٥٩	٩.٧	٧.٣
		٠.٥	٥.٦١	٦.٥٧	٢٦.٦	٢٦.١
		٠.٧	٦.٠١	٦.٨٤	٣٥.٧	٣١.٣
		١.٠	٦.٢٢	٦.٩٤	٤٠.٤	٣٣.٢
DWF	No-fiber	٠.٠	١.٩٥	-	-	-
	Waste flax	١.٠	٢.٢٠	-	١٢.٨	-
		٢.٠	٢.١٨	-	١١.٨	-
		٣.٠	١.٩٨	-	١.٥	-
		٤.٠	١.٨٧	-	-٤.١	-
EWF	No-fiber	٠.٠	٣.٣٧	-	-	-
	Waste flax	١.٠	٣.٨١	-	١٣.١	-
		٢.٠	٣.٧٦	-	١١.٦	-
		٣.٠	٣.٦٣	-	٧.٧	-
		٤.٠	٣.٢٩	-	-٢.٤	-
FWFS	No-fiber	٠.٠	٣.٩٠	٤.٥٢	-	-
	Waste flax	١.٠	٤.٣٠	٤.٨٠	١٠.٣	٦.٢
		٢.٠	٣.٩٦	٥.٠٨	١.٥	١٢.٤
		٣.٠	٣.٧٧	٤.٥٤	-٣.٣	٠.٤
		٤.٠	٣.٧١	٤.٣٣	-٤.٩	-٤.٢

The influence of steel fiber content on the splitting tensile strength at ages 28 and 90 days is shown in Figs. (4.5) and (4.6) respectively. It is obvious from these figures that the indirect tensile strength increases with increasing the percentage of crimped steel fibers. This clearly confirms that the addition of steel fibers improves the concrete tensile strength which is due to the capacity of fibers to arrest cracks and prevent them from propagating until the composite ultimate stress is reached. The observed increases are anticipated and conformed with the published data <sup>(9, 26, 28)</sup>.

From Table (4.3) it can be seen that the amount of improvement in splitting tensile strength is often higher in series ASF specimens than the other two series of SFRC. For example, at 28 days it is 74.6, 63.2 and 40.4% for series ASF, BSF and CSFS respectively with 1% steel fibers by volume. This may be related to the less coarse aggregate content of series ASF which results a better fiber distribution through the mixtures.

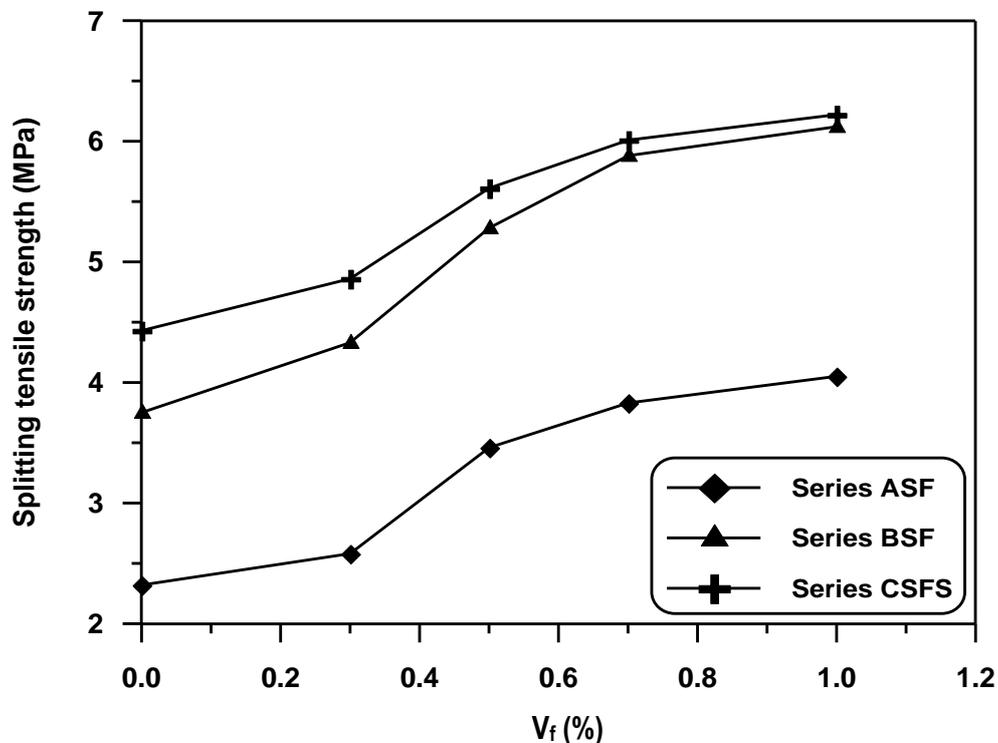


Fig.(4.5): Effect of volume fraction of steel fibers on 28 days splitting tensile strength for different series

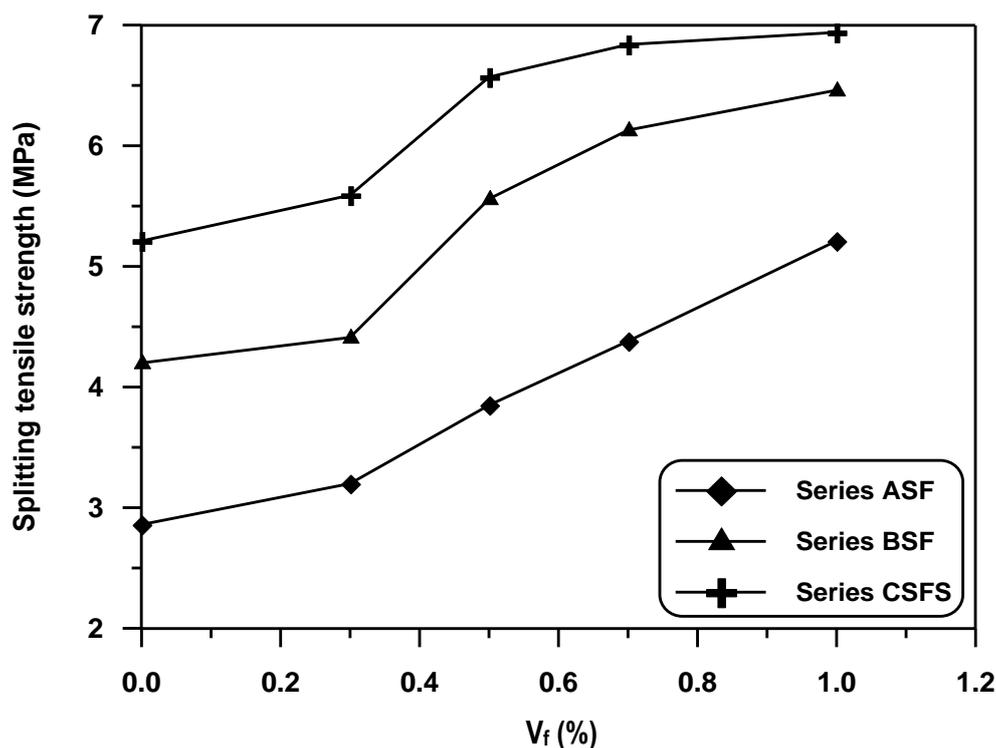


Fig.(4.6): Effect of volume fraction of steel fibers on 90 days splitting tensile strength for different series

When fibers are introduced into concrete they are separated by coarse particles which will be of a larger size than the average fiber spacing. This leads to bunching and greater interaction of fibers between the coarse aggregate particles. This effect becomes more pronounced as the volume of steel fibers and the gravel content are increased<sup>(4)</sup>.

The results plotted in Figs.(4.7) and (4.8) show the variation of splitting tensile strength with volume percentage of waste flax fibers. It can be observed that the inclusion of the waste flax fibers in concrete slightly improves the splitting tensile strength up to a certain point beyond which it starts to drop again. The maximum enhancement generally occurs with the initial inclusion of fiber content, at 1% by volume. The insignificant improvement in the tensile strength of concrete may be attributed to the high flexibility and low aspect ratio of the waste flax fibers. On the other hand, at higher volume fractions, fibers tended to cluster together resulting in an inadequate bond and reduction in strength.

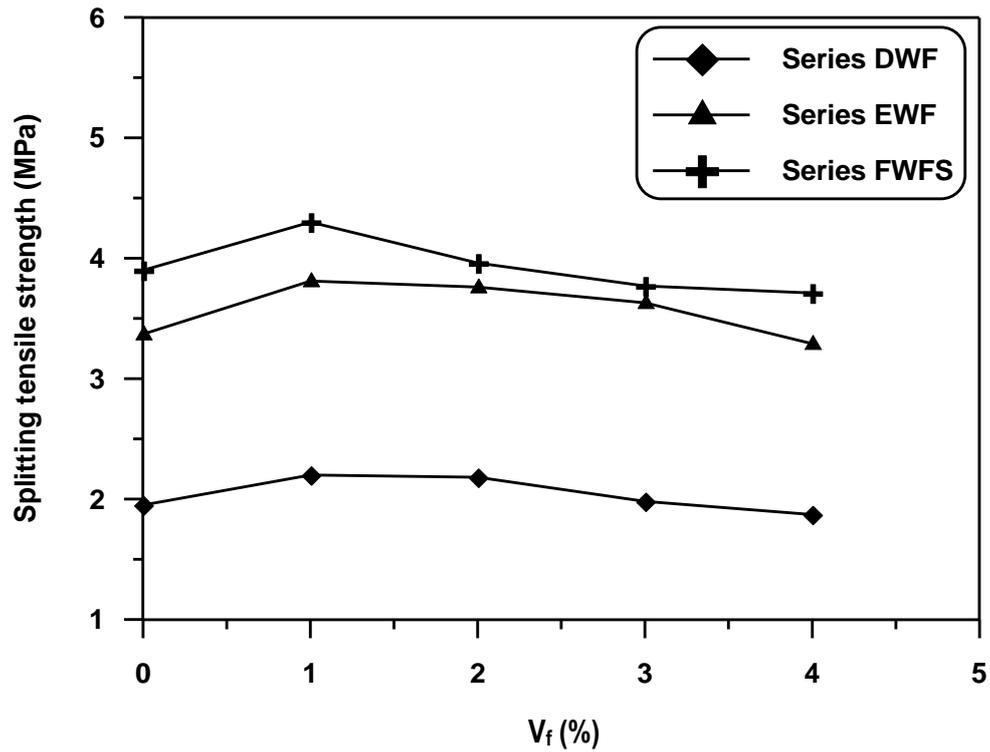


Fig.(4.7): Influence of volume percentage of waste flax fibers on 28 days splitting tensile strength for various series

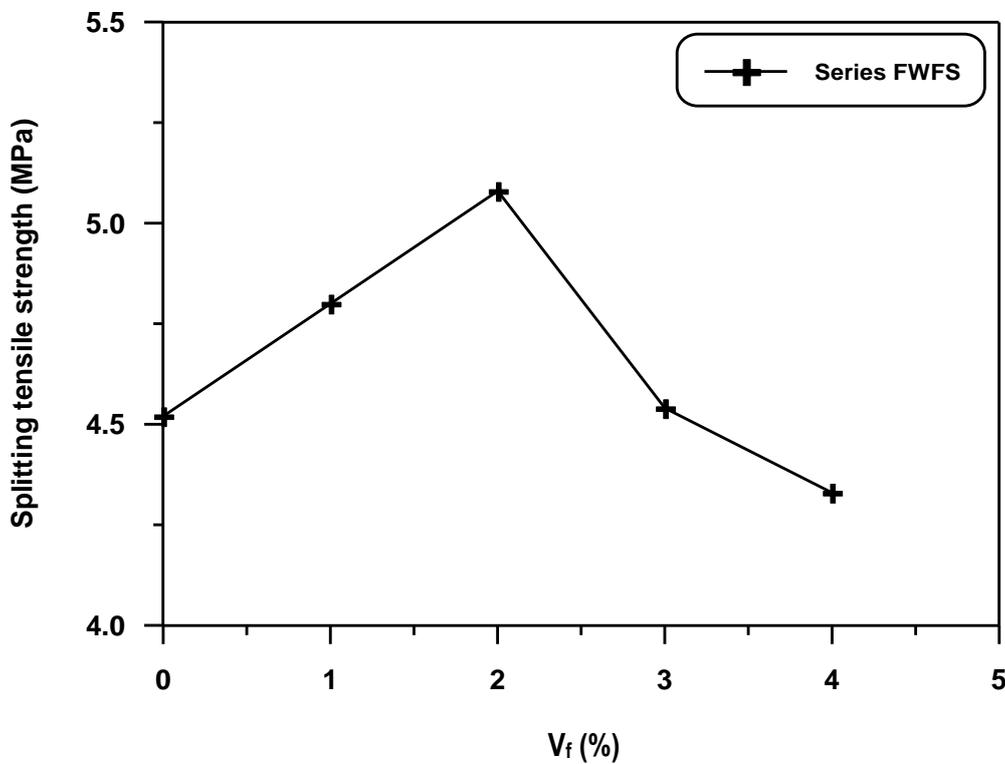


Fig.(4.8): Influence of volume percentage of waste flax fibers on 90 days splitting tensile strength

The increase in splitting tensile strength of waste flax fiber reinforced concrete (WFFRC) beyond the plain concrete is not found to be dependent on the gravel content of mixes. This is due to the little influence of waste flax fibers on concrete tensile strength.

The visual inspection indicated that the plain concrete cylinders failed suddenly and were split into two separate halves. While in SFRC or WFFRC cylinders, the mode of failure varied, the specimens just cracked at failure without any sign of separation.

## 4.5 Modulus of Rupture Test Results

A summary of the data obtained from the modulus of rupture tests is presented in Table (4.4).

The relation between 28 days and 90 days modulus of rupture (flexural strength) of specimens and volume of steel fibers is shown in Figs.(4.9) and (4.10) respectively. The figures clearly show that there is an increase in the flexural strength as the volume fraction of fibers is increased. The reason could be that, the number of fibers that arrest microcracks and delay development of unstable crack system is increased. This note agrees with the conclusions of other authors<sup>(17,22,23,24,25)</sup> that the flexural strength increases linearly with steel fiber content. However, there is a variability in the amount of increase in the published work possibly due to the differences in the geometry, aspect ratio and orientation of fibers; coarse aggregate size and content; and the workability of mixes. This is also true for other mechanical properties of FRC.

Again, as with the splitting tensile strength Table (4.4) indicates that the percentage of improvement in modulus of rupture decreases with the increase in coarse aggregate content.

Table (٤.٤): Modulus of rupture test results

Series	Fiber type	V <sub>f</sub> (%)	Modulus of rupture (MPa)		Increase in modulus of rupture (%)	
			٢٨ days	٩٠ days	٢٨ days	٩٠ days
ASF	No-fiber	٠.٠	٤.٠٤	٤.٥٢	-	-
	Steel	٠.٣	٤.٢٨	٤.٧٨	٥.٩	٥.٨
		٠.٥	٤.٨١	٥.٣٢	١٩.١	١٧.٧
		٠.٧	٥.٥٢	٦.٤٥	٣٦.٦	٤٢.٧
		١.٠	٥.٩٠	٦.٧٢	٤٦.٠	٤٨.٧
BSF	No-fiber	٠.٠	٥.٤١	٦.١٥	-	-
	Steel	٠.٣	٥.٥٠	٦.٢٩	١.٧	٢.٣
		٠.٥	٦.٥٩	٧.٠٢	٢١.٨	١٤.١
		٠.٧	٧.٢١	٧.٧٨	٣٣.٣	٢٦.٥
		١.٠	٧.٦٤	٨.١٣	٤١.٢	٣٢.٢
CSFS	No-fiber	٠.٠	٦.٤٧	٦.٨٨	-	-
	Steel	٠.٣	٦.٧٠	٧.١٢	٣.٦	٣.٥
		٠.٥	٧.٣٦	٧.٩٥	١٣.٨	١٥.٦
		٠.٧	٧.٨٧	٨.٣٥	٢١.٦	٢١.٤
		١.٠	٨.١٢	٨.٧٩	٢٥.٥	٢٧.٨
DWF	No-fiber	٠.٠	٣.٧١	-	-	-
	Waste flax	١.٠	٤.١٠	-	١٠.٥	-
		٢.٠	٤.٠٦	-	٩.٤	-
		٣.٠	٣.٩٥	-	٦.٥	-
		٤.٠	٣.٨٧	-	٤.٣	-
EWF	No-fiber	٠.٠	٥.١٦	-	-	-
	Waste flax	١.٠	٥.٥٨	-	٨.١	-
		٢.٠	٥.٥٢	-	٧.٠	-
		٣.٠	٥.٢٠	-	٠.٨	-
		٤.٠	٥.٠٦	-	-١.٩	-
FWFS	No-fiber	٠.٠	٥.٦٦	٦.٣٤	-	-
	Waste flax	١.٠	٦.١٦	٦.٨٢	٨.٨	٧.٦
		٢.٠	٥.٨٥	٦.٨٠	٣.٤	٧.٣
		٣.٠	٥.٨٢	٦.٣٥	٢.٨	٠.٢
		٤.٠	٥.٣٩	٦.١٢	-٤.٨	-٣.٥

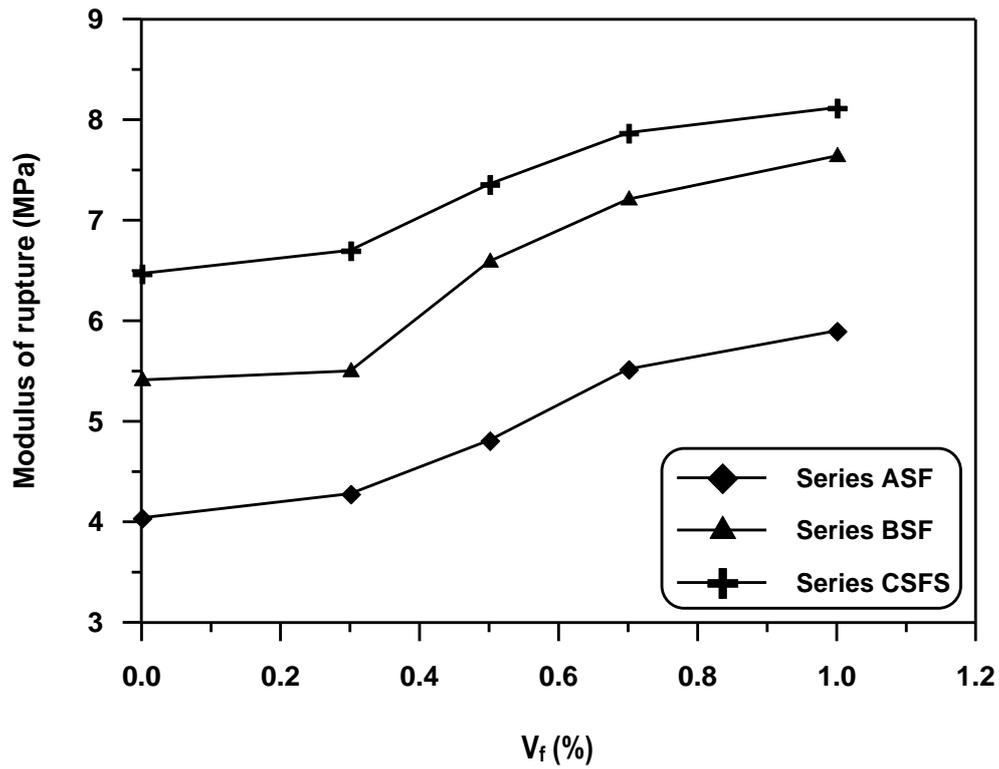


Fig.(4.9): Effect of volume percentage of steel fibers on 28 days modulus of rupture for different series

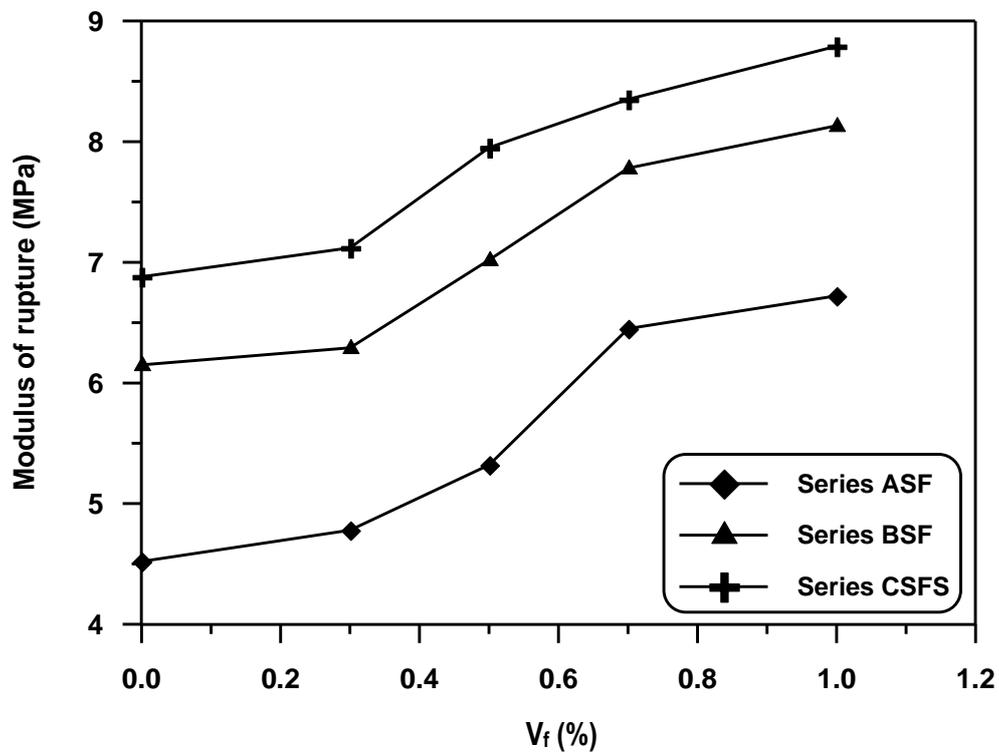


Fig.(4.10): Effect of volume percentage of steel fibers on 90 days modulus of rupture for different series

The trend of modulus of rupture variation with waste flax fiber content is very similar to that of splitting tensile strength as can be seen from Figs.(4.11) and (4.12). there is a moderate change in modulus of rupture by including fibers and so it does not depend on the gravel content of mixes.

The failure of plain concrete prisms was always brittle and the crack passed through the section causing complete collapse. With fiber reinforcement, the specimens merely cracked at failure without separation.

## 4.6 Abrasion Resistance Test Results

One of the most serious durability problems that are experienced in concrete floor is their ability to resist the abrasion forces present in an industrial environment <sup>(32)</sup>. Therefore, the abrasion resistance of plain concrete was studied by many investigators and it was found to be primarily affected by:

1. Compressive strength.
2. Aggregate properties.
3. Finishing methods.
4. Use of toppings and coatings.
5. Curing.

During recent years floor construction methods involving the addition of steel fibers into a concrete mix have become common in England and other some of developed countries <sup>(33)</sup>. However, a detailed literature survey has revealed that only a few researchers (**Liu** and **McDonald**<sup>(34)</sup>, **Eren et al.**<sup>(35)</sup> and **Vassou**<sup>(36)</sup>) have reported experimental work on the abrasion resistance of FRC specimens. The very limited experimental work reported to date has not employed the German standard test method to determine abrasion resistance of FRC.

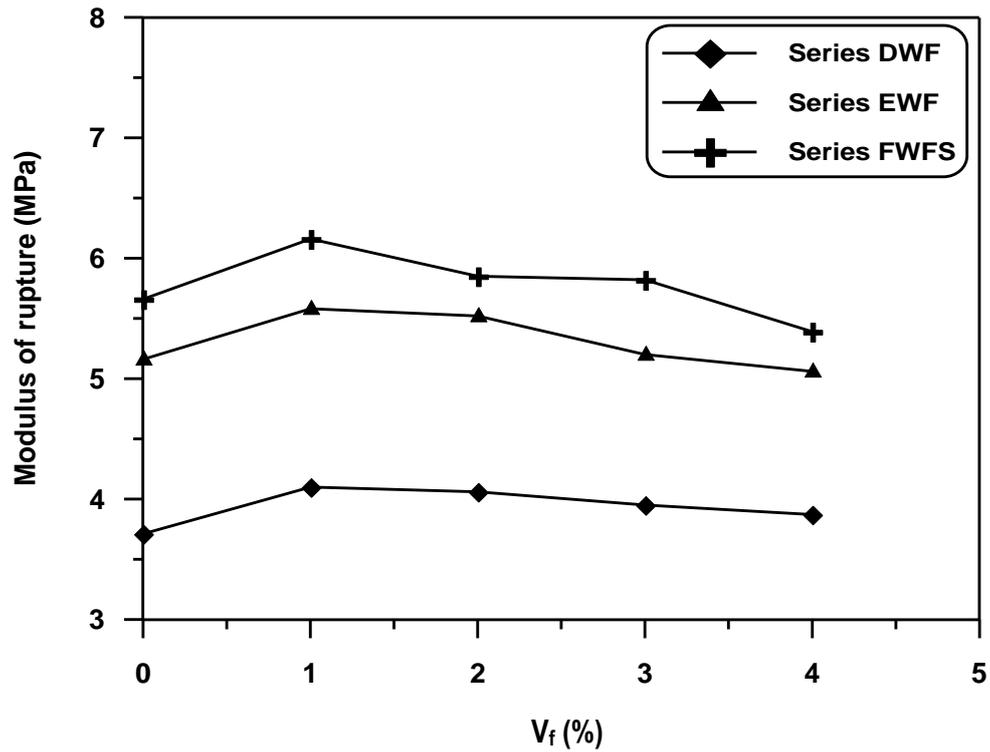


Fig.(4.11): Effect of volume fraction of waste flax fibers on 28 days modulus of rupture for different series

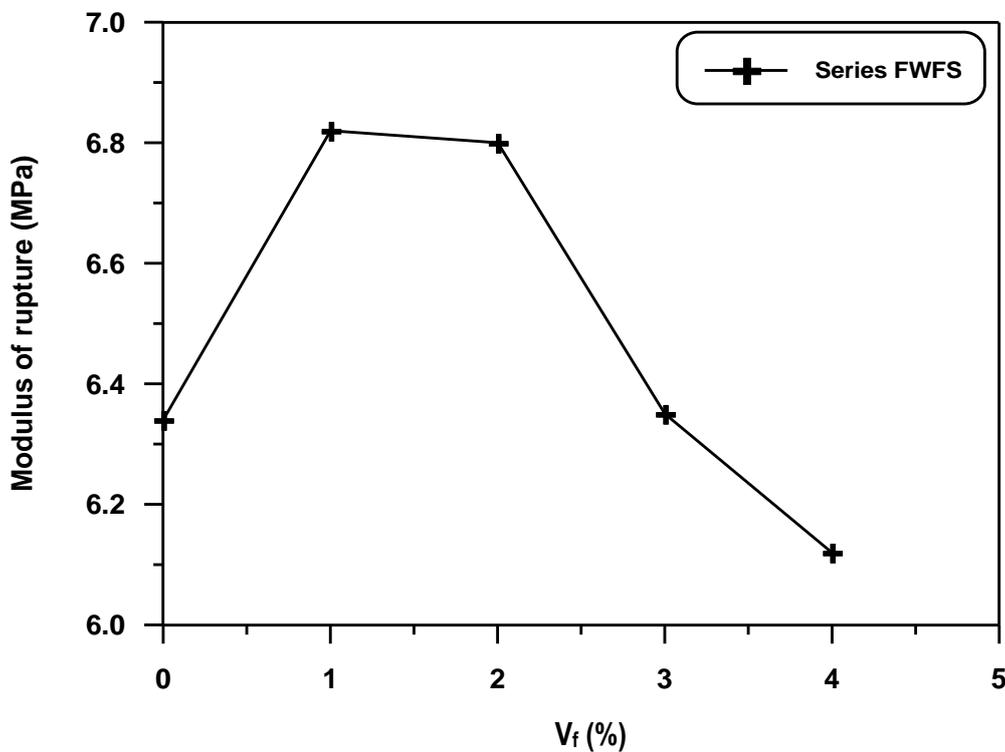


Fig.(4.12): Effect of volume fraction of waste flax fibers on 90 days modulus of rupture

In addition, other fibers than steel or polypropylene such as natural fibers have not been included. Furthermore, the investigations are contradictory in respect of the effect of fibers on abrasion resistance or the optimum fiber content for the maximum improvement in abrasion resistance. This lack of experimental data was considered to be a significant gap in the literature and it was deemed to examine in detail the above issues.

The abrasion resistance test results of the ۳۰ mixes of plain concrete and FRC are summarized in Table (۴.۵). The percentages of improvement in abrasion resistance when comparing the FRC mixes to the plain concrete mixes are also given in this table.

#### **۴.۶.۱ Effects of Fiber Type and Content on Abrasion Resistance**

The influence of steel fiber content on the depth of wear, for ages ۳۰ and ۹۲ days is shown in Figs.(۴.۱۳) and (۴.۱۴) respectively. Figs. (۴.۱۵) and (۴.۱۶) show the increase in abrasion resistance of SFRC when increasing the volume percentages of fibers compared to the plain concrete. It can be noticed from these figures that the inclusion of crimped steel fibers into the concrete improves abrasion resistance, and the higher the addition of fibers the lower is the depth of wear. It can be seen that the addition of ۱% crimped steel fibers improves the ۳۰ days abrasion resistance by ۲۸.۲, ۳۶.۴ and ۲۶.۷% for series ASF, BSF and CSFS respectively.

Table (4.5): Abrasion resistance test results

Series	Fiber type	V <sub>f</sub> (%)	Depth of wear (mm)		Increase in abrasion resistance (%)	
			۳۰ days	۹۲ days	۳۰ days	۹۲ days
ASF	No-fiber	۰.۰	۰.۷۸	۰.۶۵	-	-
	Steel	۰.۳	۰.۷۶	۰.۶۲	۲.۶	۴.۶
		۰.۵	۰.۶۲	۰.۵۱	۲۰.۵	۲۱.۵
		۰.۷	۰.۶۱	۰.۴۵	۲۱.۸	۳۰.۸
		۱.۰	۰.۵۶	۰.۴۲	۲۸.۲	۳۵.۴
BSF	No-fiber	۰.۰	۰.۵۵	۰.۴۷	-	-
	Steel	۰.۳	۰.۵۴	۰.۴۶	۱.۸	۲.۱
		۰.۵	۰.۴۵	۰.۴۰	۱۸.۲	۱۴.۹
		۰.۷	۰.۳۷	۰.۳۶	۳۲.۷	۲۳.۴
		۱.۰	۰.۳۵	۰.۳۵	۳۶.۴	۲۵.۵
CSFS	No-fiber	۰.۰	۰.۴۵	۰.۳۷	-	-
	Steel	۰.۳	۰.۴۲	۰.۳۴	۶.۷	۸.۱
		۰.۵	۰.۳۷	۰.۳۲	۱۷.۸	۱۳.۵
		۰.۷	۰.۳۳	۰.۲۷	۲۶.۷	۲۷.۰
		۱.۰	۰.۳۳	۰.۲۵	۲۶.۷	۳۲.۴
DWF	No-fiber	۰.۰	۰.۸۲	-	-	-
	Waste flax	۱.۰	۰.۷۸	-	۴.۹	-
		۲.۰	۰.۷۷	-	۶.۱	-
		۳.۰	۰.۷۵	-	۸.۵	-
		۴.۰	۰.۷۴	-	۹.۸	-
EWF	No-fiber	۰.۰	۰.۶۰	-	-	-
	Waste flax	۱.۰	۰.۶۰	-	۰.۰	-
		۲.۰	۰.۵۹	-	۱.۷	-
		۳.۰	۰.۵۵	-	۸.۳	-
		۴.۰	۰.۵۳	-	۱۱.۷	-
FWFS	No-fiber	۰.۰	۰.۴۶	۰.۳۷	-	-
	Waste flax	۱.۰	۰.۴۴	۰.۳۵	۴.۳	۵.۴
		۲.۰	۰.۴۳	۰.۳۴	۶.۵	۸.۱
		۳.۰	۰.۳۹	۰.۳۴	۱۵.۲	۸.۱
		۴.۰	۰.۳۸	۰.۳۳	۱۷.۴	۱۰.۸

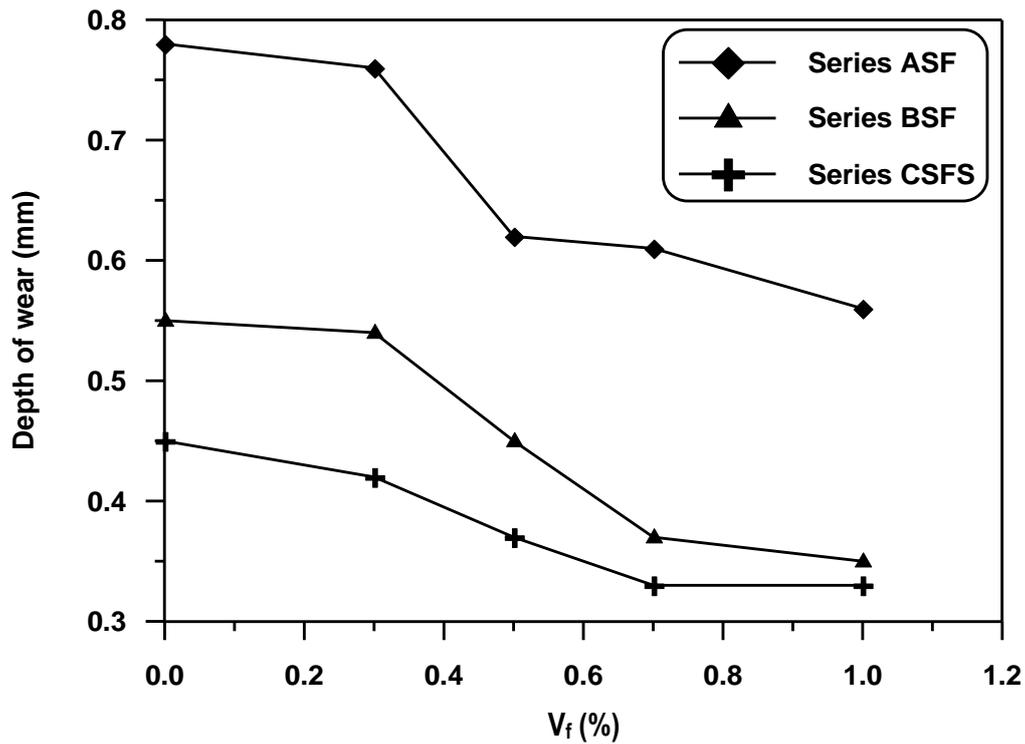


Fig.(4.13): Variation of the depth of wear at 30 days with volume percentage of steel fibers for different series

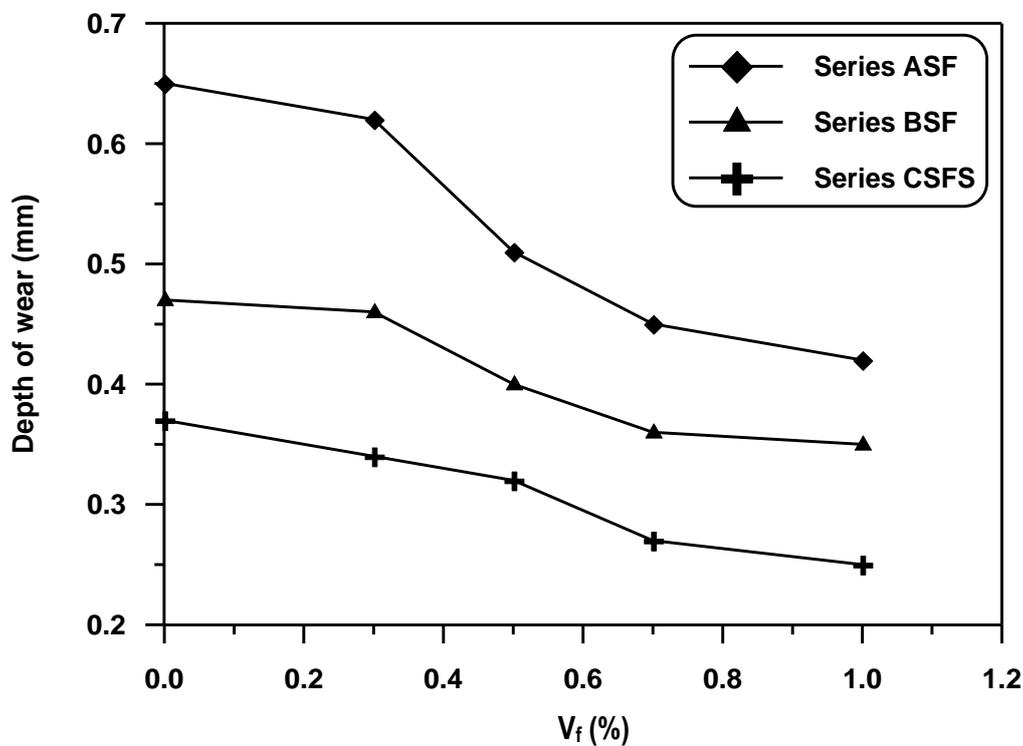


Fig.(4.14): Variation of the depth of wear at 90 days versus volume percentage of steel fibers for different series

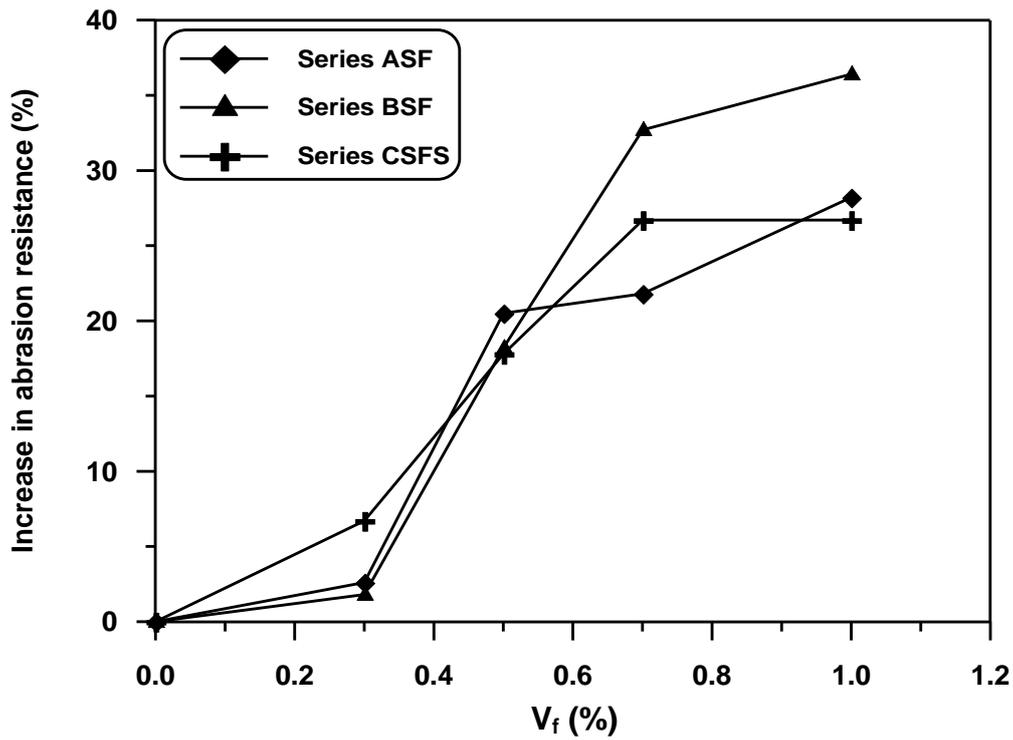


Fig.(4.15): The percentage of increase in abrasion resistance at 30 days versus volume fraction of steel fibers for different series

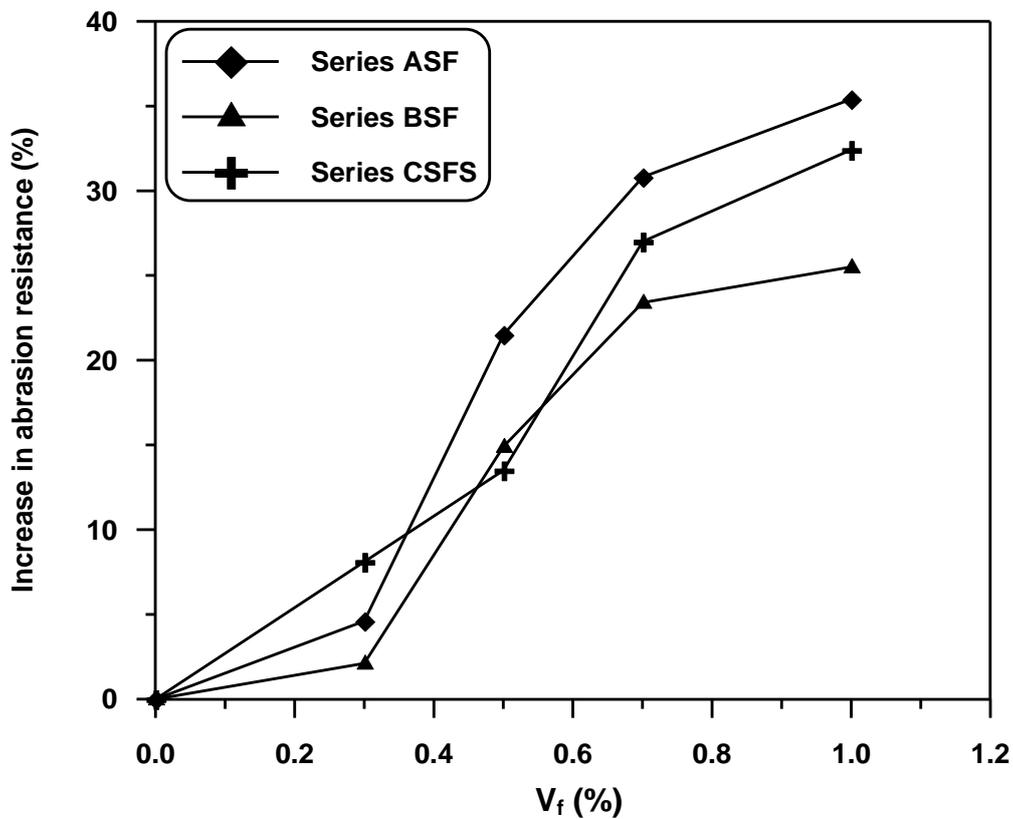


Fig.(4.16): The percentage of increase in abrasion resistance at 90 days against volume fraction of steel fibers for different series

The values of the depth of wear of plain and WFFRC mixes are plotted against fiber content in Figs.(4.17) and (4.18). The improvement percentages in abrasion resistance are given in Figs.(4.19) and (4.20). It can be observed that the presence of waste flax fibers also enhances abrasion resistance of concrete and as the fiber content is increased the depth of wear decreases. The following is a possible explanation of the improvement achieved in surface abrasion resistance due to the inclusion of both types of fibers. When FRC is subjected to abrasion, the film of surface mortar resist the abrasion forces initially; but as the surface mortar is worn away, fibers are exposed to abrasion. These fibers now begin to provide resistance to abrasion in addition to that of concrete and the influence becomes more pronounced with increasing the percentage of fibers.

It can be concluded from the results that the crimped steel fibers are more effective in improving the surface quality of concrete than waste flax fibers. This may be due to the higher surface hardness of steel fibers and their positive effects on compressive strength.

The test results emphasize recent researches conducted by **Eren *et al.***<sup>(47)</sup> and **Vassou**<sup>(48)</sup> which stated that metallic (steel) and non-metallic (polypropylene) fibers improve the abrasion resistance of concrete. However, the general trend of abrasion resistance variation with fiber content experienced in the present investigation is in agreement with that obtained by **Eren *et al.*** and disagreement with **Vassou**. These differences may be attributed to the variation in abrasion testing techniques adopted throughout the investigations. In addition, fiber type, fiber content and workability of mixes may also affect the trend.

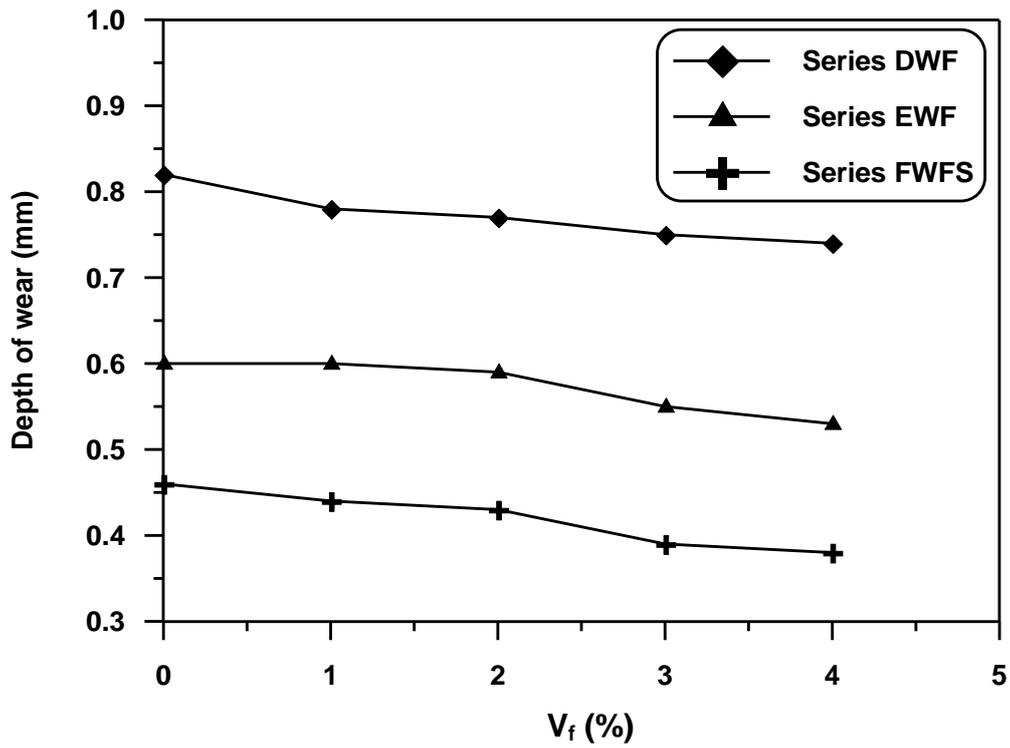


Fig.(4.17): Effect of volume percentage of waste flax fibers on depth of wear at 30 days for various series

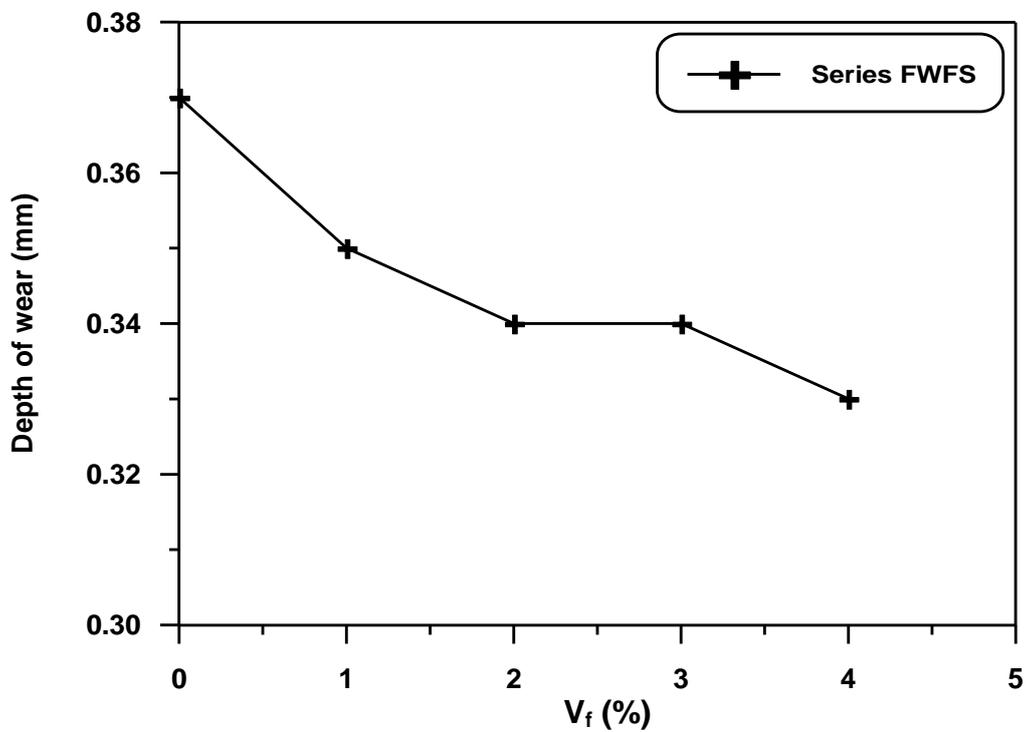


Fig.(4.18): Effect of volume percentage of waste flax fibers on depth of wear at 90 days

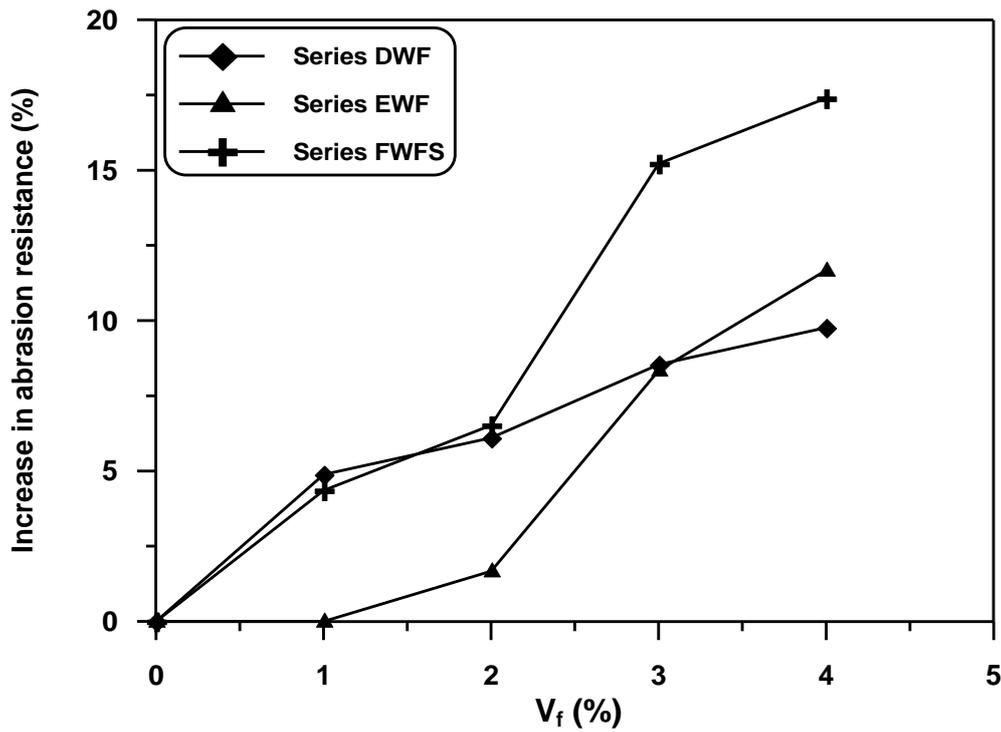


Fig.(4.19): The percentage of increase in abrasion resistance at 30 days versus volume fraction of waste flax fibers for different series

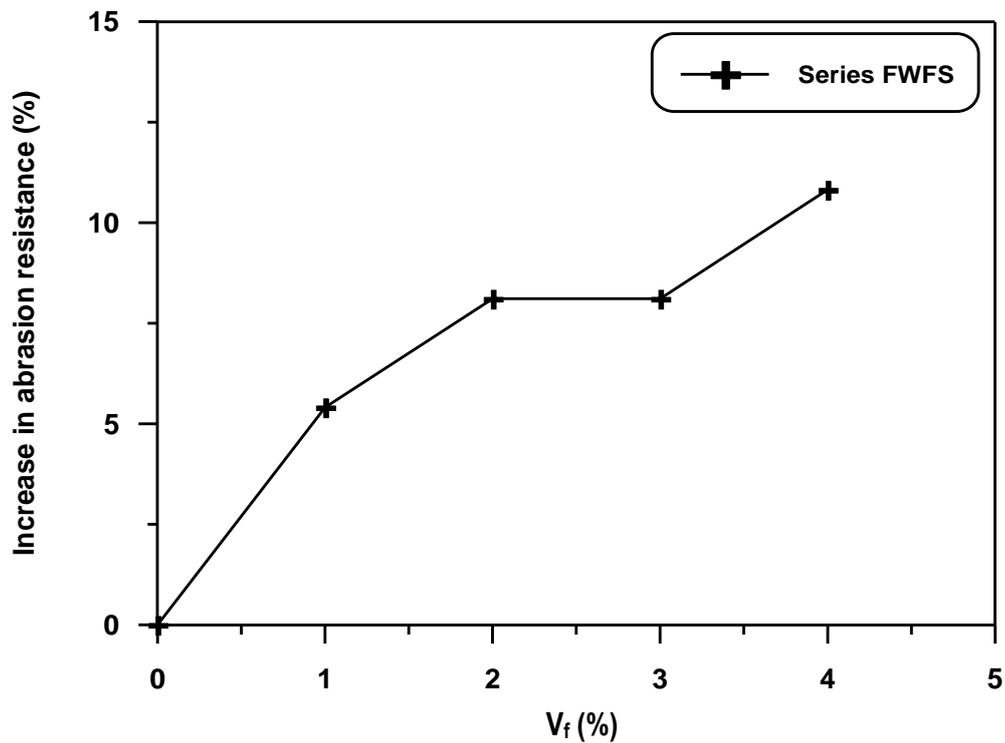


Fig.(4.20): The percentage of increase in abrasion resistance at 90 days versus volume fraction of waste flax fibers

### 4.6.2 Effect of Compressive Strength on Abrasion Resistance

The abrasion resistance of plain concrete and FRC having compressive strength ranging from 24 to 62 MPa was investigated.

The relationship between the depth of wear and the compressive strength for all the mixes and ages is shown in Fig.(4.21). This graph suggests that the compressive strength and the depth of wear are inversely proportional and so the abrasion resistance and the compressive strength are in direct proportion. This finding confirms the conclusions of other investigators (30, 39, 40), but direct comparison is not possible, as the previous researchers only considered plain concrete.

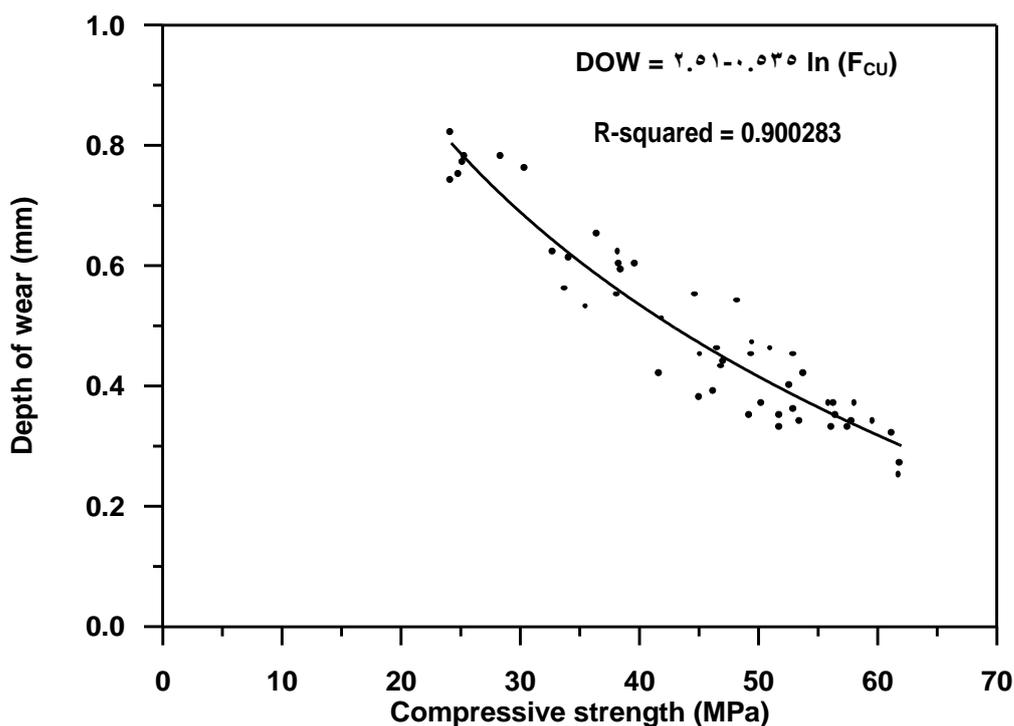


Fig.(4.21): Fitted relationship between depth of wear and compressive strength

The equation of the best fit line for the results obtained in this study is

$$DOW = 2.01 - 0.030 \times \ln(F_{cu}) \quad \dots\dots\dots(4.1)$$

where

$DOW$  : depth of wear (mm).

$F_{cu}$  : compressive strength of concrete (MPa).

### 4.6.3 Relationships of Abrasion Resistance with Splitting Tensile Strength and Modulus of Rupture

Figs.(4.22) and (4.23) present results of statistical analysis, where the abrasion property (depth of wear) is plotted against split – cylinder tensile strength and modulus of rupture respectively. The proposed equations with their coefficients of determination ( $R^2$ ) are also shown. Higher results of  $R^2$  indicate that there is a significant correlation between dependent and independent variables. The most suitable regression equations are found to be of logarithmic form as shown below:

$$DOW = 1.17 - 0.014 \times \ln(F_{sp}) \quad \dots\dots\dots(4.2)$$

$$DOW = 1.63 - 0.043 \times \ln(F_r) \quad \dots\dots\dots(4.3)$$

where

$DOW$ : depth of wear (mm).

$F_{sp}$  : split – cylinder tensile strength (MPa).

$F_r$  : modulus of rupture of  $100 \times 100 \times 400$  mm prisms (MPa).

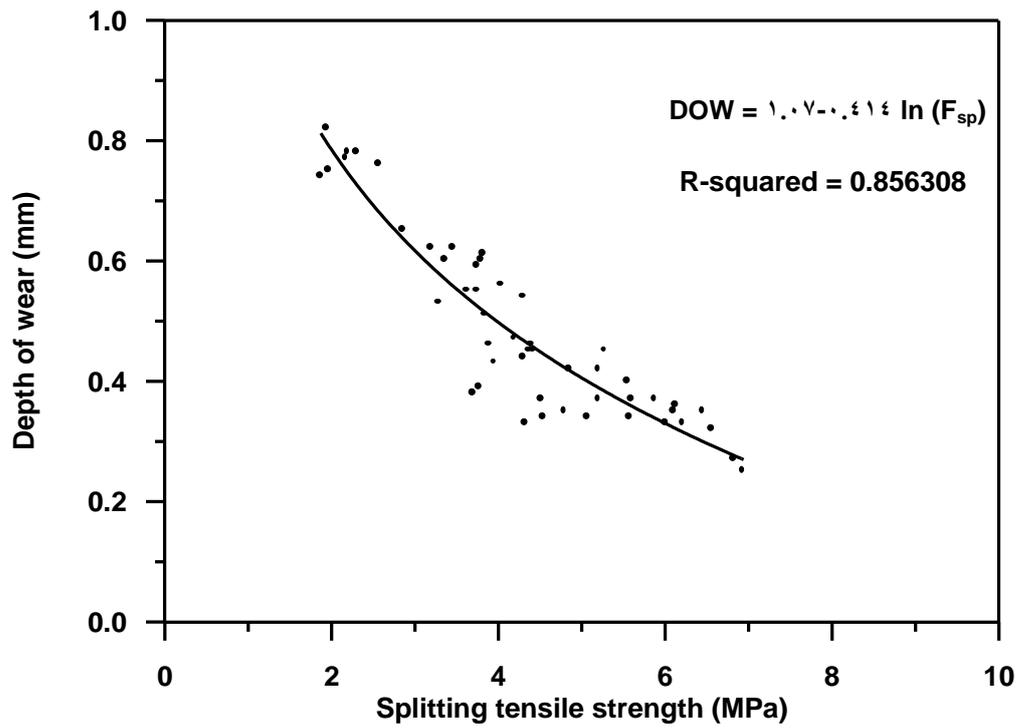


Fig.(4.22): Fitted relationship between depth of wear and splitting tensile strength

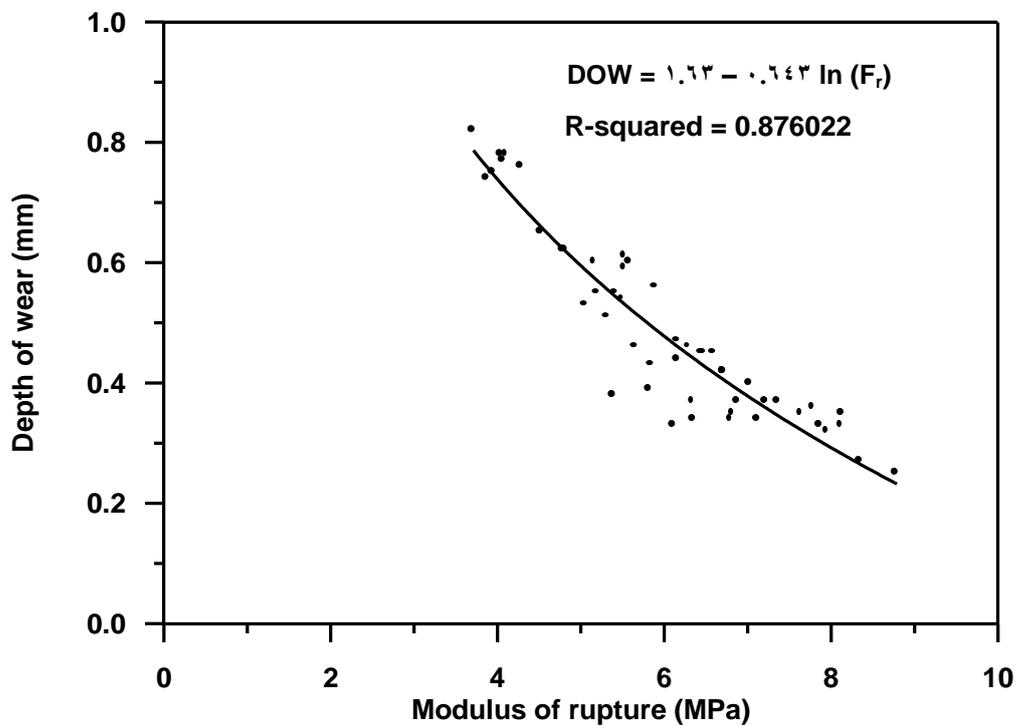


Fig.(4.23): Fitted relationship between depth of wear and modulus of rupture

### 4.6.4 Effect of Age of the Specimens on Abrasion Resistance

The specimens were tested at ages of 30 and 90 days except those of series DWF and EWF which were tested at 30 days only.

Examination of Table (4.5) shows that the depth of wear decreases with the age of plain and FRC specimens investigated. Considering the average values of depth of wear for each series, the abrasion resistance at 90 days age was 20.4, 9.7, 18.4 and 17.6% higher than that of 30 days age for the series ASF, BSF, CSFS and FWFS respectively. There is no available data which concerns the effect of curing age on the abrasion resistance of concrete samples.

### 4.7 Impact Resistance Test Results

The results of impact resistance for the 6 series are given in Table (4.6). The table includes measured thickness of the specimens and the impact behavior expressed by three indices: the number of blows required to cause the first visible crack, the number of blows required to cause the full failure and the calculated impact energy. The impact energy delivered to the specimen produce by the hammer until failure is calculated as follows:

$$E_I = \frac{1}{2} M V_I^2 N \quad \dots\dots\dots (4.4)$$

where

$E_I$  : impact energy (N.m).

$M$  : mass of the drop hammer (kg).

$V_I$  : impact speed (m/s).

$N$  : number of blows to produce failure.

The speed of the drop hammer ( $V_I$ ) was calculated as 2.9929 m/s.

The percentages of increase in impact resistance of FRC specimens beyond the corresponding plain concrete specimens are provided in Table (4.7).

Table (٤.٦): Impact resistance test results

Series	Fiber type	V <sub>f</sub> (%)	Specimen thickness (mm)	Impact resistance (number of blows)				Impact energy at complete failure (N.m)	
				٢٨ days		٩٠ days		٢٨ days	٩٠ days
				First crack	Complete failure	First crack	Complete failure		
ASF	No-fiber	٠.٠	٦٤.٠	١٩	٢٤	٢٨	٣١	٤٨٨	٦٣.٠
	Steel	٠.٣	٦٤.٠	٣٢	٨٦	٧٢	١٠٠	١٧٤٩	٢١٣٥
		٠.٥	٦٣.٠	١٢٤	٢٩٠	١٣٤	٣٢٢	٥٨٩٧	٦٥٤٧
		٠.٧	٦٣.٠	١٨٢	٤٧٢	١٧٦	٦٥٤	٩٥٩٧	١٣٢٩٨
		١.٠	٦٥.٠	٢٨١	٨٤٦	٧٣٣	٩٨٨	١٧٢.٢	٢٠.٨٩
BSF	No-fiber	٠.٠	٦٤.٠	٣٦	٣٩	١٠	١٥	٧٩٣	٣.٥
	Steel	٠.٣	٦٣.٠	٥٢	٩٥	٢٩	٥٣	١٩٣٢	١.٧٨
		٠.٥	٦٥.٠	١٨٦	٣٣٩	١٢٤	٢١٦	٦٨٩٣	٤٣٩٢
		٠.٧	٦٤.٠	٢٢٦	٧٠٨	١٦٥	٢٩٥	١٤٣٩٦	٥٩٩٨
		١.٠	٦٤.٠	٤٥٥	١١٢٥	١٠٢	٥١١	٢٢٨٧٥	١.٣٩.٠
CSFS	No-fiber	٠.٠	٦٣.٠	٦٥	٦٧	١٥٣	١٥٨	١٣٦٢	٣٢١٣
	Steel	٠.٣	٦٣.٠	٣١	٩٦	١٦٤	١٩٢	١٩٥٢	٣٩.٤
		٠.٥	٦٤.٠	١٧٣	٣١٥	١٩٥	٢٨٩	٦٤.٥	٥٨٧٦
		٠.٧	٦٤.٠	٢٦١	٤٦٩	٣٦٢	٤٥٣	٩٥٣٦	٩٢١١
		١.٠	٦٥.٠	٤١٧	٨٠٩	٤٣٧	٧٣١	١٦٤٥.٠	١٤٨٦٤
DWF	No-fiber	٠.٠	٦٤.٠	١٠	١٢	-	-	٢٤٤	-
	Waste flax	١.٠	٦٣.٠	١٥	٩٥	-	-	١٩٣٢	-
		٢.٠	٦٣.٠	١٣	١٩٦	-	-	٣٩٨٥	-
		٣.٠	٦٤.٠	١٠	٥٧٦	-	-	١١٧١٢	-
		٤.٠	٦٥.٠	١١	١٠١٨	-	-	٢٠.٦٩٩	-
EWF	No-fiber	٠.٠	٦٤.٠	١٧	١٨	-	-	٣٦٦	-
	Waste flax	١.٠	٦٤.٠	٢٢	١٢٢	-	-	٢٤٨١	-
		٢.٠	٦٤.٠	٢١	٢٩٣	-	-	٢٩٥٨	-
		٣.٠	٦٣.٠	٢١	٥٩١	-	-	١٢.١٧	-
		٤.٠	٦٣.٠	١٩	١١٣٧	-	-	٢٣١١٩	-
FWFS	No-fiber	٠.٠	٦٥.٠	٣٨	٤٢	٧٦	٨٢	٨٥٤	١٦٦٧
	Waste flax	١.٠	٦٥.٠	٥٣	١٤٨	٨٢	٢٢٧	٣٠.٩	٤٦١٦
		٢.٠	٦٣.٠	٤٥	٣٥٦	٨٠	٣٢٨	٧٢٣٩	٦٦٦٩
		٣.٠	٦٣.٠	٣٦	٨١١	٧٥	٩٧٣	١٦٤٩.٠	١٩٧٨٤
		٤.٠	٦٣.٠	٢٥	١٢٢٥	٧١	١٢٦٢	٢٤٩.٨	٢٥٦٦١

Table (٤.٧): Improvement in impact behavior due to fiber inclusion

Series	Fiber type	V <sub>f</sub> (%)	Increase in impact resistance (%)				Increase in impact energy at complete failure (%)	
			٢٨ days		٩٠ days		٢٨ days	٩٠ days
			First crack	Complete failure	First crack	Complete failure		
ASF	No-fiber	٠.٠	-	-	-	-	-	-
	Steel	٠.٣	٦٨	٢٥٨	١٥٧	٢٣٩	٢٥٨	٢٣٩
		٠.٥	٥٥٣	١١٠٨	٣٧٩	٩٣٩	١١٠٨	٩٣٩
		٠.٧	٨٥٨	١٨٦٧	٥٢٩	٢٠١٠	١٨٦٧	٢٠١٠
		١.٠	١٣٧٩	٣٤٢٥	٢٥١٨	٣٠٨٧	٣٤٢٥	٣٠٨٧
BSF	No-fiber	٠.٠	-	-	-	-	-	-
	Steel	٠.٣	٤٤	١٤٤	١٩٠	٢٥٣	١٤٤	٢٥٣
		٠.٥	٤١٧	٧٦٩	١١٤٠	١٣٤٠	٧٦٩	١٣٤٠
		٠.٧	٥٢٨	١٧١٥	١٥٥٠	١٨٦٧	١٧١٥	١٨٦٧
		١.٠	١١٦٤	٢٧٨٥	٩٢٠	٣٣٠٧	٢٧٨٥	٣٣٠٧
CSFS	No-fiber	٠.٠	-	-	-	-	-	-
	Steel	٠.٣	-٥٢	٤٣	٧	٢٢	٤٣	٢٢
		٠.٥	١٦٦	٣٧٠	٢٧	٨٣	٣٧٠	٨٣
		٠.٧	٣٠٢	٦٠٠	١٣٧	١٨٧	٦٠٠	١٨٧
		١.٠	٥٤٢	١١٠٧	١٨٦	٣٦٣	١١٠٧	٣٦٣
DWF	No-fiber	٠.٠	-	-	-	-	-	-
	Waste flax	١.٠	٥٠	٦٩٢	-	-	٦٩٢	-
		٢.٠	٣٠	١٥٣٣	-	-	١٥٣٣	-
		٣.٠	٠	٤٧٠٠	-	-	٤٧٠٠	-
		٤.٠	١٠	٨٣٨٣	-	-	٨٣٨٣	-
EWF	No-fiber	٠.٠	-	-	-	-	-	-
	Waste flax	١.٠	٢٩	٥٧٨	-	-	٥٧٨	-
		٢.٠	٢٤	١٥٢٨	-	-	١٥٢٨	-
		٣.٠	٢٤	٣١٨٣	-	-	٣١٨٣	-
		٤.٠	١٢	٦٢١٧	-	-	٦٢١٧	-
FWFS	No-fiber	٠.٠	-	-	-	-	-	-
	Waste flax	١.٠	٣٩	٢٥٢	٨	١٧٧	٢٥٢	١٧٧
		٢.٠	١٨	٧٤٨	٥	٣٠٠	٧٤٨	٣٠٠
		٣.٠	-٥	١٨٣١	-١	١٠٨٧	١٨٣١	١٠٨٧
		٤.٠	-٣٤	٢٨١٧	-٧	١٤٣٩	٢٨١٧	١٤٣٩

### 4.7.1 Effects of Fiber Type and Content on Impact Resistance

The variation of impact resistance with volume percentage of fibers for SFRC series is shown in Figs. (4.24) to (4.27). Figs.(4.24) and (4.25) show the relationship at the age of 28 days, while Figs.(4.26) and (4.27) show the relationship at the age of 90 days. It is obvious from these figures that the SFRC has a tremendous ability to absorb impact load. This ability increases as the steel fiber content is increased both at first crack (except for a few specimens of series BSF and CSFS) and at failure. The exceptions are related to the natural scatter of the results. The improvement in first crack resistance is achieved mainly through the arrest of microcracks by fibers. While, the substantial increase in impact resistance at failure could be due to the large energy required to de-bond and pull out or fracture the steel fibers when the cracks open at impact loading <sup>(1)</sup>.

It can be seen that the inclusion of 1% crimped steel fibers by volume increases the impact resistance to produce first visible crack at the age of 28 days by 137%, 116% and 54% for series ASF, BSF and CSFS respectively. While the corresponding increase in impact resistance or the impact energy to produce failure is 342%, 278% and 110% respectively compared to the plain concrete specimens.

**Ramakrishnan et al.** <sup>(1)</sup> used the same impact test adopted in this study. They used two types of steel fibers, namely, hooked and straight fibers with aspect ratios of 100 and 60 respectively. Their results indicated that the 28 days increase in impact resistance to produce failure due to the addition of 1% straight fibers and 0.6% hooked fibers was ranging from 116 to 120% respectively. The crimped steel fibers used in the present work are somewhat comparable to hooked steel fibers and greater capacity to absorb impact energy than straight fibers. This could be mainly attributed to the favorable bond characteristics of crimped and hooked fibers compared to the poor bond between the straight fiber and the matrix.

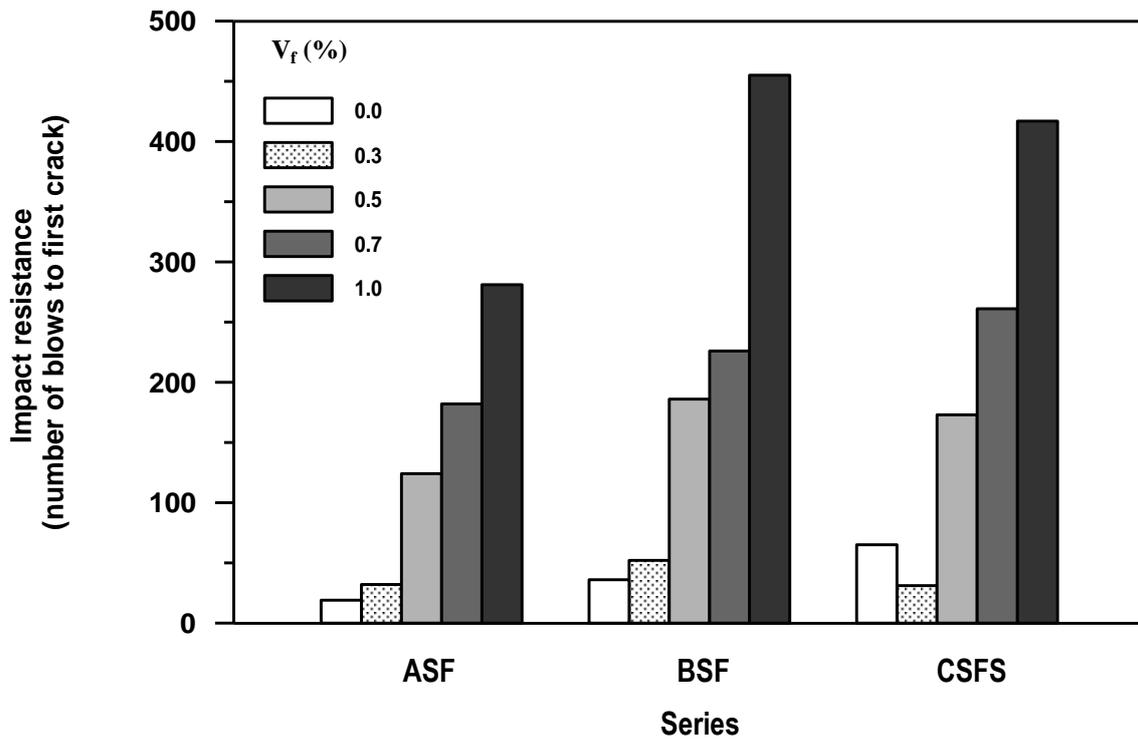


Fig.(4.24): Variation of the 28 days impact resistance at first crack with volume percentage of steel fibers for different series

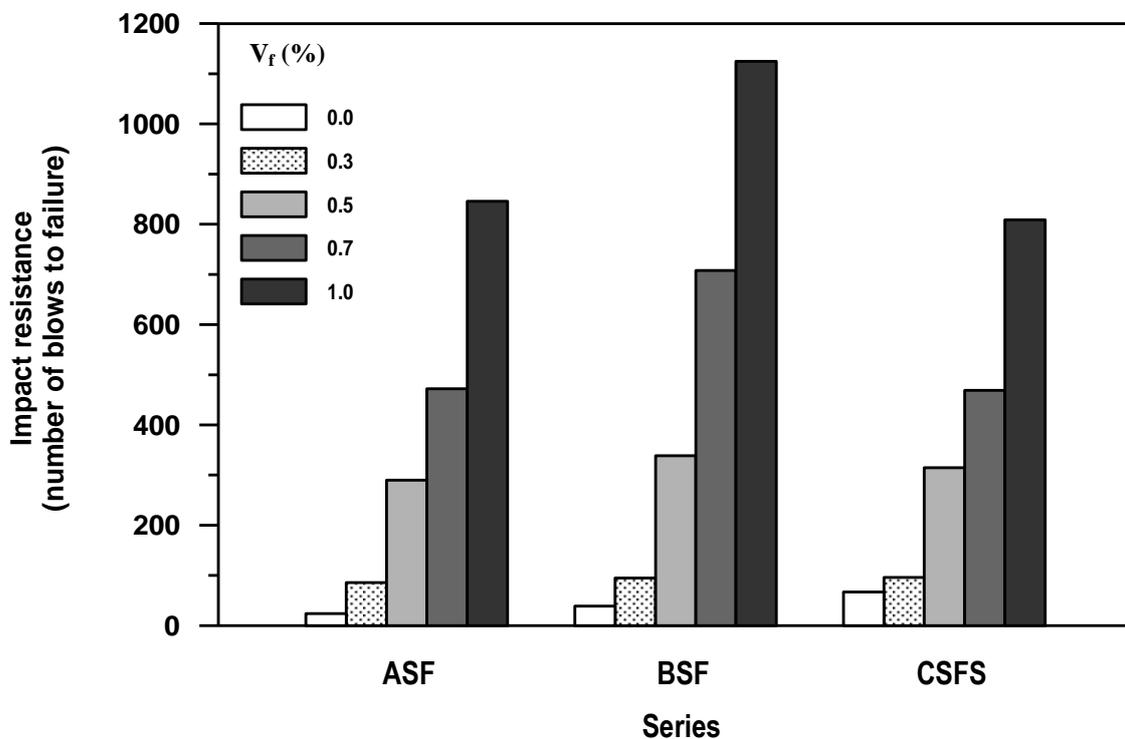


Fig.(4.25): Variation of the 28 days impact resistance at failure with volume percentage of steel fibers for different series

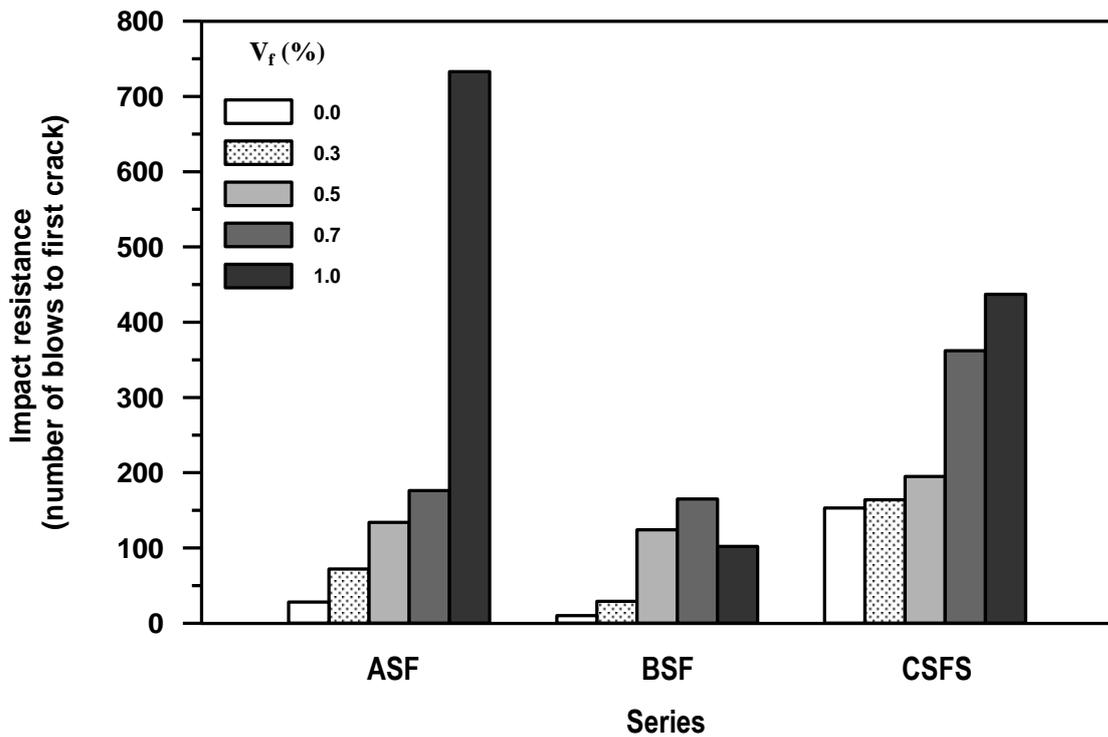


Fig.(4.26): Variation of the 90 days impact resistance at first crack with volume percentage of steel fibers for different series

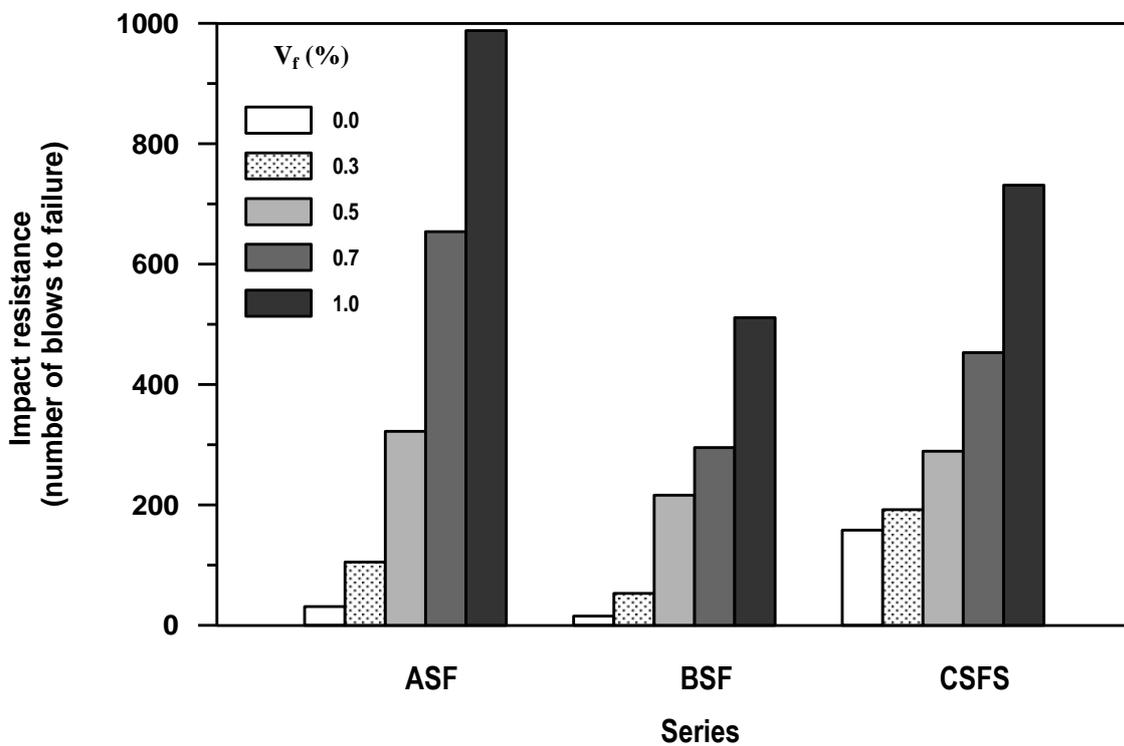


Fig.(4.27): Variation of the 90 days impact resistance at failure with volume percentage of steel fibers for different series

The superior ability of SFRC to resist impact load has been also reported by other investigators <sup>(1, 6, 16, 17, 22)</sup> using totally different testing procedures. A direct comparison is not reliable due to the fact that the recorded value of impact is strongly dependent on many factors such as the energy and velocity of the impacting mass, the size of specimen, rigidity of supports, the type of test and even the definition of failure <sup>(1, 6)</sup>.

Figs.(4.28) to (4.30) show the impact resistance against waste flax fiber content. It can be noticed that the waste flax fibers, in general, slightly delay the appearance of visual cracks regarding the fiber content. The reason is thought to be due to the significant flexibility of these fibers and thus their capacity to arrest microcracks is very small. On the other hand, the impact resistance or the impact energy at failure substantially improves as the percentage of waste flax fibers is increased. This enhancement could be related to the large amount of energy absorbed in debonding and pulling out the fibers which is required after the matrix has been cracked.

It can be seen that the addition of 4% waste flax fibers to the concrete increases the impact resistance or the impact energy to produce complete failure at 28 days by 83.83, 62.17 and 28.17% for series DWF, EWF and FWFS respectively.

According to the results obtained, it can be summarized that the introduction of 4% waste flax fibers to concrete leads to produce impact strength comparable or higher than that obtained when 1% crimped steel fibers are included.

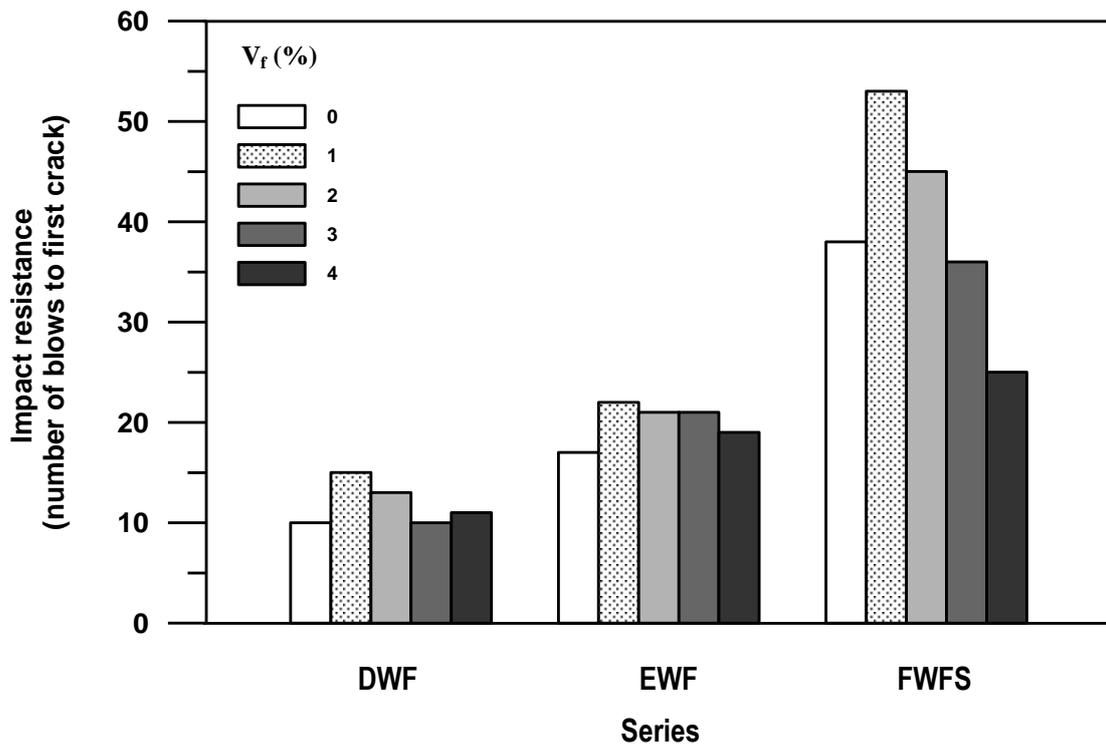


Fig.(4.28): Variation of the 28 days impact resistance at first crack against volume fraction of waste flax fibers for different series

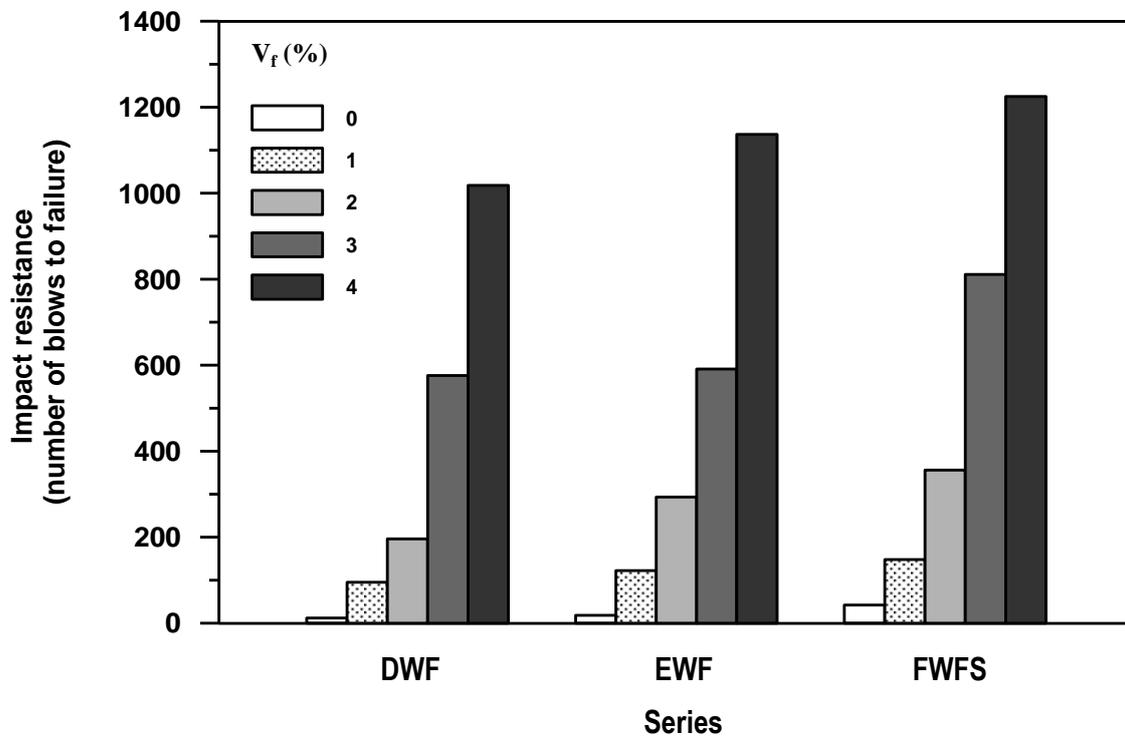


Fig.(4.29): Variation of the 28 days impact resistance at failure against volume fraction of waste flax fibers for different series

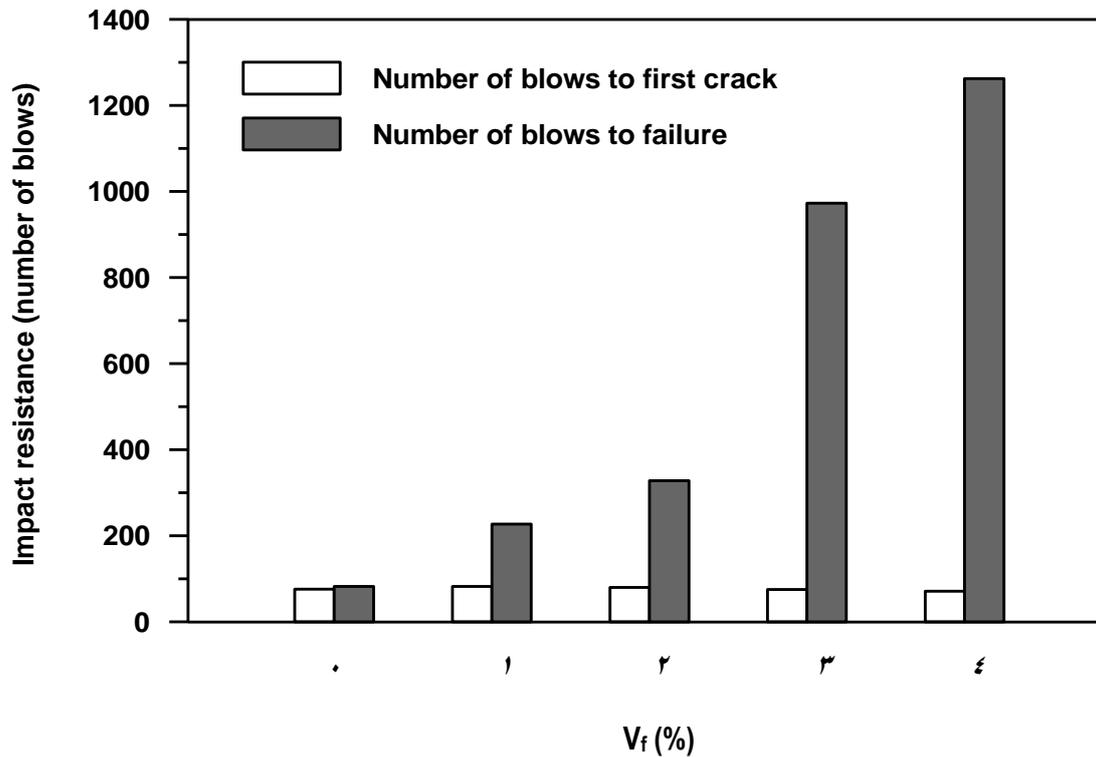


Fig.(4.30): Variation of the 90 days impact resistance against volume fraction of waste flax fibers for series FWFS

## 4.7.2 Effect of Compressive Strength on Impact Resistance

### 4.7.2.1 The Effect on Plain Concrete Specimens

Tables (4.2) and (4.7) show that, keeping the same workability for the mixes, as the compressive strength increases the impact resistance of plain concrete also increases both to initiate the first crack and to produce failure. However, the plain specimens of series BSF at 90 days age adversely behaved when the number of blows at failure were even less than that produced by the weaker series ASF plain samples. Although the exact reason for this behavior is not clear, **Bischoff** and **Pery**<sup>(30)</sup> also reported similar results and stated that the failure to account for stress wave propagation effects, especially at the impact loading, may lead to incorrect conclusions. Both aggregate-matrix bond and the relative stiffness of the aggregate and matrix have a part to play in impact resistance similar to their effect on compressive strength and thus the resistance of concrete to impact improves with increasing the strength.

On the other hand, increasing the water content leads to reduce the impact resistance significantly more than reducing compressive strength. Comparing the results of plain specimens of SFRC series with those of corresponding specimens of WFFRC series, the impact resistance at failure is found to be decreased in the order of 47 to 54%, while the reduction in strength is only about 7 to 10% due to the increase in water content. This conclusion is in a good agreement with that obtained by **Sandhu** <sup>(6)</sup>. A possible explanation of this behavior is that, under static loading a highly – stressed weak region may transfer load to a region of lower stress or high strength through the effect of creep. Under impact this redistribution of stress can not take place during the short period of deformation and the effect of local weakness may therefore have a great influence on the strength of the specimen <sup>(6)</sup>.

#### 4.1.2.2 The Effect on SFRC Specimens

For the same steel fiber content, the impact resistance at failure generally increases with increasing compressive strength of the matrix up to a certain limit beyond which any increase in compressive strength reduces the impact resistance. This limit for the compressive strength is found to be around 40 MPa. For example, the values of the impact resistance to produce failure for concrete containing 1% crimped steel fibers are 147, 1120 and 109 blows for the matrix strength of 24.4, 44.1 and 53.1 MPa respectively. This behavior may be related to the dependence of the fiber pull out resistance on the strength of the matrix; at higher matrix strengths, more instances of fiber fractures has been reported to occur <sup>(1)</sup> and so the percentage of fibers which are effective in impact resistance control will be reduced. As a result, the SFRC will behave less ductile than the state before fracturing of fibers.

Recently, **Banthia et al.** <sup>(1)</sup> found a similar trend that the effectiveness of steel fibers in improving impact resistance decreases with the increase in compressive strength of the matrix. This conclusion was drawn when they used an instrumented impact machine as a testing tool and 1.0% volume fraction of different types of steel fibers. According to the available information, no other work has been previously published in this area.

It is clear from Figs. (4.31) and (4.32) that the percentages of improvement in impact strength due to fiber inclusion are higher for the weak series ASF specimens than the strong series BSF specimens which are in turn higher than that for the strongest series CSFS specimens. This finding is also in accordance with results obtained by **Banthia et al.** <sup>(1)</sup>. However, Fig.(4.32) shows that the series BSF exhibits very close trend to that for series ASF, the reason may be due to the brittle response under impact of series BSF plain specimens at 7 days age.

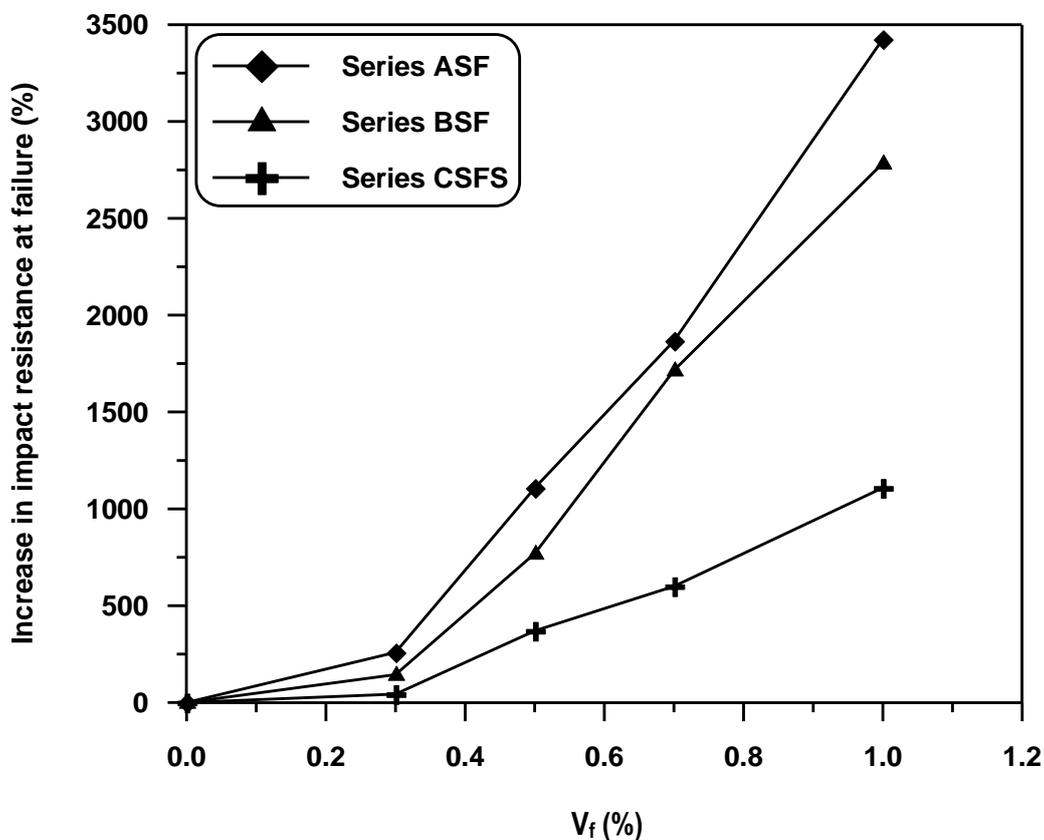


Fig.(4.31): The percentage of increase in 7 days impact resistance at failure with volume fraction of steel fibers for different series

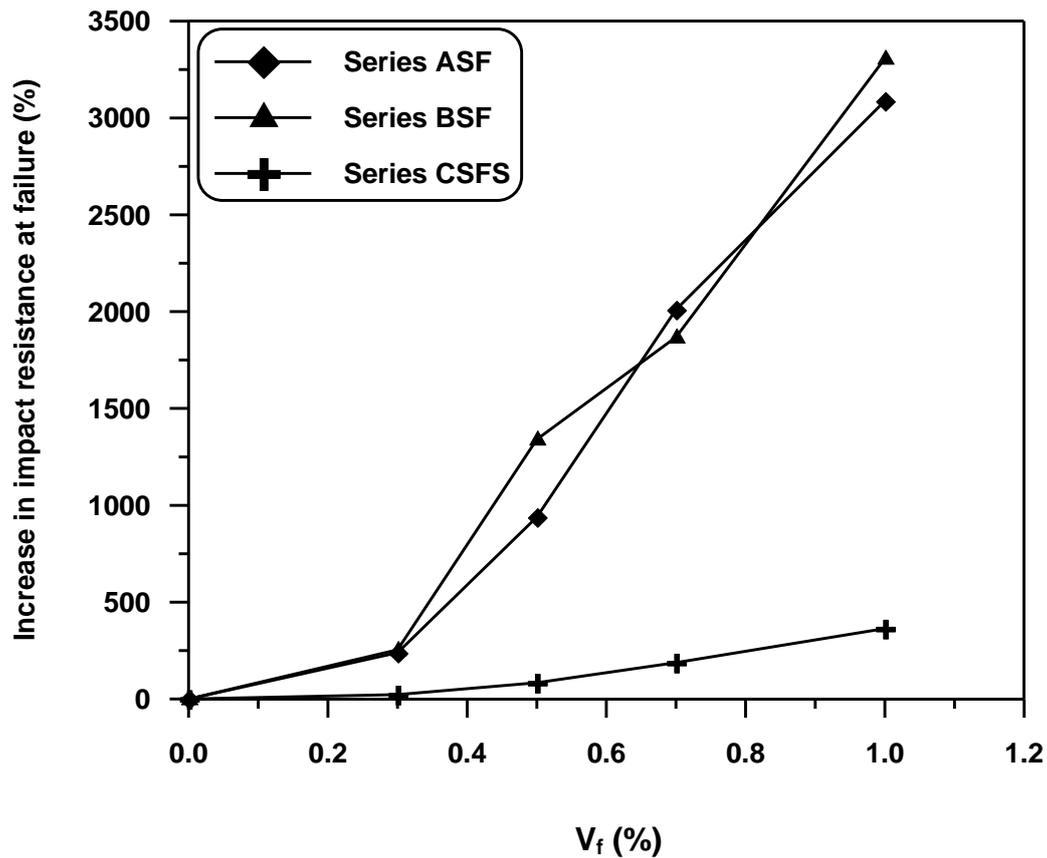


Fig.(4.32): The percentage of increase in 90 days impact resistance at failure with volume fraction of steel fibers for different series

On the basis of the data recorded here, the observed value of the impact resistance at first crack of SFRC does not seem to be dependent on the matrix strength.

#### 4.1.2.3 The Effect on WFFRC Specimens

For the same waste flax fiber concentration, the impact resistance at first crack and at failure generally increases with the increase in matrix compressive strength. On the other hand, Fig.(4.33) illustrates that the higher the strength of the matrix the lower is the improvement in impact strength of WFFRC beyond the corresponding plain concrete.

It was found that it is difficult to formulate a strict relationship between impact resistance and compressive strength for each SFRC and WFFRC samples.

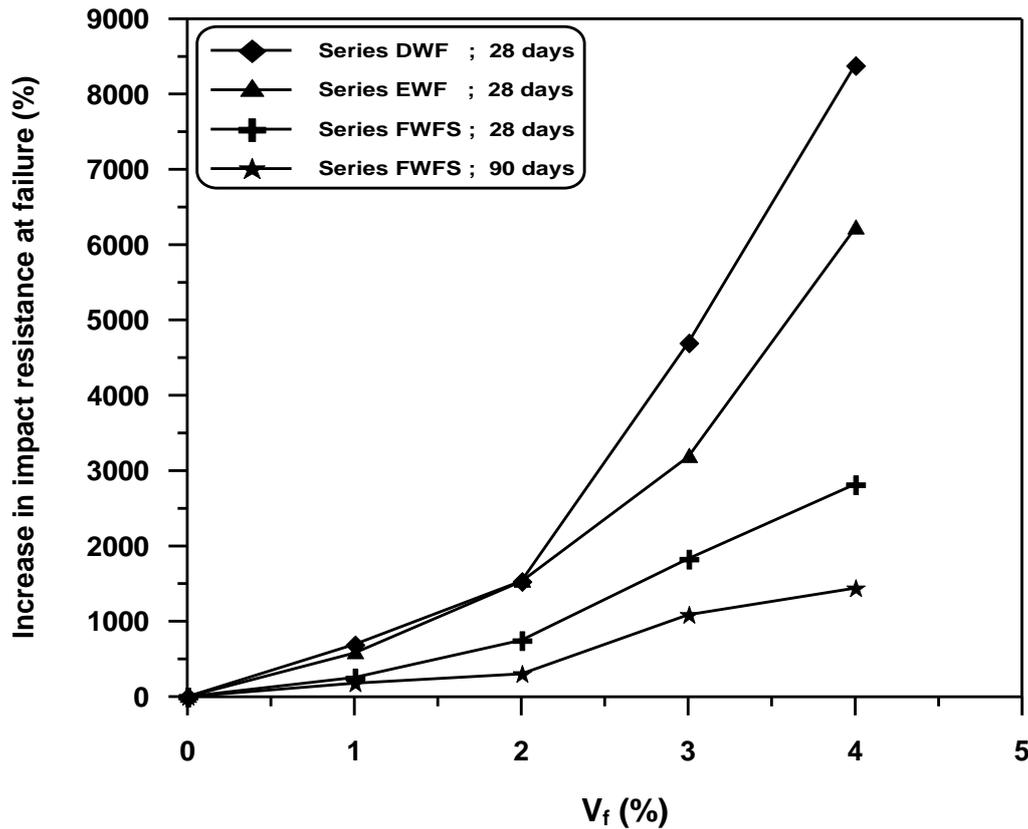


Fig.(4.23): The percentage of increase in impact resistance at failure with volume fraction of waste flax fibers for different series

#### 4.1.3 Effect of Age of the Specimens on Impact Resistance

Table (4.7) shows that the impact resistance at initial cracking and at failure of the plain concrete increases with age except for series BSF plain samples. It can also be seen from this table that the first crack resistance of SFRC in general increases with age with the exception of series BSF specimens. On the other hand, series ASF of SFRC experienced further resistance to impact at failure with increasing age, while series BSF and CSFS were adversely affected. Again, this behavior may be resulted from the higher strength of the later two series which is significantly developed with age and hence some of steel fibers are thought to be fractured during impact.

The results of series ASF of SFRC are generally in agreement with that recorded by **Ramakrishnan et al.**<sup>(11)</sup>, which are only reported work on

this issue. In the case of the other series of SFRC, a similar comparison is not available as these workers considered the matrix strength of only  $42 \text{ MPa}$  at 90 days which is lower than the upper strength level for complete pulling out of fibers obtained in this study.

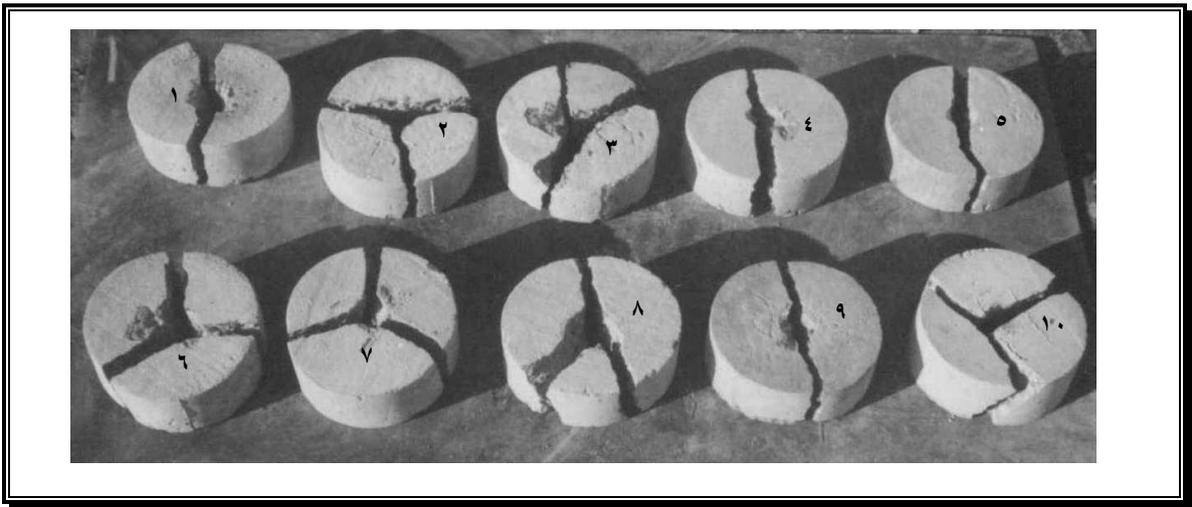
With a few exceptions, increasing the age of series FWFS samples leads to increase the impact resistance both to initiate first visual crack and to produce failure.

### 4.1.4 Modes of Failure Under Impact

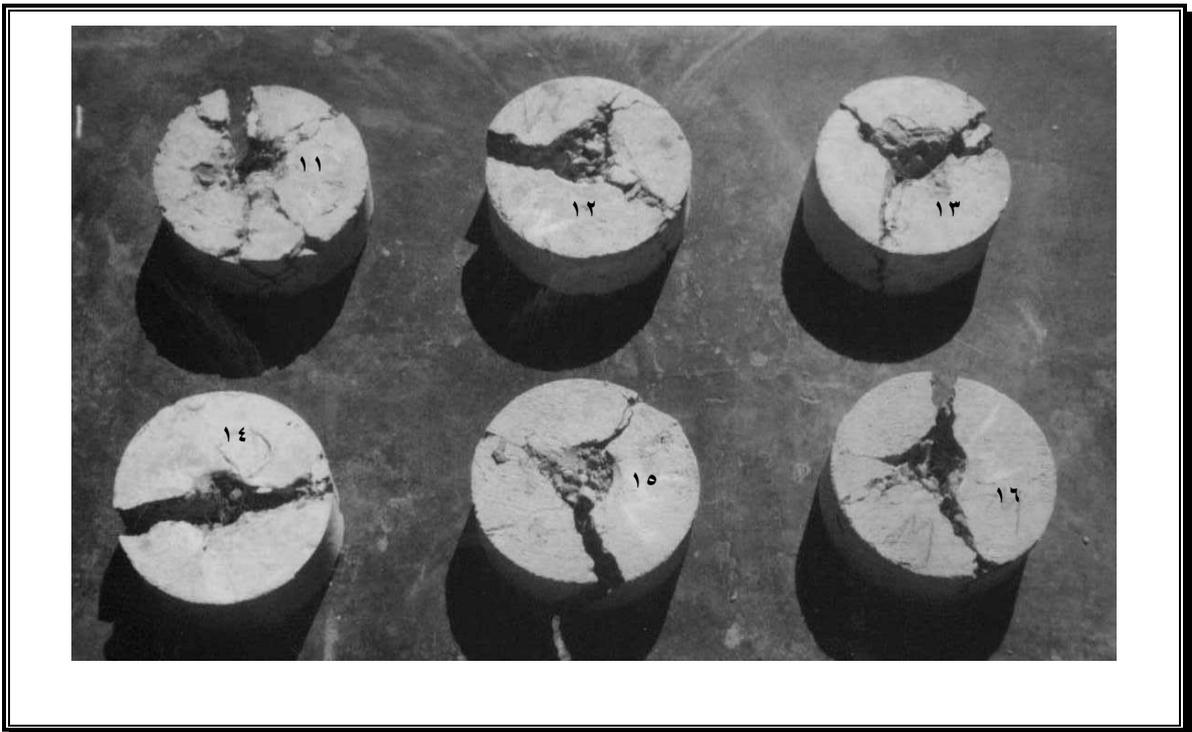
Plate (4.1a) shows the different modes of failure of plain concrete specimens subjected to the falling weight test used in this study. The tested plain cylinders were broken into two or three segments. The mode of failure of the specimens was brittle and generally occurred through the aggregate-matrix interface.

In the case of FRC (Plate (4.1b) to (4.1f)), the mode of failure was different. It can be stated that even after the matrix has cracked the samples could carry the additional blows. This is owing to the action of fibers that bridge the crack which hampered the failed pieces to be separated. Only a few exceptions occurred in samples which containing 0.3 and 1% volume fraction of steel fibers and waste flax fibers respectively.

The FRC test cylinders showed multiple cracking, multiple failure planes, crushing, spalling and disintegration.



(a) Plain concrete samples

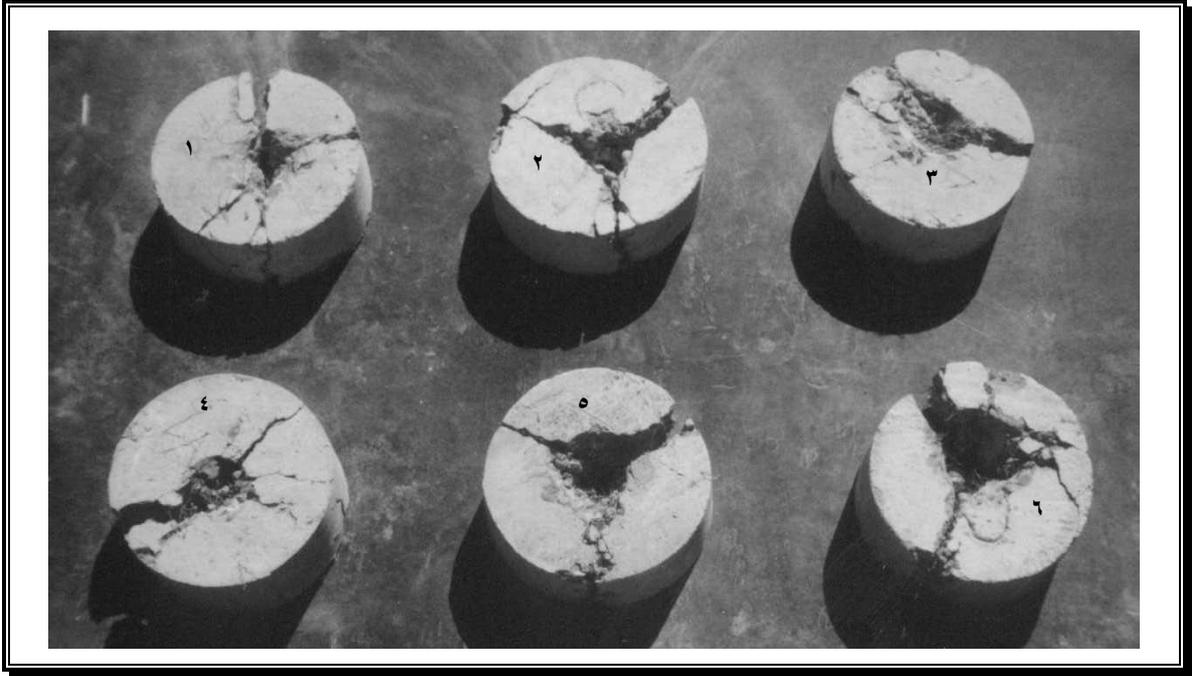


(b) 1.0% SFRC samples

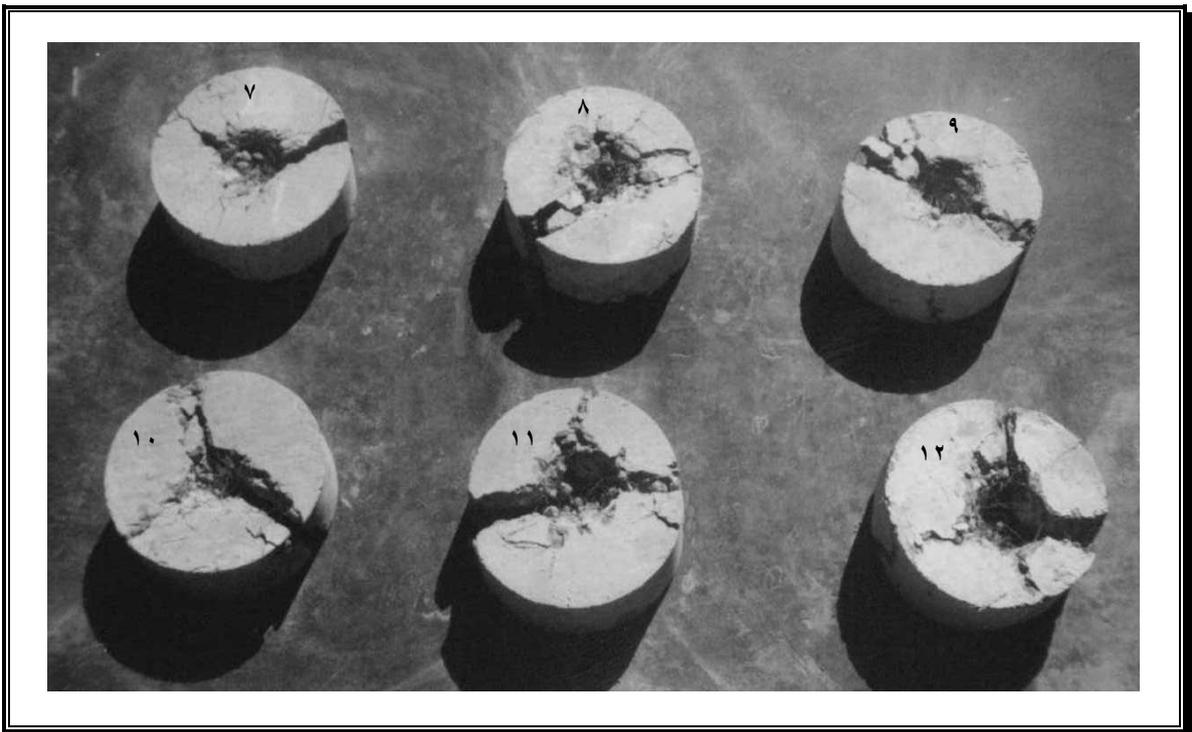
**Plate (ε. 1):** Failure modes under impact of plain concrete and 1.0% SFRC samples for different series

(1, 11) ASF (2, 12) BSF (3, 13) CSFS (4) DWF (5) EWF (6) FWFS; 28 days

(7, 14) ASF (8, 15) BSF (9, 16) CSFS (10) FWFS; 90 days



(a) 0.7% SFRC specimens

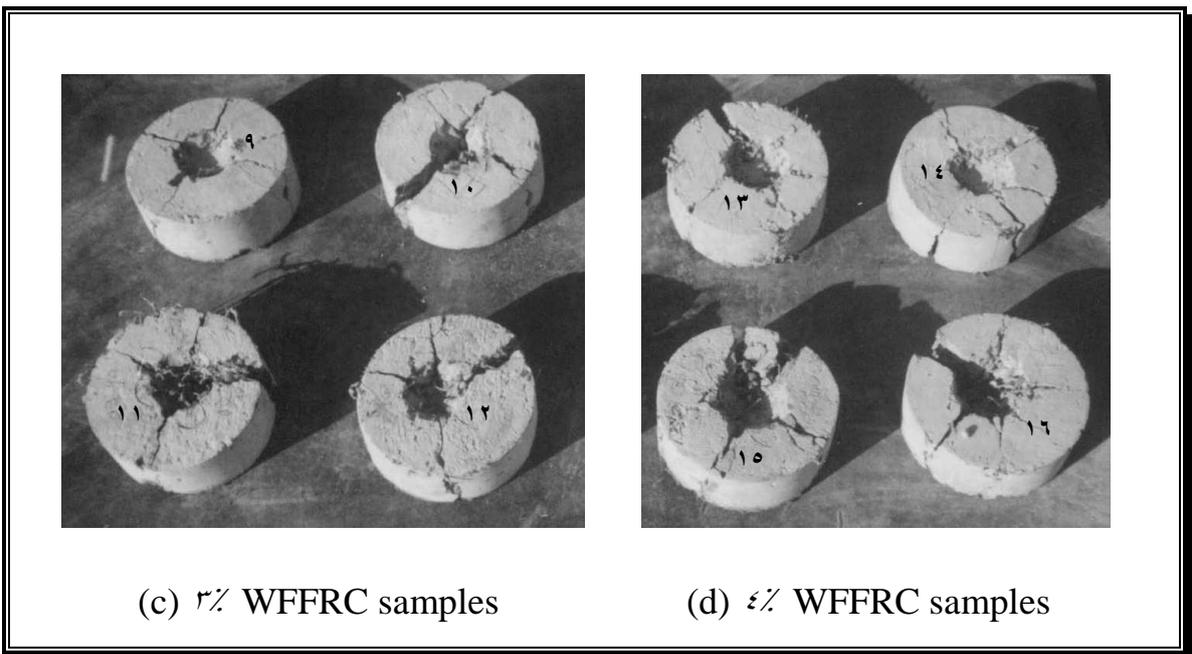
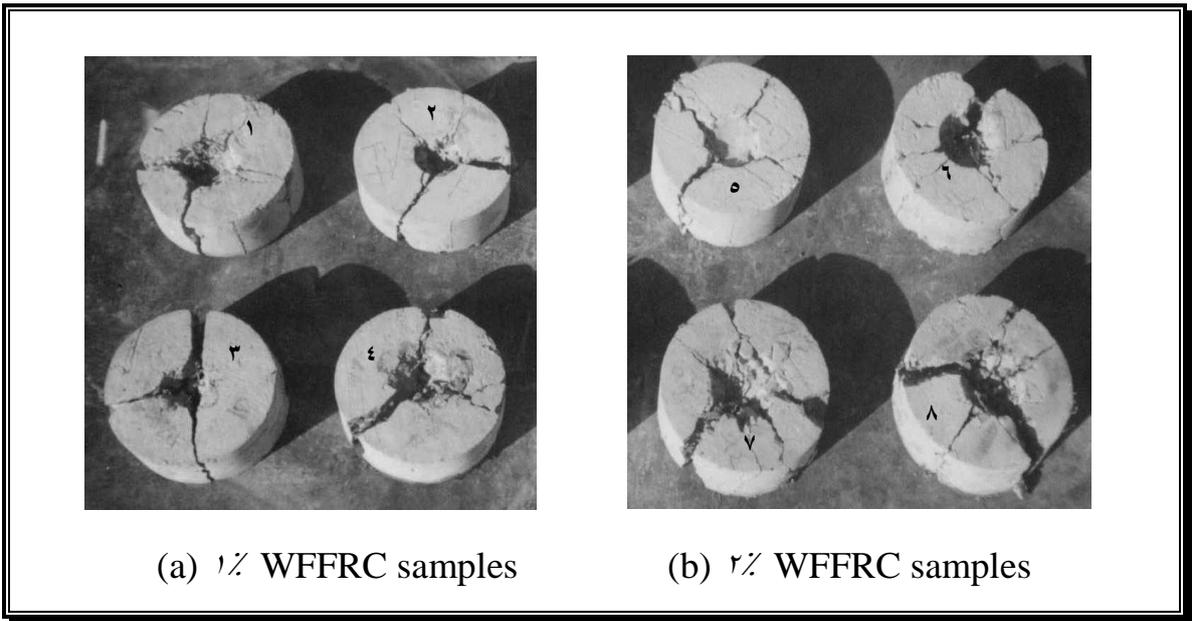


(b) 1.0% SFRC specimens

Plate (ε, η): Failure modes under impact of 0.7% and 1.0% SFRC specimens

(1, 7) ASF (2, 8) BSF (3, 9) CSFS; 28 days

(4, 10) ASF (5, 11) BSF (6, 12) CSFS; 90 days



**Plate (4.7): Failure modes under impact of WWFRC samples**

(1, 2, 3, 4) DWF (5, 6, 7, 8) EWF (9, 10, 11, 12) FWFS; 28 days

(13, 14, 15, 16) FWFS; 90 days

### 4.1.8 Relationships of Compressive Strength, Splitting Tensile Strength, Modulus of Rupture and Volume of Fibers with Impact Resistance

Mathematical models were developed in this study in order to correlate the static strength and the volume of fibers to the impact resistance for each type of FRC investigated. The coefficients of correlation were also determined for each regression to check its statistical significance.

The general form of the regression is

$$Z = a_0 + a_1 \times e^{(a_2 X + a_3 Y)} \quad \dots\dots\dots (4.8)$$

where the regression coefficients  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$  were determined by using a statistical computer program called "Statistica 7".

The empirical relationships of compressive strength and volume percentage of fibers with impact resistance are listed below:

$$I_{vs} = -190 + 170 \times e^{(0.0046 F_{cus} + V_{fs})} \quad \dots\dots\dots (4.9)$$

$$I_{fs} = -485 + 541 \times e^{(-0.0023 F_{cus} + V_{fs})} \quad \dots\dots\dots (4.10)$$

$$I_{vw} = 2.198 + 1.206 \times e^{(0.0731 F_{cuw} + 0.027 V_{fw})} \quad \dots\dots\dots (4.11)$$

$$I_{fw} = -217 + 157 \times e^{(0.0092 F_{cuw} + 0.4536 V_{fw})} \quad \dots\dots\dots (4.12)$$

where

$I_{vs}$ ,  $I_{vw}$ : impact resistance at first visible crack of SFRC and WFFRC respectively (number of blows).

$I_{fs}$ ,  $I_{fw}$ : impact resistance at failure of SFRC and WFFRC (number of blows).

$F_{cus}$ ,  $F_{cuw}$ : cube compressive strength of SFRC and WFFRC (MPa).

$V_{fs}$ ,  $V_{fw}$ : volume fraction of steel and waste flax fibers (%).

Considering the values of splitting tensile strength, the following empirical equations can be written:

$$I_{vs} = -163 + 155 \times e^{(0.0461 F_{sps} + V_{fs})} \quad \dots\dots\dots (\xi. 1 \circ)$$

$$I_{fs} = -510 + 543 \times e^{(-0.0168 F_{sps} + V_{fs})} \quad \dots\dots\dots (\xi. 1 \textcircled{1})$$

$$I_{vw} = -0.6229 + 1.787 \times e^{(0.7838 F_{spw} + 0.0081 V_{fw})} \quad \dots\dots\dots (\xi. 1 \textcircled{2})$$

$$I_{fw} = -195 + 146 \times e^{(0.1019 F_{spw} + 0.4739 V_{fw})} \quad \dots\dots\dots (\xi. 1 \textcircled{3})$$

where

$F_{sps}$  ,  $F_{spw}$  : split-cylinder tensile strength of SFRC and WFFRC respectively (MPa).

The following relationships of modulus of rupture and volume of fibers with impact resistance are also formulated by using Eq.(  $\xi. \circ$ ):

$$I_{vs} = -171 + 160 \times e^{(0.0335 F_{rs} + V_{fs})} \quad \dots\dots\dots (\xi. 1 \textcircled{4})$$

$$I_{fs} = -517 + 573 \times e^{(-0.0196 F_{rs} + V_{fs})} \quad \dots\dots\dots (\xi. 1 \textcircled{5})$$

$$I_{vw} = -0.7552 + 0.3996 \times e^{(0.7877 F_{rw} + 0.03361 V_{fw})} \quad \dots\dots\dots (\xi. 1 \textcircled{6})$$

$$I_{fw} = -187 + 108 \times e^{(0.117 F_{rw} + 0.484 V_{fw})} \quad \dots\dots\dots (\xi. 1 \textcircled{7})$$

where

$F_{rs}$ ,  $F_{rw}$  : modulus of rupture of SFRC and WFFRC respectively (MPa).

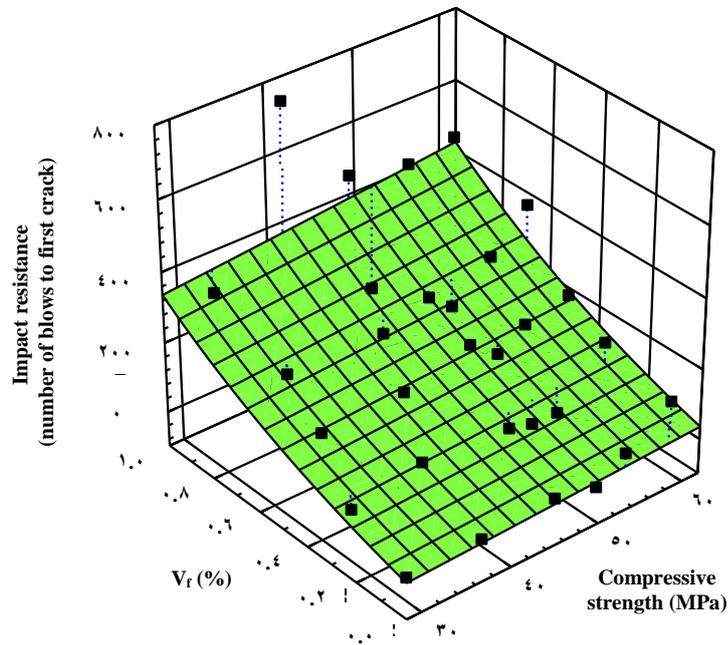
The above correlation equations are also graphically represented in Figs.(  $\xi. \textcircled{8}$ ) to (  $\xi. \textcircled{14}$ ).

From the values of coefficient of correlation, R it can be concluded that these regressions are statistically significant.

Due to the very limited published data in the previous research work on the impact resistance of FRC, no attempts were made to correlate the variables. In addition, the possibility of analyzing the previous investigations data is not available mainly due to the variation in impact resistance testing techniques <sup>( $\xi \textcircled{9}$ )</sup>.

$$I_{vs} = -190 + 170 \times e^{(0.0046 F_{cus} + V_{fs})}$$

$$(R = 0.99)$$



$$I_{fs} = -485 + 541 \times e^{(-0.0023 F_{cus} + V_{fs})}$$

$$(R = 0.97)$$

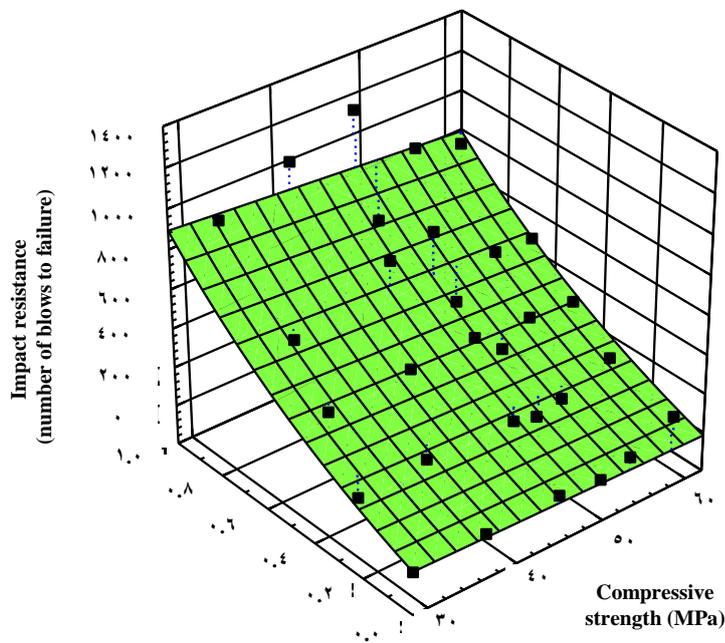
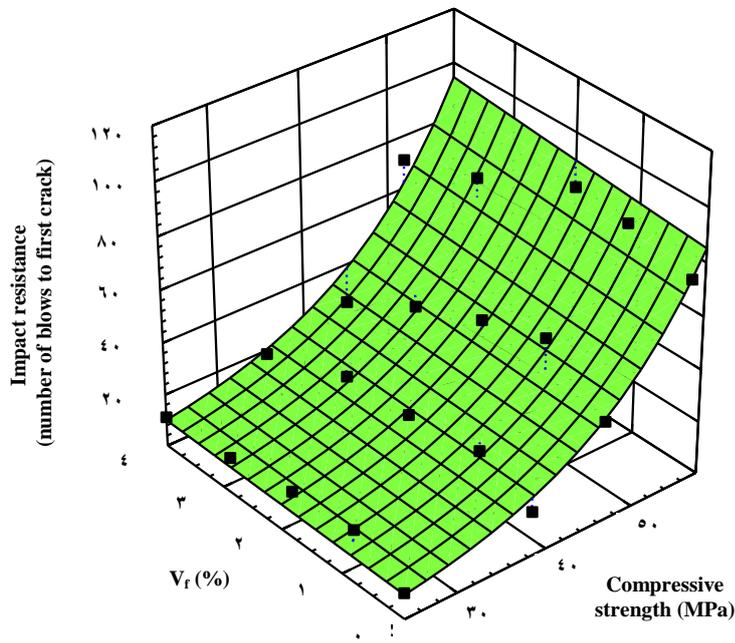


Fig.(4.34): Relationship of compressive strength and volume of steel fibers with impact resistance

$$I_{vw} = 2.198 + 1.206 \times e^{(0.0731F_{cuw} + 0.027V_{fw})}$$

$$(R = 0.99)$$



$$I_{fw} = -217 + 157 \times e^{(0.0092F_{cuw} + 0.4536V_{fw})}$$

$$(R = 0.99)$$

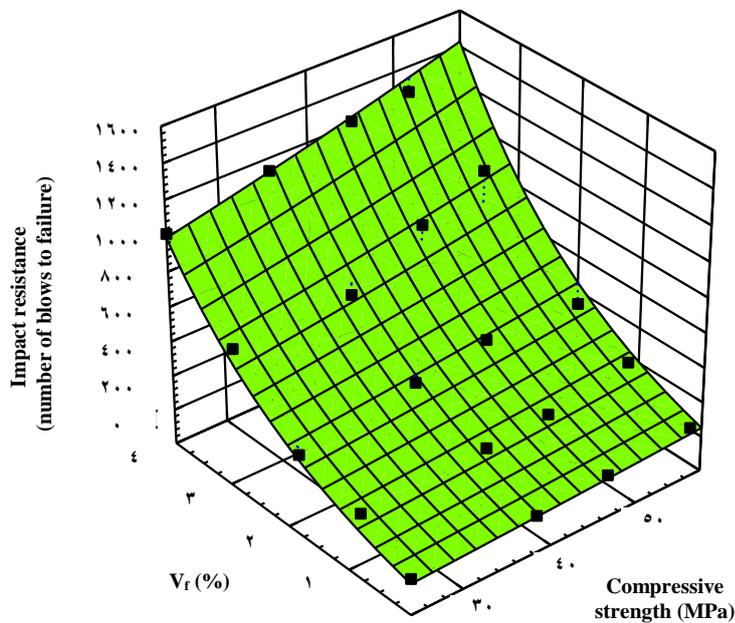
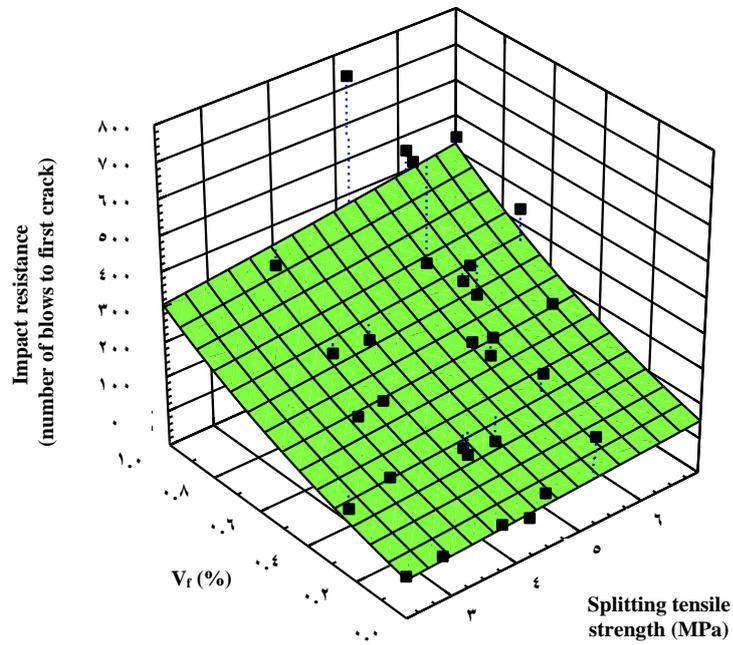


Fig.(4.30): Relationship of compressive strength and volume of waste flax fibers with impact resistance

$$I_{vs} = -163 + 155 \times e^{(0.0461 F_{sps} + V_{fs})}$$

$$(R = 0.99)$$



$$I_{fs} = -510 + 543 \times e^{(-0.0168 F_{sps} + V_{fs})}$$

$$(R = 0.97)$$

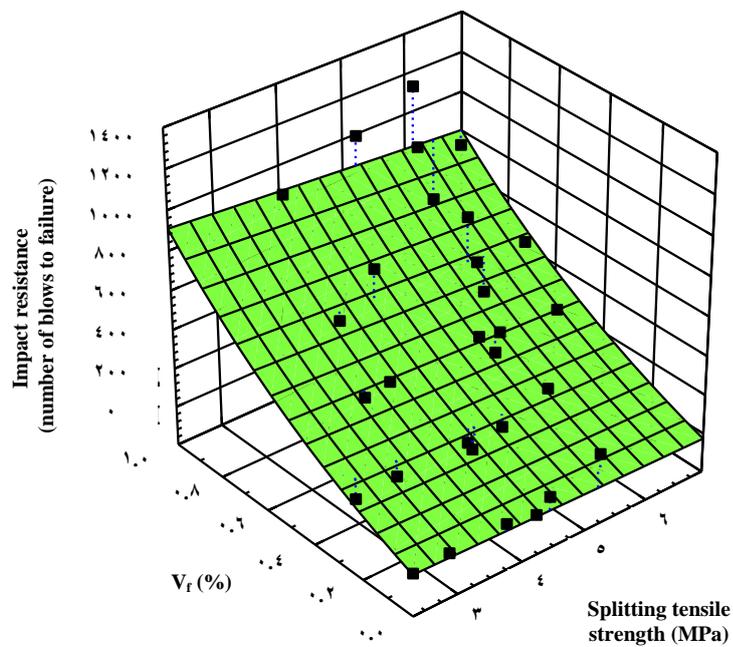
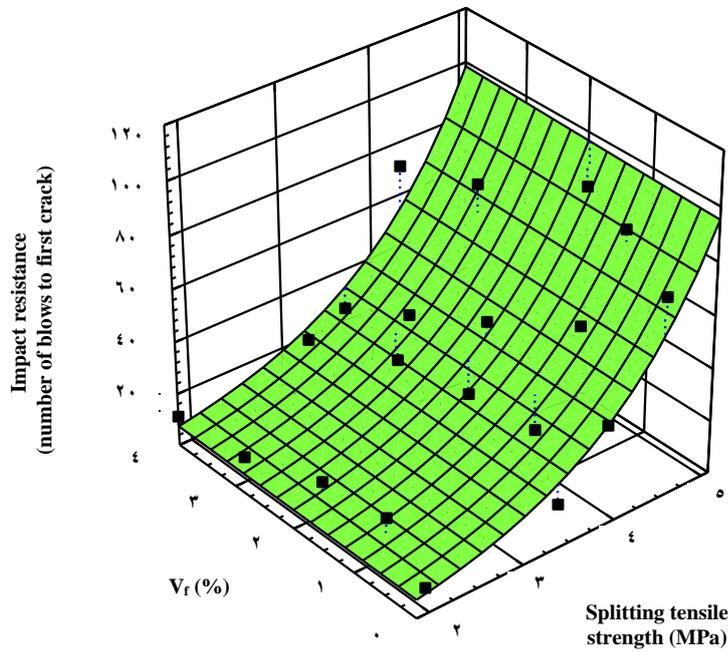


Fig.(4.36): Relationship of splitting tensile strength and volume of steel fibers with impact resistance

$$I_{vw} = -0.6229 + 1.787 \times e^{(0.7838 F_{spw} + 0.0081 V_{fw})}$$

$$(R = 0.94)$$



$$I_{fw} = -195 + 146 \times e^{(0.1019 F_{spw} + 0.4739 V_{fw})}$$

$$(R = 0.99)$$

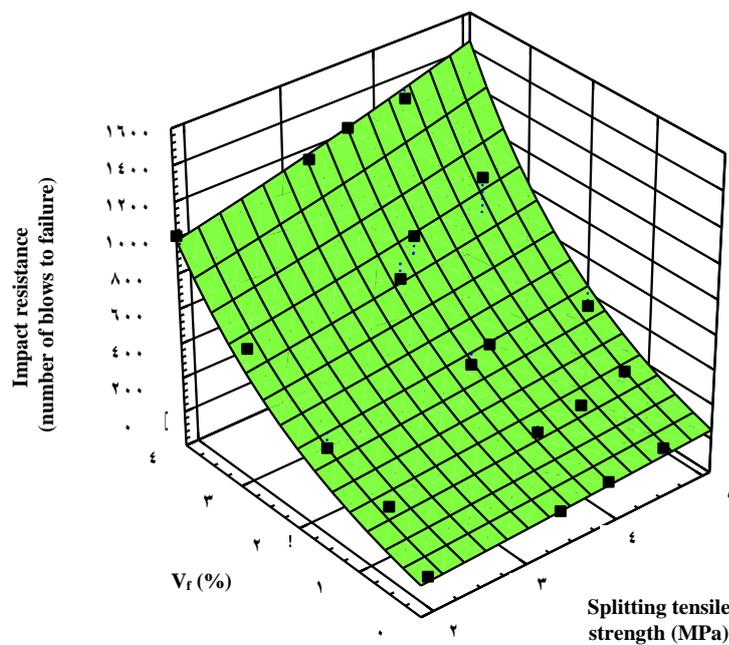
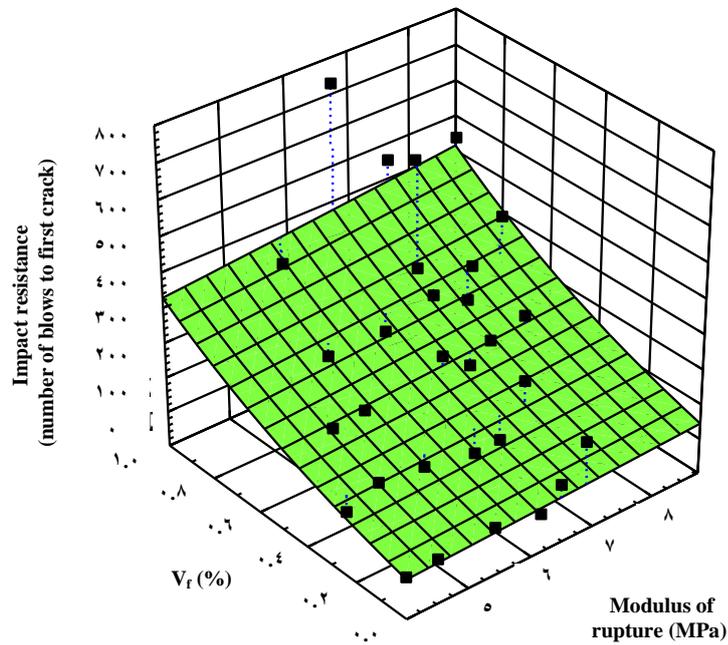


Fig.(4.37): Relationship of splitting tensile strength and volume of waste flax fibers with impact resistance

$$I_{vs} = -171 + 160 \times e^{(0.0335 F_{rs} + V_{fs})}$$

$$(R = 0.97)$$



$$I_{fs} = -517 + 573 \times e^{(-0.0196 F_{rs} + V_{fs})}$$

$$(R = 0.97)$$

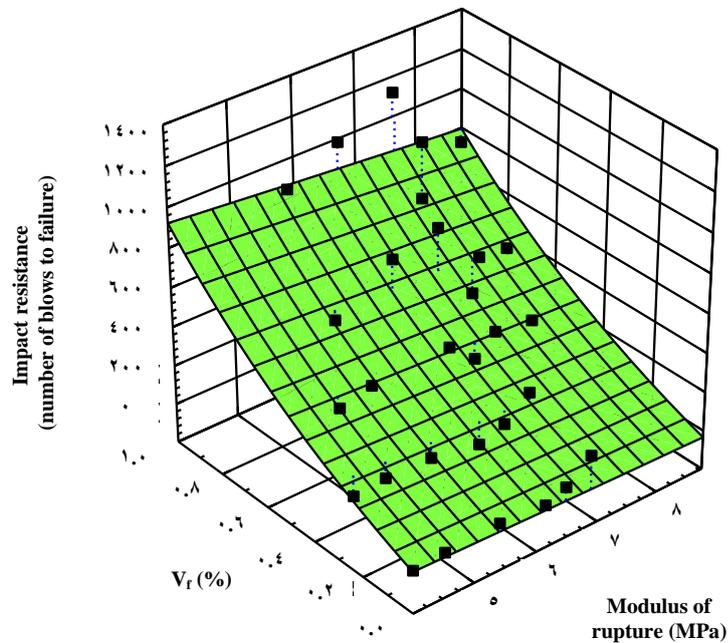
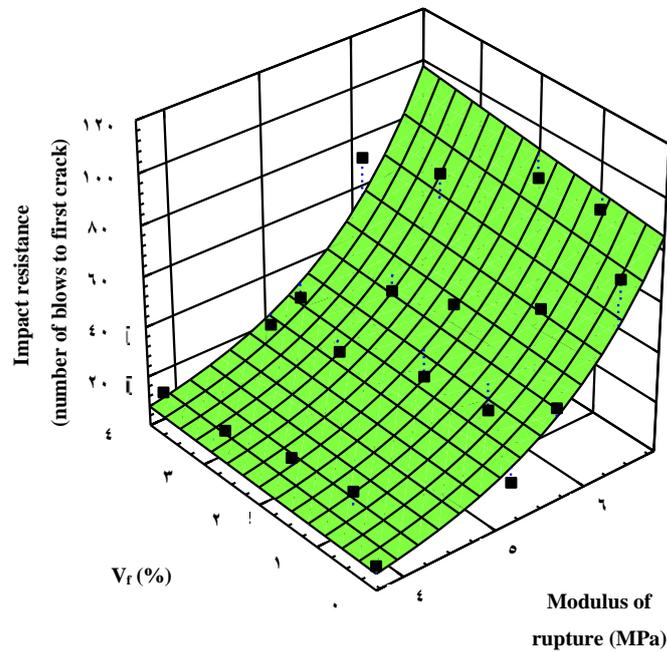


Fig.(4.38): Relationship of modulus of rupture and volume of steel fibers with impact resistance

$$I_{vw} = -0.7552 + 0.3996 \times e^{(0.7877 F_{rw} + 0.03361 V_{fw})}$$

$$(R = 0.92)$$



$$I_{fw} = -187 + 108 \times e^{(0.117 F_{rw} + 0.484 V_{fw})}$$

$$(R = 0.97)$$

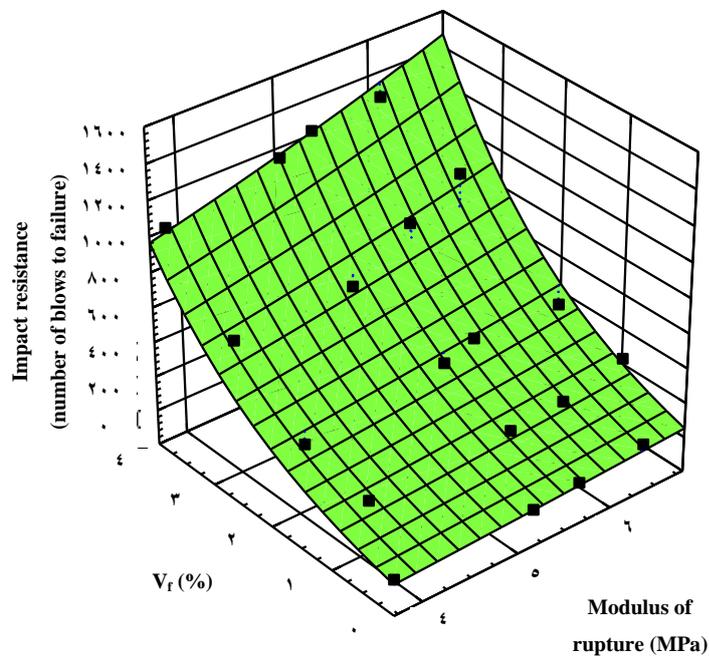


Fig.(4.39): Relationship of modulus of rupture and volume of waste flax fibers with impact resistance

# CHAPTER 5

## CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

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

1. The inclusion of crimped steel fibers improves the compressive strength of concrete. Nevertheless, the maximum improvement is achieved at 1.5% volume of fibers. This improvement is about 1.0 to 20.4% at 28 days and 6.0 to 22.8% at 90 days.
2. The presence of waste flax fibers in concrete has insignificant effect on the compressive strength. The compressive strength of WFFRC is varied from +0 to -1% with respect to plain concrete.
3. The percentage of increase in splitting tensile strength and modulus of rupture is directly proportional to the crimped steel fiber content. The 28 and 90 days increase in splitting tensile strength is in the range of 40.4 to 74.6% and 33.2 to 82.2% respectively for 1% steel fibers. The corresponding increase in modulus of rupture is about 20.0 to 46.0% and 27.8 to 48.7%.
4. It was found that the inclusion of waste flax fibers to plain concrete results in a slight increase in splitting tensile strength and modulus of rupture. The maximum increase is generally observed with

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the initial inclusion of fiber content, at 1% by volume. However, in general, there appears to be a limiting fiber content,  $V_f = 3\%$ , beyond which the both strengths marginally reduce.

6. The results indicate that increasing the amount of crimped steel fibers leads to increase the abrasion resistance significantly. When steel fibers are included at 1%, enhancement in the range of 26.7 to 36.4% and 20.0 to 30.4% is recorded at ages of 30 and 92 days respectively.
7. The abrasion resistance of concrete was found to be increased with the increase in the percentage of waste flax fibers. Increasing the fiber content from 0 to 4% increases the abrasion resistance by 9.8 to 17.4% at 30 days and 10.8% at 92 days.
8. It was found that the compressive strength and age of specimens have a significant enhancement effect on abrasion resistance of plain concrete and FRC.
9. It was found that there is an obvious statistical relationships between the surface property (depth of wear) and bulk characteristics (compressive strength, splitting tensile strength and modulus of rupture). The proposed logarithmic equations are found to give an accurate representation of these relations.
10. The impact resistance at first crack can be improved when increasing the percentage of crimped steel fibers.
  - 10.1. The results show that the higher the volume fraction of crimped steel fibers the more resistant to impact at failure is the composite.
  - 10.2. It was found that waste flax fibers have a moderate effect on the impact resistance up to first visible crack.

١٢. The results reveal that the capacity of concrete to resist impact loading at failure can be significantly improved by increasing the content of waste flax fibers.
١٣. It was found that reinforcing concrete by ٤% waste flax fibers produces impact strength comparable or higher than that obtained when ١% standard crimped steel fibers is added.
١٤. Maintaining the same mix workability, the impact resistance of plain concrete generally increases with compressive strength and age. Impact resistance was found to be drastically lowered as the W/C ratio of the mix is increased.
١٥. With the SFRC, there appears to be a limit to matrix compressive strength beyond which the impact resistance at failure starts to decrease. A strength of around ٤٥ MPa is such a limit.
١٦. It was found that WFFRC generally exhibits more resistance to impact at the higher matrix strengths and the later ages.
١٧. With an adequate fiber content, it was found that the failure mode under repeated impact loads involves multiple cracking, spalling and disintegration.
١٨. New and more accurate models were developed for correlating static strength and the volume of fibers to the impact resistance for each SFRC and WFFRC.
١٩. Among the most serious problems that are experienced in industrial floors, overlays, pavements and other such concrete applications, are their ability to resist impact and abrasion forces. For those problems the following solutions can be suggested:
  - a. If the impact resistance, then abrasion resistance are of major concern, the use of superplasticized concrete mix ١:١:٢:٠.٣٦ (cement: sand: gravel: water by wt.) reinforced with ٤% volume of waste flax fibers will give the most significant resistance to impact and good resistance to abrasion.

- b. If the abrasion resistance, then impact resistance are of major importance, the use of superplasticized concrete mix 1:1:2:0.33 containing 1% crimped steel fibers will produce a composite with a maximum resistance to abrasion and a significant resistance to impact.

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## Recommendations

١. Further work is required to investigate the effect of surface coatings on abrasion resistance of SFRC and WFFRC.
٢. The influence of the testing conditions (air-dry or wet) on abrasion resistance of SFRC and WFFRC should be investigated.
٣. Further research is necessary to provide information about the effect of the curing method, rather than that used in this research, on the impact and abrasion resistance of SFRC and WFFRC (i.e. one week moist curing and accelerated curing).
٤. More experimental work is required to investigate the effect of other types of fibers such as glass, polyethylene and cellulose fibers on impact and abrasion resistance of concrete.

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