Effect of Steel Fibers on the Properties of Refractory Free Cement Concrete

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Abstract

Free cement refractory concrete is a type of refractory concrete with replacing alumina cement by bonding materials such as white kaolin, red kaolin and fumed silica. The free cement refractory concrete used in many applications like Petrochemicals, iron furnaces and cement production industries.

The research clarifies the effect of steel fibers with two types crimped steel fibers and hooked steel fibers with percentages 0.5%, 1% and 1.5% by volume from weight of bauxite aggregates.

The additions of steel fibers with two types gave good properties in high temperatures where the specimens keep the dimension without failure and the properties made the best. the percentage of increasing for thermal conductivity was 44% for 1.5% crimped fibers and 42.8% for 1.5% hooked end fibers and the percentage increasing in bulk density of free cement refractory concrete was 30% for 1.5% crimped fibers and 27% for 15% hooked end fibers .

From this study can be concluded that the best types of steel fibers which used in free cement refractory concrete is the crimped type with percentage 1.5%.

Key words: Refractory concrete, steel fibers, free cement, fumed silica, white kaolin

تأثيرالالياف الحديدية على خواص الخرسانة الحرارية الخالية من السمنت الالوميني

الخلاصة

الخرسانة الحراريه الخاليه من السمنت هي احد انواع الخرسانة الحرارية والتي يتم انتاجها باستبدال السمنت الالوميني بأي مادة رابطه مثل الكاؤولين الابيض والكاؤولين الاحمر ومسحوق ابخرة السليكا. تستخدم الخرسانه الحراريه في العديد من التطبيقات الهندسية المختلفه مثل افران معامل السمنت وافران معامل انتاج الحديد والبتروكيماويات.

البحث تتضمن دراسه تاثير الالياف الحديديه وبنوعيها المجعده والمعقوفه النهايات وبنسب 0,5%، 1% و 1,5% من حجم الخليط بعد اختيار النسبه المثلى للمواد الرابطه على خواص الخرسانة الحراريه الخاليه من السمنت.

اوضحت نتائج الفحوصات ان الخرسانة الحراريه الخاليه من السمنت بأن اضافه الالياف الحديدية وبنوعيها المجعده والمعقوفه النهايات اعطت الخرسانة الحرارية الخاليه من السمنت خواص جيده بسبب خواصها المطيليه وتقليل نسبة الفشل للنماذج حيث حافظت النماذج على تماسكها دون ان تشظي او تشقق .وصلت نسبه الزياده في الموصليه الحراريه الى 44% عند اضافه 1,5% من الالياف المجعده و42,8% عند اضافه 1,5% من الالياف المعقوفه النهايات كما وصلت نسبه الزياده في الكثافه الكليه الى 30% عند اضافه 1,5% من الالياف المجعده و27% عند اضافه 1,5% من الالياف المعقوفه النهايات.

من خلال هذه الدراسه نستنتج انه بالامكان انتاج خرسانة حرارية خاليه من السمنت ذات خواص جيده عند اضافة الالياف الحديديه المجعــــــــــــــــده بنـــــــــــــسبه 1,5%.

1.0 Introduction

Refractories defines as "non-metallic materials having those chemical and physical properties that make them applicable for structures, or as components of systems, that are exposed to environments above 1000 °F (811 K; 538 °C).

Refractory materials are used in linings for furnaces, kilns, incinerators and reactors. They are also used to make crucibles

The refractory concrete suitable for use at high temperatures is composed of hydraulic cement (calcium aluminates cement) as the binding agent, combined with heat resistant refractory aggregates and or fillers. **(Newman and Choo 2003)**

Lee et al 2004 found that the refractories are composite materials used in large volumes in extreme, usually corrosive, environments as furnace linings for high temperature materials processing and other applications in which thermomechanical and thermochemical properties are critical. Many types of refractories range from relatively density (up to 90%) bricks to low density (10%) fibrous thermal insulation.

Hosseini et al 2008 studied the refractory concrete and presented it as a special type of concrete for high temperature usage, which consists of refractory aggregates, binders, plasticizer liquid and special admixtures if needed. Special binders are used in this type of concrete which are different in ordinary concrete structures. In normal or low temperatures, reaction between plasticizer liquid and binder harden the mixtures .In these concretes, like other types of concretes, water is necessary for forming and hardening process.

During heating process, the excess water will flow out of the concrete and by this reason, the amount of water should be carefully optimized in mixture design. Using admixtures and other chemical compounds can improve the curing process and reaching to some special properties.

Free cement refractory concrete (FCRC) is a type of refractory concrete made without cement using additives and different material bonds. It has a good volume stability and less vulnerable to the main destructive forces in service slags, molten metals and chemical attack.

Peng et al 2007 studied the advantages of adding microsilica to bauxite based on low cement castables (LCC) and ultra low cement castables (ULCC) by reducing cement content and it affects the reheology and packing of refractory concrete.

The use of microsilica in refractory concrete provides better particle packing, it allows less water to be used while maintaining the same flow characteristics. It also promotes low temperature sintering and the formation of mullite in the matrix of the refractory concrete. This produces a refractory concrete that has a low permeability to avoid gas, slag and metal penetration.

Badiee and Sasan 2009 concluded that the addition of colloidal silica on refractory concrete decreases the bulk density of refractory concrete at all temperature because colloidal silica content leads to higher liquid content in the refractory concrete composition. Therefore the removal of moisture during drying causes increasing in porosity in the body. Also they found that the higher contents of colloidal silica have disadvantage in the strength development where the mechanical strength increases and the highest strength value at 1500 C° because of a higher degree of sintering and high ceramic bond.

1.2 Objective of this Research

The research aims for studying the effect of two types of steel fibers such as crimped steel fibers and hooked end steel fibers with different percentages on the properties of free cement refractory concrete.

1.3 Fiber Reinforced Refractory Concrete

Lankerd and sheets 1971 showed that the history of adding steel fibers to ceramic materials begin in 1954, where this material showed an improvement in tensile strength and impact resistance and thermal stresses. This improvement was not effective at high temperatures due to fiber damage during the smelting process of the ceramic fiber ferrous oxidation result.

ACI 544.1R-1996 Stainless steel fibers have been used as reinforcement in monolithic refractories since 1970. Steel fiber reinforced refractories(SFRR)have shown excellent performance in a number of refractory application areas including ferrous and nonferrous metal production and processing. Historically, steel fibers have been added to refractory concretes to provide improvements in resistance to cracking and spalling in applications where thermal cycling and thermal shock have limited the service life of the refractory. Also clarified that the fiber strength, stiffness, and the ability of the fibers are important for bond the refractory concrete.

Bond is dependent on the aspect ratio of the fiber. Typical aspect ratios range from about 20 to 100, while length dimensions range from 0.25 to 3 in. (6.4 to 76 mm).Steel fibers have a relatively high strength and modulus of elasticity, they are protected from corrosion by the alkaline environment of the cementitious matrix, and their bond to the matrix can be enhanced by mechanical anchorage or surface roughness.

Samadi and Fard 1999 observed that the refractory concrete was a brittle materials but it has high temperature resistance, chemical stability and thermal, mechanical shock. This happens because of rigid bond in ceramic. A rigidity of ceramic is considered a problem affect the properties of refractory and to solve this problem need steel fibers to increase toughness. They concluded that increasing fiber amount lead to:

1. Flow ability and workability decrease.
2. Modulus of rupture (MOR) and cold crushed strength (CCS) increase.
3. Hot modulus of rupture (HMOR) does not increase.
4. Thermal shock resistance increases up to 3% wt and then decreases.
5. Bulk density and apparent porosity make no change.

Alrawi 2000 found that the addition f steel fiber on refractory concrete improved the properties of refractory concrete in temperature reaching to 1000c°and it increases the density of refractory cncrete. The compressive strength and the hot properties, because the steel fibers work to decrease the cracks and limit it and also increasing the force of bond between the matrix.

Samadi 2003 presented the factors affecting the fibers functions, they are:

1. Fiber length.
2. Fiber orientation.
3. Amount of fiber.

The figure below show the stress-strain curve for refractory concrete with and without steel fibers

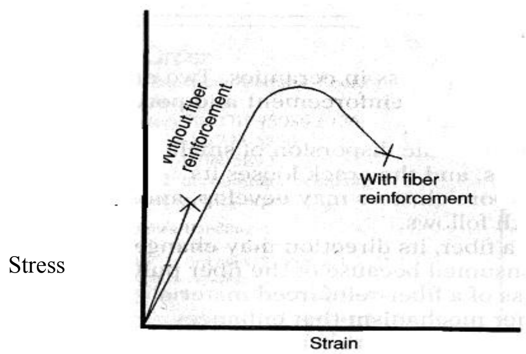

Fig 1 The stress-strain curve for reinforced refractory by **Samadi 2003**

Regin et al 2011 found that refractory concrete reinforced with steel fibers and adding microsilica observed increasing in density about 2% at 100 C° and it reaches to 7% at 800 C°. also referred that the reinforcement with steel fibers and microsilica leads to increase cold crushed strength from (22% to 47%) at 100 C°. This increase decreases in high temperature at 1000 C° where the increase becomes 9% with microsilica and steel fiber, they also observed that the optimum value of fiber 1% and microsilica 5% to increase strength

2. Raw Materials

2.1 Bauxite Aggregate

It is a fine aggregate produced by a State Company for the manufacture of refractories and it equipped from Building Research Center. It is available in the west area of Iraq.

Tables (1) and (2) show the sieve analysis and chemical analysis of bauxite aggregate .The sieve analysis indicates that the aggregate has a maximum size 4.75mm according

to the requirement of **ACI report 547-2008** and the chemical analysis shows the compound of aggregate which consist of mainly from alumina , silicate and impurities (F_2O_3 , CaO and MgO).

2.2 White kaolin

It is used as a bonding material in refractory concrete free cement (FCRC) with percentages 5, 10, 12 and 15 % by weight of bauxite aggregate and the chemical composition $Al_2Si_2O_5(OH)_4$ which transfer to metakaolin $Al_2Si_2O_7$ at 600 C° and later formed mullite $3Al_2O_3.2SiO_2$ at 1050 C°.

It is available at Ardama region in west of Iraq and equipped from Building Research Center.

Table (3) shows the result of sieve analysis of white kaolin with maximum size 0.15 mm. It also shows thermal withstand of white kaolin at 1400 C°.

Table (4) shows the result of chemical analysis for white kaolin which mainly consist of silica SiO_2 with percent 48.10% and alumina Al_2O_3 with percent 35.55%. It also contains a little percentage of Fe_2O_3, CaO and MgO which are considered as fluxes. This test made in the Laboratories of General Direction of Geological survey and Mining.

2.3 Fumed Silica

Fumed silica is produced by a vaporphase hydrolysis process by using chlorosilanes such as: silicon tetrachloride in a flame of hydrogen and oxygen. Fumed silica is described as a white and fluffy powder **ACI 234R-(1996)**. It is produced by Wacker Silicones Company in Germany and it is obtained from local markets with 10kg in one sack.

Fumed silica used as a bonding material with percentages 2, 3, 4 and 5% by weight of bauxite aggregate.

Chemical compositions are tested in the Laboratories of General Direction of Geological Survey and Mining is given in Table (5) and the physical information about this product is given in Table (6).

4. Steel Fiber

The steel fibers are used type of 309 with two forms: hook end and crimped fibers. These fibers are associated with others with adhesive material separate from other at mixing, it is used

according to **ACI 5441-R -1996**.

These fibers are known as Dramix with rectangular section 0.5*0.4mm.The length of crimped fiber is 30mm and 34mm for hooked end fiber. The Ultimate Tensile Strength 1050 MPa, Elastic Modulus 210 kN/mm², Aspect ratio l/d=80 and Specific Gravity 8. It equipped from Building Center Research.

In this research three percentages are used for each type of fibers (0.5%, 1% and1.5%) by volume.

3. Program of Experimental Laborary

There is no standard method to design the mixes of free cement refractory concrete so depending on the previous research and some limitation like:

1. The modulus of rupture for refractory concrete after drying on 110 C° not less than 2 MPa according to **ASTM C401-2000**.
2. The apparent porosity for drying samples is not greater than 45% according to **BS 1902: 3.8:1989**.

3.1 Preparation of Free Cement Refractory Concrete

In this research, the material has been mixed as a manual mix to obtain a homogenous mixture and good workability where the materials mixed in drying stage for 3 min, which begins with bauxite aggregate, adding white or red kaolin, fumed silica, steel fibers and later adding water with 4.5-5.5% by weight of aggregate. Table (7) shows the percentages of materials and water for each mixture.

For manual mixing, limited the percentage of water/dry weight according to **ASTM C860-2000** which is named as Ball- in- Hand which gave the standard consistency for refractory concrete. It is obtained for each percentage of white, red kaolin, fume silica and steel fibers. Where the percentage of water/dry weight is changed when adding fume silica and steel fibers where the fume silica need more water because of high surface area and when added steel fibers needs to increase water demand to increase workability of mixture. This process needs at least 5 min.

3.2 Molding and Compaction Models

The mixture placed in moulds after finishing from mixed where the dimensions of mould are 50*50*50 mm for cubic specimens and 40*40*160 mm for prism specimens. The moulds must be coated from the internal interface with a thin layer of oil to prevent adhesion of mixture to aspects of mould.

The mixture compact in moulds with two layers by small steel hammer to obtain specimens with homogenous frame and with two shapes cubic and prisms. This process is done according to **ASTM C 862-2001**.

6.3.2 Drying and Firing

After compacting the specimens leave for 24 hours at laboratory temperature, after that open the molds and place the specimens in oven for drying at 110 C° for 24 hour according to **ASTM C865-1995**.

After drying the specimens are placed for firing until they reach the temperature 1200C° with burn rate 3.33 C°/min according to **ASTM C865-1995** then leave the specimens at this temperature for 2 hours known as socking time where the specimens withstand high temperatures without sintering. The firing for FCRC effective on increasing the bonding force between the matrix. Fig 2 show the X-ray diffraction analysis for free cement refractory concrete with white kaolin and fume silica.

4. Experimental Tests

The tests are due to American Standard for Testing and Materials, where the Bulk Density is made according to ASTM C 20, the compressive strength due to ASTM C133 and thermal shock resistance according to BS1902: Section 7.6-1987 and reheat test according to ASTM C 113.

5. Result and Discussion

The steel fibers used with two types and different percentage 0.5%,1% and 1.5% by volume with white kaolin with different percentage 5%, 10%,12% and 15% by weigh of bauxite aggregate and 2% by weight bauxite aggregate of fumed silica and study the effect of fibers on properties of free cement refractory concrete.

5.1 Bulk Density

Table (8) and table (9), Figure (3,4) show the results of the density of free cement refractory concrete which increases with adding steel fibers because the high density of steel fibers reaches to 7.86 gm/cm³that increase the density .The presence of white kaolin with fume silica forming mullite which improved the bonding force of matrix. The type of fiber also increases the bonding between matrix, the crimped steel fibers increase the density of free cement refractory concrete more than the hooked end fibers. The percentage of increasing was 30% for 0.5-1.5% crimped fibers and 27% for 0.5-1.5% hooked fibers.

5.2 Permanent Linear Change

From table (10) and table (11) figures (5), (6) show the result of permanent linear change of reinforced free cement refractory concrete. The additions of steel fibers on free cement refractory concrete lead to limited thermal shrinkage through retard. The attraction exists between particles of free cement refractory concrete in high temperature but the steel fibers with two types work to distribute the stresses which lead to keep the dimensions of samples. The permanent linear change decreases at adding the crimped steel fibers where reaches to 71.3% at increased from 0.5-1.5% and the percentage of decreasing for hooked end fibers reaches to 75.5% when increased from 0.5-1.5%.

5.3 Compressive Strength

Figures (7), (8) and table (12), (13) show that the compressive strength of free cement refractory concrete increased when the steel fibers adding. The steel fibers withstand the stresses that act on refractory concrete without breakage because the steel fibers failure in pullout which lead to increase the compressive strength. Different types of steel fibers affect on increasing compressive strength where the hooked end fiber have higher compressive strength than crimped fibers because of hooked end fibers make more strength bonds with matrix than crimped fibers result from the length of fibers that affect on Flexural Toughness Index which limit the force caused the first crack according to **ACI 5441-R 1996**. The percentage of increasing was 22.7% for 0.5-1.5% crimped fibers and 28.4% for 0.5-1.5% hooked end fibers.

5.4 Reheat Test

Figures (9) and (10) and table (14),(15) show that the reheat test of free cement refractory concrete decreased because the permanent linear change when steel fiber content increased where the fibers may decrease the cracks which may cause decreasing in shrinkage and expansion of specimens that also result from increasing the bonding force of matrix.

The decrease reaches to 84% for crimped steel fibers and 75% for hooked steel fibers.

5.5 Thermal Conductivity

The additions of steel fibers with the two types of fibers increase the thermal conductivity of free cement refractory concrete where steel fibers have a good thermal conductivity. It formed a continuous phase of steel fibers. This phase increased when the steel fiber content increased also the increasing in density for free cement refractory concrete improved the property of thermal conductivity. Thermal conductivity measured by lee disk device. Figure (11),(12) and table (16),(17) show the test result of thermal conductivity of free cement refractory concrete with two types of steel fibers.

The percentage of increase of thermal conductivity reaches to 44.7% for crimped fibers and 42.8% for hooked fibers.

5.6 Thermal Shock Resistance

Figures (13) and (14) and table (18),(19) below shows that the steel fibers work to decrease the cracks which are caused through the 20 cycles of cooling and heating for the specimens of free cement refractory concrete and distribute the stresses that lead to increase the resistance for spalling and bind the cracking parts which improve the thermal shock resistance.

The percentage of decreasing 50% when using 0.5-1.5% crimped fibers 46% for 0.5-1.5% hooked end fibers.

5.7 Modulus of Rupture

The modulus of rupture increased when the steel fibers content increased which work to increase density and bond strength between matrix. But this increasing was limited because of the oxidation of fibers at high temperatures where

the steel fibers loss the ductility at high temperatures.

The crimped steel fibers have percentage of increasing was 19.7% for 0.5-1.5% and the percentage of increasing for 0.5-1.5% hooked end steel fibers was 25.4% as shown in Figure (15) and (16) and table (20),(21).

6. Conclusions

Based on the field work and the testing technique adopted, the following conclusions can be drawn:

1. Bulk density of FCRC increased when using two types of steel fibers because of high density of steel fibers the percentage of increasing was 30% for 1.5% crimped fibers and 27% for 15% hooked end fibers.

2. Permanent linear change decreased when using two types of steel fibers for FCRC, the percentage of decreasing was 71.3% for 1.5% crimped fibers and 75.5% for 1.5% hooked end fibers.

3. Compressive strength of FCRC increased when using steel fibers with two types where the percentage of increasing was 22.7% for 1.5% crimped fibers and 28.4% for 1.5% hooked end fibers.

4. Permanent linear change decreasing after reheat test when using two types of steel fibers and the percentage of decreasing was 84% for 1.5% crimped fibers and 75% for 1.5% hooked end fibers.

5. Thermal conductivity of FCRC improved when using two types of steel fibers where the percentage of increasing was 44.7% for 1.5% crimped fibers and 42.8% for 1.5% hooked end fibers.

6. Thermal shock resistance improved with addition of two types of steel fibers where the specimens keep their dimension after 20 cycles of heating and cooling without failure.

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LIST OF NOTATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
B.S	British Standard
CAC	Calcium Alumina Cement
CCS	Cold Crush Strength
FCRC	Free Cement Refractory Concrete
HMOR	Hot Modulus of Rupture
LCC	Low Cement Castables
MOR	Modulus of Rupture
PLC	PermanentLinear Change
SFC	Self Flow Castables
SFRR	Steel Fiber Reinforced Refractories
ULCC	Ultra Low Cement Castables

Table .1 Sieve analyses for bauxite aggregate

Sieve size	%Passing	ACI report 547 requirements
4.75mm	100	
2.36mm	87.3	
1.18mm	64.2	
600 µm	46.6	
300 µm	24.5	Retaining on this sieve 75%
150 µm	12.8	Passing on this sieve 10-15%
Specific gravity	2.49	

Table .2 chemical analyses for bauxite aggregate
(The National Center Construction Laboratories)

Oxides	Percent
Al_2O_3	66.1
SiO_2	27.4
Na_2O+K_2O	0.61
CaO	2.46
MgO	0.95
Fe_2O_3	1.21
L.O.I	0.14
Total	99.42

Table .3 Sieve analysis and thermal properties for white kaolin

Sieve size	%Passing
0.3 mm	100
0.15 mm	96
0.075 mm	55
Thermal bearing	>1400 C°

Table .4 Chemical analysis for white kaolin
(The National Center Construction Laboratories)

Oxides	Percent
Al_2O_3	35.00
SiO_2	48.10
Fe_2O_3	0.85
CaO	1.42
MgO	0.45
SO_3	0.68
L.O.I.	13.50
Total	100.00

Table .5 Chemical analysis of fumed silica

Oxides	Percent
SiO_2	99.1
Fe_2O_3	0.0035
Al_2O_3	<0.035
TiO_2	<0.006
MgO	0.0052
CaO	0.03
SO_3	<0.7
L.O.I.	0.7

Table.6 Physical properties of fumed silica (weaker company 47 *)

Physical properties	Test result
Density gm/cm^3	2.2
SiO_2 (when firing at 1000 C° for 2hours)	>99.8
Loss of weight (when firing at 1000 C° for 2 hours)	< 2%
Surface area m^2/gm	(170-230)
PH	3.9-4.3
Loss at drying for two hours at 105 C°	< 1.5%
Moisture %	0.82
% retained on 40 μm sieve	< 0.04

*Technical data

Table .7 The percentages of materials in mixture as %of weight of aggregate

Mix no.	White kaolin %	Fumed silica %	Steel fibers %	Water %	Bauxite aggregate %
1	5	2	0.5	4.5	88
			1	5	87
			1.5	5.5	86
2	10		0.5	4.5	83
			1	5	82
			1.5	5.5	81
3	12		0.5	4.5	81
			1	5	80
			1.5	5.5	79
4	15		0.5	4.5	78
			1	5	77
			1.5	5.5	76

Table .8 Test result of bulk density of reinforced free cement refractory concrete with crimped fibers

White kaolin %	Bulk Density gm/cm^3		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	1.83	1.86	1.9
10	1.92	1.95	1.99
12	2	2.1	2.15
15	2.14	2.22	2.38

Table .9 Test result of bulk density of reinforced free cement refractory concrete with hooked fibers

White kaolin %	Bulk Density gm/cm^3		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	1.81	1.85	1.88
10	1.9	1.92	1.96
12	1.98	2.06	2.12
15	2.08	2.16	2.3

White kaolin %	Permanent Linear Change %		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	0.08	0.06	0.034
10	0.045	0.024	0.021
12	0.033	0.016	0.013
15	0.015	0.0043	0.002

Table .10 Test result of permanent linear change of reinforced free cement refractory concrete with crimped fibers

Table .11 Test result of permanent linear change of reinforced free cement refractory concrete with hooked fibers

White kaolin %	Permanent Linear Change %		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	0.11	0.12	0.146
10	0.032	0.066	0.08
12	0.022	0.046	0.066
15	0.013	0.022	0.053

Table .12 Test result of compressive strength of reinforced free cement refractory concrete with crimped fibers

White kaolin %	Compressive Strength MPa		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	5	5.12	5.25
10	5.4	5.6	5.76
12	5.81	5.9	6.24
15	6.2	6.35	6.56

Table.13 Test result of compressive strength of reinforced free cement refractory concrete with hooked fibers

White kaolin %	Compressive Strength MPa		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	5.1	5.2	5.32
10	5.39	5.53	5.68
12	5.65	5.8	6.2
15	6.23	6.44	6.65

Table .14 Test result of Permanent Linear Change after reheat of reinforced free cement refractory concrete with crimped fibers

White kaolin %	Permanent Linear Change %		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	0.35	0.24	0.15
10	0.18	0.1	0.08
12	0.083	0.077	0.046
15	0.038	0.04	0.024

Table .15 Test result of permanent linear change after reheat of reinforced free cement refractory concrete with hooked fibers with hooked fibers

White kaolin %	Permanent Linear Change %		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	0.18	0.15	0.13
10	0.14	0.11	0.083
12	0.12	0.1	0.075
15	0.08	0.053	0.02

Table .16 Test result of thermal conductivity of reinforce free cement refractory concrete with crimped fibers

White kaolin %	Thermal Conductivity wt/k.m		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	0.35	0.42	0.5
10	0.4	0.45	0.58
12	0.45	0.52	0.61
15	0.47	0.57	0.67

Table .17 Test result of thermal conductivity of reinforce free cement refractory concrete with hooked fibers

White kaolin %	Thermal Conductivity wt/k.m		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	0.3	0.38	0.45
10	0.35	0.43	0.5
12	0.4	0.47	0.58
15	0.46	0.55	0.63

Table .18 Test result of compressive strength after 20 cycles of cooling and heating of reinforced free cement refractory concrete with crimped fibers

White kaolin %	% of decreasing in Compressive Strength		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	59	56	55
10	53.5	53	52.3
12	52.6	52.2	51.1
15	51.3	50.7	48.3

Table .19 Test result of % decreasing compressive strength after 20 cycles of cooling and heating of reinforced free cement refractory concrete with crimped fibers

White kaolin %	% of decreasing in Compressive Strength		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	58.8	55	54.3
10	56.5	54.2	52.8
12	55.6	52.6	51.9
15	51.3	50.2	48.1

Table .20 Test result of modulus of rupture for reinforced free cement refractory concrete with crimped fibers

White kaolin %	Modulus of Rupture MPa		
	Fumed silica 2%		
	0.5% crimped fiber	1% crimped fiber	1.5% crimped fiber
5	4.25	4.38	4.61
10	4.7	4.79	4.97
12	4.88	5.06	5.19
15	5.01	5.18	5.33

Table .21 Test result of modulus of rupture for reinforced free cement refractory concrete with hooked fibers

White kaolin %	Modulus of Rupture MPa		
	Fumed silica 2%		
	0.5% hooked fiber	1% hooked fiber	1.5% hooked fiber
5	4.56	4.73	4.94
10	4.83	5.02	5.08
12	5.16	5.24	5.37
15	5.2	5.38	5.46

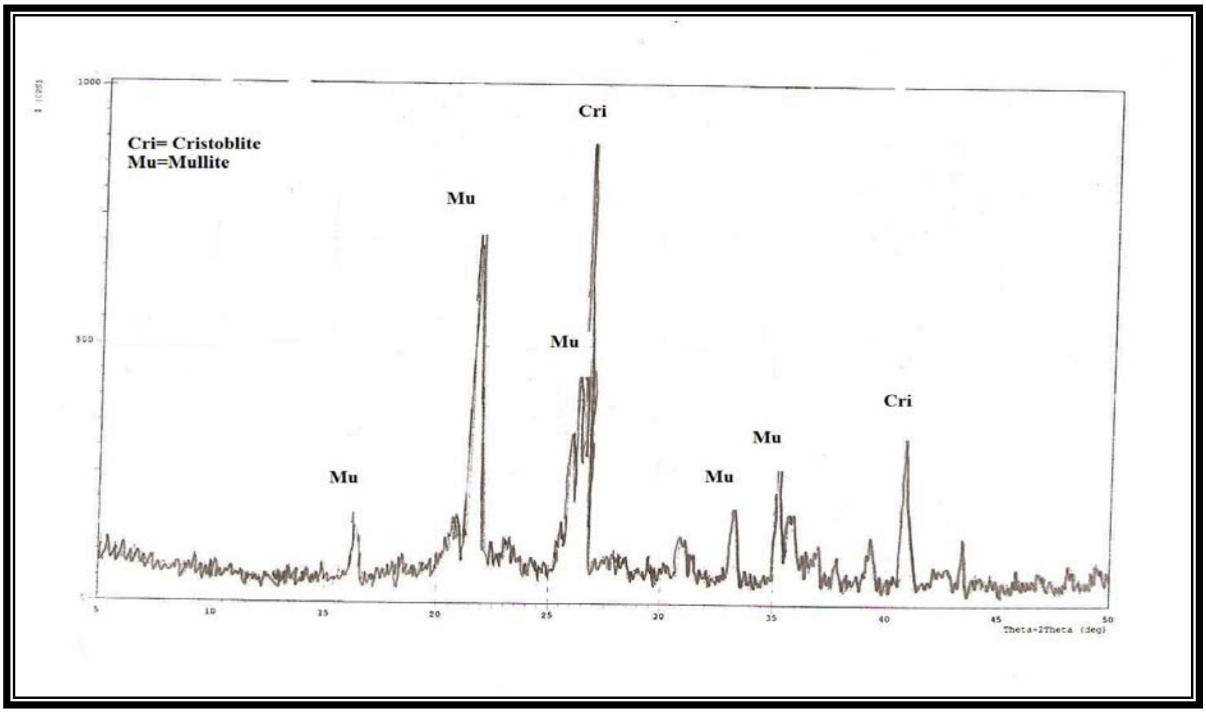

Fig. 2 X-ray diffraction analysis for free cement refractory concrete with white kaolin and fume silica

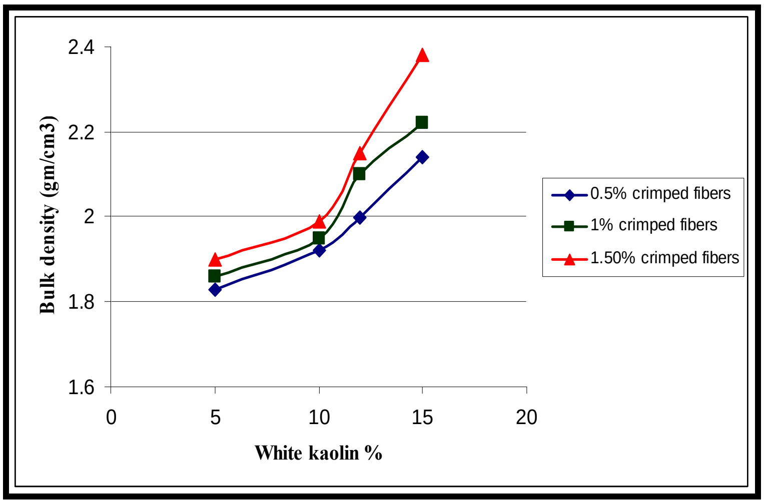

Fig .3 The relation between bulk density of reinforced free cement refractory concrete with crimped fibers and white kaolin

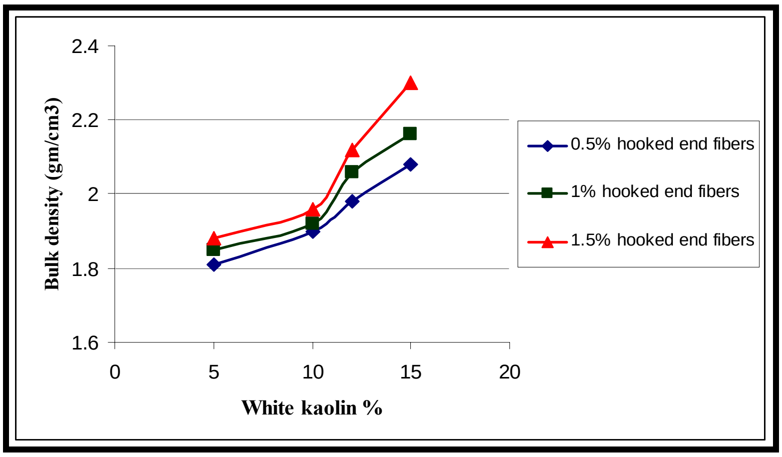

Fig. 4 The relation between bulk density of reinforced free cement refractory concrete with hooked end and white kaolin

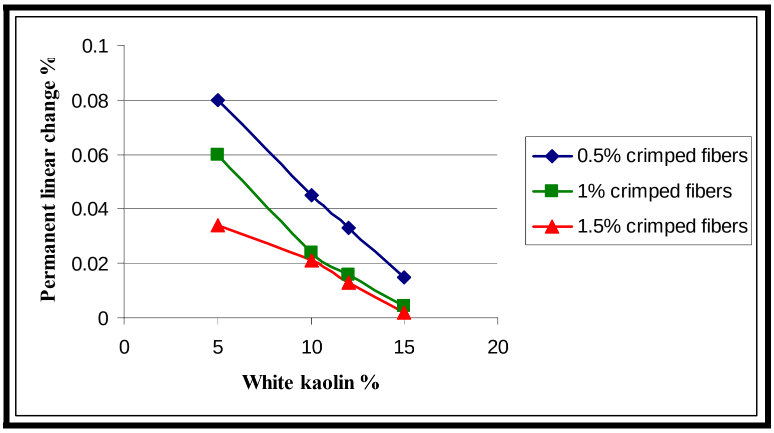

Fig .5 The relation between permanent linear change of reinforced free cement refractory concrete with crimped fibers and white kaolin

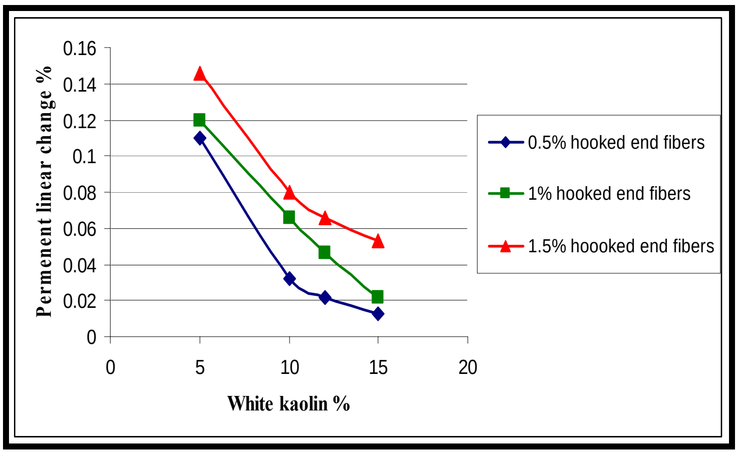

Fig .6 The relation between permanent linear change of reinforced free cement refractory concrete with hooked fibers and white kaolin

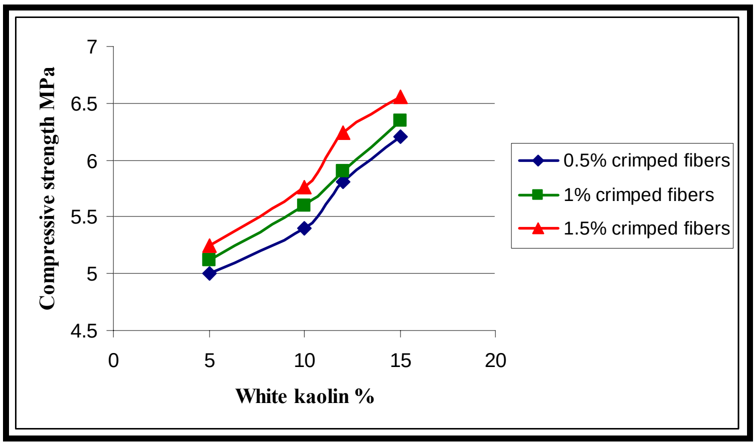

Fig .7 The relation between compressive strength of reinforced free cement refractory concrete with crimped fibers and white kaolin

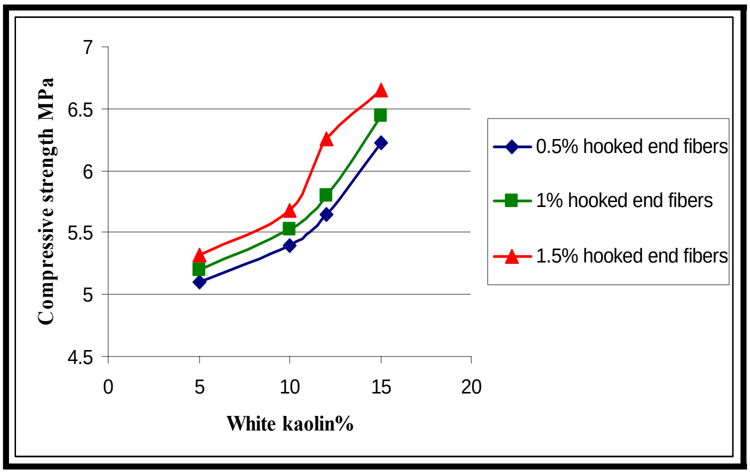

Fig .8 The relation between compressive strength of reinforced free cement refractory concrete with hooked fibers and white kaolin

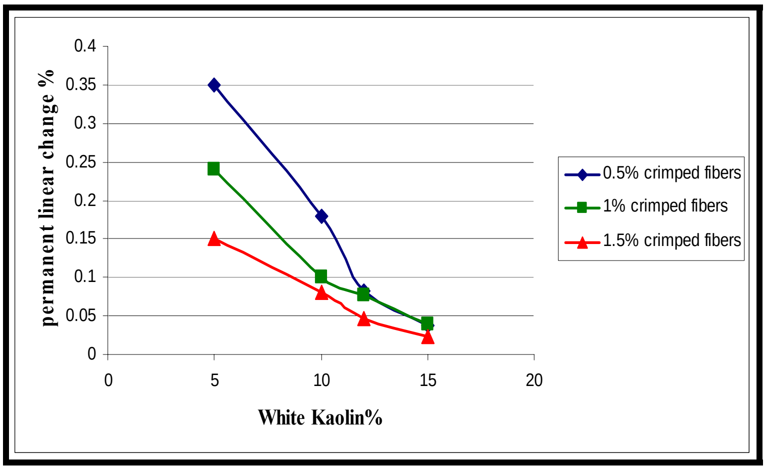

Fig .9 The relation between permanent linear change of reinforced free cemen t refractory concrete with crimped fibers and white kaolin after reheating

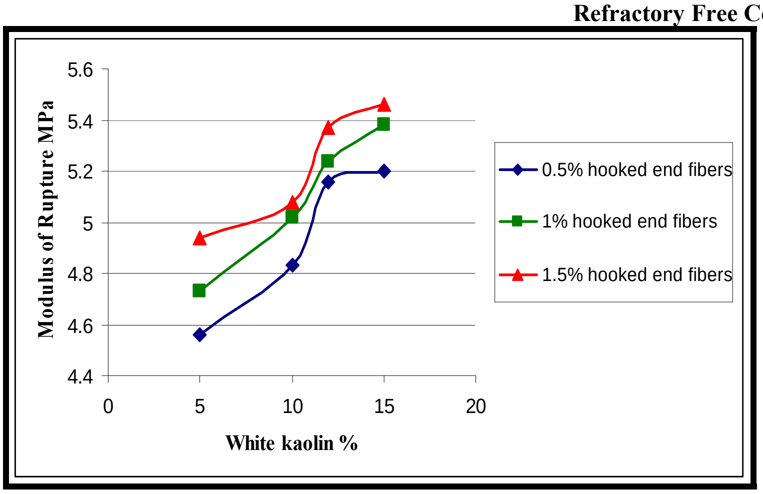

Fig .10 The relation between modulus of rupture of reinforced free cement refractory concrete with hooked fibers and white kaolin

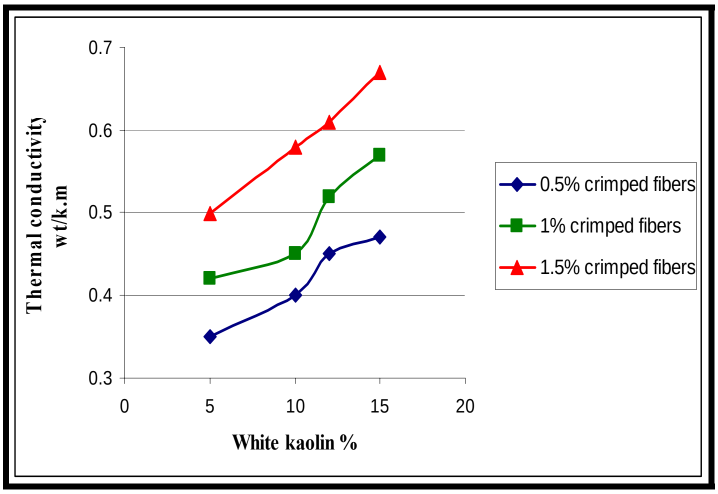

Fig .11 The relation between thermal conductivity of reinforced free cement refractory concrete with crimped fibers and white kaolin

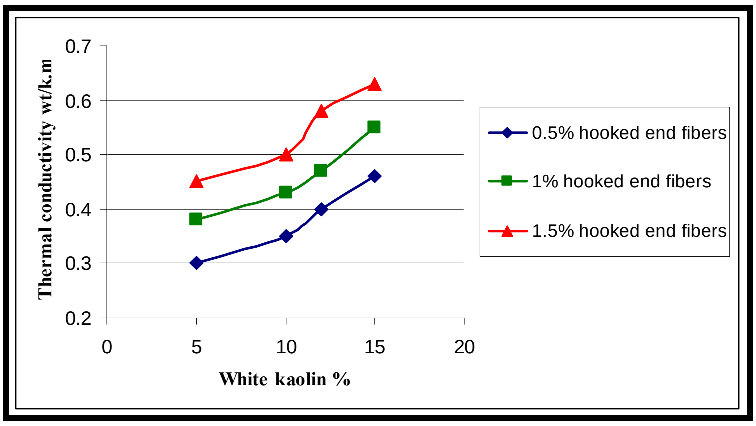

Fig .12 The relation between thermal conductivity of reinforced free cement refractory concrete with hooked fibers and white kaolin

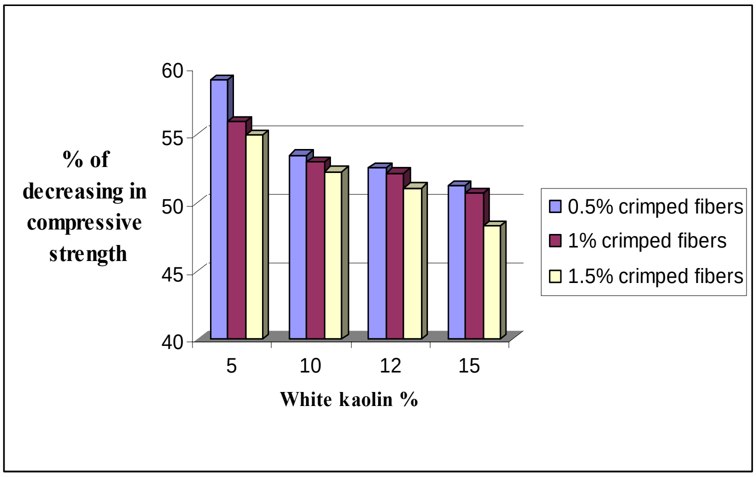

Fig .13 The relation between compressive strength of reinforced free cement refractory concrete with crimped fibers and white kaolin

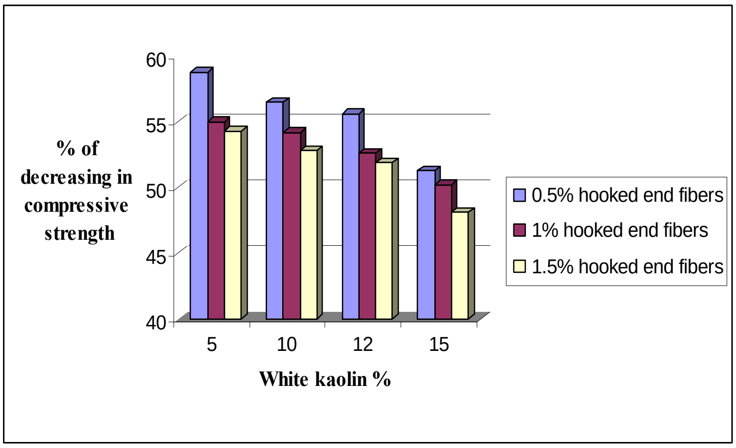

Fig.1 4 The relation between compressive strength of reinforced free cement refractory concrete with hooked fibers and white kaolin

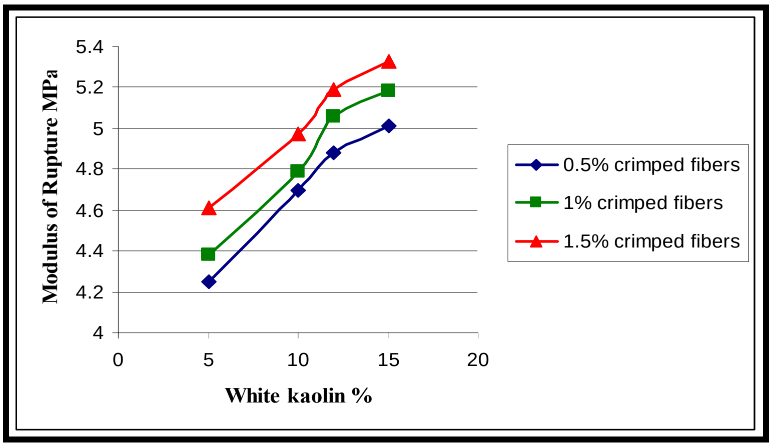

Fig .15 The relation between modulus of rupture of reinforced free cement refractory concrete with crimped fibers and white kaolin

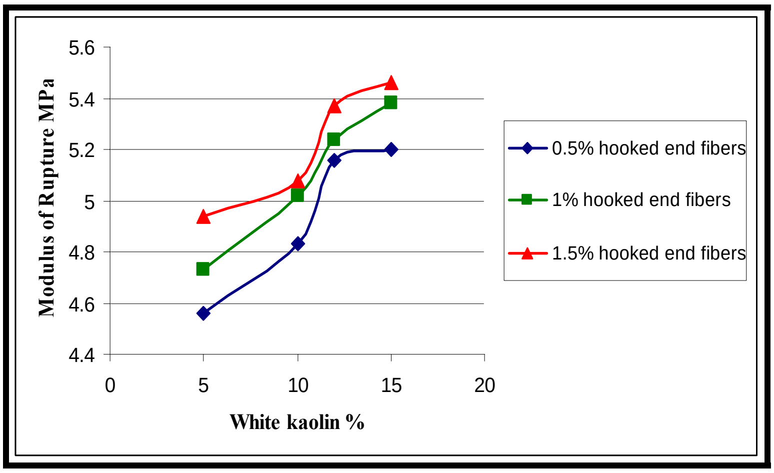

Fig .16 the relation between modulus of rupture of reinforced free cement refractory concrete with hooked fibers and white kaolin