ROPERTIES OF HIGH PERFORMANCE STEEL FIBER REINFORCED CONCRETE CONTAINING HIGH REACTIVITY METAKAOLIN+

خواص الخرسانة العالية الاداء المسلحة بألالياف الفولاذية الحاوية على الميتاكاؤلين العالي الفعالية

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Abstract:

This paper investigates the effect of using high reactivity metakaolin (HRM) on the properties of high performance steel fiber reinforced concrete . Compressive strength , splitting tensile strength , flexural strength , Impact resistance and absorption for five mixes were investigated . HRM content used in this study was 5% , 10% and 15% as a partial replacement of cement with 2% fibers by volume of concrete .

The results indicated that the reference concrete reinforced with 2% steel fibers by volume showed a significant increase in splitting tensile strength , flexural strength and impact resistance, the percentage increase after 60-day relative to reference concrete were 29.6% , 30.7% and 179% respectively .

The results also showed that the incorporation of 10% HRM as a partial replacement by weight of cement with 2% steel fibers showed considerable improvement in all properties , the percentage increase in compressive strength , splitting tensile strength , and flexural strength after 60-day compared to reference concrete were 12.3% , 46.8% , and 46.5% respectively .

المستخلص:

هذه الدراسة تبحث في تأثير استخدام الميتاكاؤلين العالي الفعالية على خـواص الخرسـانة العاليـة الاداء المسلحة بالالياف الفولاذية . اجريت فحوص مقاومة الانضغاط ، شد الانفلاق ، مقاومة الانثنـاء ، مقاومـة الـصدم والامتصاص لخمس خلطات خرسانية . أستخدم في هذا البحث ٥% و ١٠% و ١٥% من الميتاكاؤلين العالي الفعالية كأستبدال جزئي من وزن السمنت و٢% من الالياف الفولاذية من حجم الخرسانة .

النتائج بينت ان الخرسانة المسلحة بالالياف الفولاذية بنسبة ٢% من حجم الخرسانة تبدي زيادة ملحوظـة في مقاومة شد الانفلاق ، مقاومة الانثناء ومقاومة الصدم .النسبة المئوية للزيادة بعد عمر٦٠ يوم كانت ٢٩,٦ % ، ٣٠,٧ % ، ١٧٩ % على التوالي مقارنة بالخلطة المرجعية .

كما بينت النتائج ايضا بأن الخرسانة الحاوية على ١٠ % من الميتاكاؤلين العالي الفعالية كأستبدال جزئـي من وزن السمنت مع ٢ % الياف فولاذية تبدي تحسن كبير في جميع الخصائص حيث كانت الزيـادة فـي مقاومـة الانضغاط ، مقاومة شد الانفلاق ، ومقاومة الانثناء بعد عمر ٦٠ يـوم كـالاتي ١٢,٣ %، ٤٦,٨ % ، و ٤٦,٥ % على التوالي مقارنة بالخلطة المرجعية

Introduction:

Fiber reinforced concrete (FRC) is a composite materials made with Portland cement , aggregate , and incorporating discrete discontinuous fibers [1] .

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Normal unreinforced concrete is brittle with a low tensile strength and strain capacity [2] . The addition of steel fibers to concrete makes it more homogeneous and isotropic and transform it from a brittle to a more ductile materials [3] .

Ordinary concrete includes numerous microcracks which are rapidly increase under the applied stresses . These cracks are responsible for the low tensile , flexural strength , and impact resistance of concrete [4] .

Concrete reinforced with steel fibers impedes the crack growth and therefore enhances its strength and impact characteristics [5] , but it will also reduce the workability [6] , the addition of superplasticizer (Sp) is helpful to solve the potential problem of tangling or balling of steel fibers . Thus the workability of the steel fiber reinforced concrete (SFRC) with the aid of (Sp) is ensured as a result [7] .

High performance concrete (HPC) has been defined as a concrete that possesses high workability , high strength and high durability . The main ingredients of (HPC) are cement , fine aggregate , coarse aggregate , water , mineral admixtures and chemical admixture [8] .

In recent years, high performance concrete (HPC) has become widely used in transportation structures where strength and durability are two important considerations . In HPC, a part of Portland cement is replaced by pozzolanic materials . These pozzolans improve the strength and durability of concrete [9] .

The use of highly active pozzolanic material in conjunction with (Sp) may produce high performance concrete with special feature in both fresh and hardened states . A pozzolan is defined as a siliceous or siliceous and aluminous material , it chemically reacts with calcium hydroxide $Ca(OH)_2$ at ordinary temperatures to form compounds possessing cementitious properties [10] , calcium hydroxide is liberated during the hydration of Portland cement .

Lately , there has been much interest in the use of high reactivity metakaolin (HRM) as a supplementary cementing material [11] , produced by calcining purified kaolin clay in the temperature of 700^0 C [12] .

$$Al_2O_3 \,.\, 2SiO_2 \,.\, 2H_2O \rightarrow Al_2O_3 \,.\, 2SiO_2 + 2H_2O \qquad \text{--------------} \quad (1)$$

Kaolinite Metakaolin Steam

HRM (Al_2O_3 . $2SiO_2$) is a poorly crystallized white powder with a high pozzolanic reactivity, when HRM reacts with calcium hydroxide, a ppozzolanic reaction takes place whereby new cementitious compounds are formed . These newly formed compounds will contribute cementitious strength and enhanced durability properties to the system in place of the otherwise weak and soluble calcium hydroxide [13] .

The use of (HRM) with (Sp) can enhance the strength and durability of steel fiber reinforced concrete due to reduction of permeability .

Problem of the research:

Although concrete is a widely used construction material , it has major disadvantages such as low tensile strength , impact resistance , and it is liable to cracking . It is generally agreed that the higher the strength of concrete , the lower its ductility so that the observed inverse relationship between strength and ductility is considered in some structural application .

<u>Objective of the research</u>:

The brittle nature of plain concrete cannot be neglected and an approach to make concrete
a ductile material is necessary . The incorporation of steel fibers as a randomly distributed reinforcement is an alternative solution , the presence of fiber improve the tensile strength , flexural strength , ductility , and much more efficient at controlling cracking at the aggregate – matrix interface , but it will be also reduce the workability . The addition of superplasticizer can solve the problem of the workability and the utilization of metakaolin (in addition to the cement paste) to fill the void between blended aggregates will increase the density of concrete and improved the durability , therefore , to develop fiber reinforced concretes with specialized mineral admixtures where the problem of brittleness is reduced .

<u>Materials:</u>

Cement

Ordinary Portland cement was used in this work . The chemical composition and the physical properties of the cement are shown in Table (1) and (2) respectively . Test results indicated that the cement conformed to the Iraqi specification No . 5 / 1984 [14] .

Fine Aggregate

The fine aggregate was natural sand of 4.75 mm maximum size with grading limits in zone 3 . The grading of fine aggregate is shown in Table (3) . The specific gravity , absorption , bulk density and sulfate content of fine aggregate are (2.60) , (0.8%) , (1760 Kg/m^2) and (0.24%) respectively. Results indicated that the fine aggregate grading and the sulfate content were within the requirement of the Iraqi specification No. 45 / 1984 [15] .

Coarse Aggregate

Crushed aggregate of 10mm maximum size was used . Table (4) illustrate the grading of coarse aggregate . The specific gravity , absorption , bulk density and sulfate content of coarse aggregate are (2.62) , (0.49%) , (1640 Kg/m^2) and (0.04%) respectively . Results illustrated that the grading of coarse aggregate , sulfate salt content of coarse aggregate conformed to the Iraqi specification No. 45 / 1984 [15] .

Steel Fibers

Hooked end steel fibers were used throughout this work . These fibers were 30 mm long and 0.5 mm diameter making an aspect ratio L/D of 60 .

Superplasticizer (Sp)

Superplasticizer consists of long chain , high – molecular – weight 20000 to 30000 anionic surfactants with a long number of polar groups in the hydrocarbon chain . When adsorbed on cement particles , the surfactant imparts a strong negative charge , which helps to tower the surface tension of the surrounding water considerably and greatly enhances the fluidity of the system [6] .

A sulphonated melamine formaldehyde condensate , which is known commercially as (melment L_{10}) , was used throughout this work as a superplasticizer (Sp) , it was prepared as a solution (solid in aqueous solution approx. 20%) , it's clear to slightly milky in appearance . Sp was used to produce high strength concrete by reducing the w/c ratio while maintaining equal workabilities , (7 ± 0.5) seconds vebe - time .

High Reactivity Metakaolin (HRM)

Metakaolin is an aluminosilicate pozzolan , prepared by heating bad – crystallized and fine grain size of kaolin in a fixed – bed furnace at 700^0C .

The Doekhla Iraqi kaolin was used in this investigation in three different percentage (5% , 10% , 15%) as a partial replacement by weight of cement . The chemical composition of (HRM) comprises nearly 95 percent of (SiO_2 + Al_2O_3 + Fe_2O_3) . The specific gravity of (HRM) was find according to ASTM C_{188} [16] , this was found to be (2.6) .

Table (1) chemical composition of cement

Oxide composition	Abbreviation	Content	Limits of Iraqi specification No. 5/1984
Lime	CaO	61.3	-
Silica	SiO_2	20.2	-
Alumina	Al_2O_3	5.45	-
Iron Oxide	Fe_2O_3	3.09	-
Magnesia	MgO	2.0	≤ 5.0 %
Sulfate	SO_3	2.15	≤ 2.8 %
Loss on ignition	L.O.I	2.1	≤ 4.0 %
Insoluble residue	I.R	0.8	≤ 1.5 %
Lime saturation factor	L.S.F	0.92	0.66-1.02

Table (2) physical properties of cement

physical properties	Test results	Limits of Iraqi specification No. 5/1984
Specific surface area , Blaine method , m^2/Kg	309	≥ 230 m^2/Kg
Soundness , Autoclave method	0.30	≤ 0.8%
Setting time , Vicat 's method Initial setting , hrs : min Final setting , hrs : min	 1 : 50 3 : 20	 ≥ 1 hr ≤ 10 hrs
Compressive strength 3 days , N/mm^2 7 days , N/mm^2	 19.6 28.3	 ≥ 15 N/mm^2 ≥ 23 N/mm^2

Table (3) Grading of fine aggregate

Sieve size (mm)	Cumulative passing (%)	Limits of Iraqi specification No. 45/1984
4.75	100	90 - 100
2.36	88.6	85 - 100
1.18	77.0	75 - 100
0.6	63.2	60 – 79
0.3	29.3	12 – 40
0.15	8.0	0 - 10

Table (4) Grading of coarse aggregate

Sieve size (mm)	Cumulative passing (%)	Limits of Iraqi specification No. 45/1984
14	100	100
10	98.5	85 - 100
5	17.1	0 - 25
2.36	0.5	0 - 5

Mix Proportions:

Concretes with (cement : sand : gravel) ratio of (1 : 1.19 : 1.77) were prepared .The design was made accordance with Building Research Establishment Method . The reference concrete mixture was designed to give a 28 – day compressive strength of 65 N/mm^2 . Table (5) indicated the mix proportions used throughout this investigation .

Table (5) – Mix proportions

ix description	Cement Kg/m^3	Sand Kg/m^3	Gravel Kg/m^3	Water Kg/m^3	W/C	Steel bers by vol. of onc.%	by wt. of cement %	HRM Kg/m^3	ebe time ± 0.5 sec.
Reference		655	974	168.3	0.306	-	5.5	-	6.9
Reference +2% Fibers		655	974	180.4	0.328	2	5.5	-	6.6
Reference + 2% Fibers + 5% HRM		655	974	176.0	0.32	2	5.5	27.5	7.0
Reference + 2% Fibers + 10% HRM		655	974	173.8	0.316	2	5.5	55	7.2
Reference + 2% Fibers + 15% HRM	467.5	655	974	174.9	0.318	2	5.5	82.5	7.1

Testing Program:

Workability

The workability of all concrete mixes were determined by vebe – time test according to B.S. 1881 : part 104 [17] .

The water / cement ratio for all concrete mixture were adjusted to give equal workabilities , vebe – time of (7 ± 0.5) seconds .

Compressive Strength

The compressive strength of 100 mm cube concrete specimens was measured in accordance with B.S. 1881 : part 116 [18] .

Splitting Tensile Strength

Based on ASTM C494 – 86 [19] , the splitting tensile was carried out on 100 x 200 mm cylindrical concrete specimens .

Flexural Strength

The flexural strength test was determined according to B.S. 1881 : part 118 [20] , 100 x 100 x 400 mm prism specimens were tested . The flexural strength of the specimens were calculated by the following equation :-

$$Fr = \frac{PL}{bd^2} \qquad \text{----------------} \quad (2)$$

Where :-

Fr = modulus of rupture , (N/mm^2) .
P = maximum applied load , (N) .
L = span length , (mm) .
b = width of the specimen , (mm) .
d = depth of the specimen , (mm) .

Impact Resistance

Impact resistance of concrete was performed according to the ACI committee 544 on fiber reinforced concrete [21] . By dropping a 4.5 Kg hammer for which tests on the top of a
(150 diameter and 63.5 mm thickness) specimen .

Absorption

This test was measured on 100 mm cubes according to B.S. 1881 : part 122 [22] .

Results and Discussion:

Compressive Strength

The compressive strength results for specimens of reference concrete and fiber reinforced concrete with and without (HRM) are given in Table (6) and plotted in Fig. (1) .

Results indicated that all concrete specimens exhibited continuous increase in compressive strength with increase in curing .

The values of compressive strength of HRM concretes showed considerable increase relative to the reference concrete . The better performance of these concretes may be attributed to the fact that with highly active pozzolans , the pozzolanic reaction can start as soon as calcium hydroxide is liberated during the hydration of Portland cement compounds .

Accordingly , reducing the permeability of the matrix phase and reducing the microcracks in the transition zone [6] .

Results also showed that the compressive strength of fiber reinforced concrete with 15% HRM is less than the compressive strength of fiber reinforced concrete with 10% HRM .

Table (6) Compressive strength of various types of concrete at different ages

Mix description	Compressive strength (N / mm^2)		
	7 – day	28 – day	60 - day
Reference	53.9	67.7	71.5
Reference +2% Fibers	55.0	70.1	75.2
Reference + 2% Fibers + 5% HRM	56.5	72.1	77.3
Reference + 2% Fibers + 10% HRM	59.8	74.8	80.3
Reference + 2% Fibers + 15% HRM	59.0	73.6	78.0

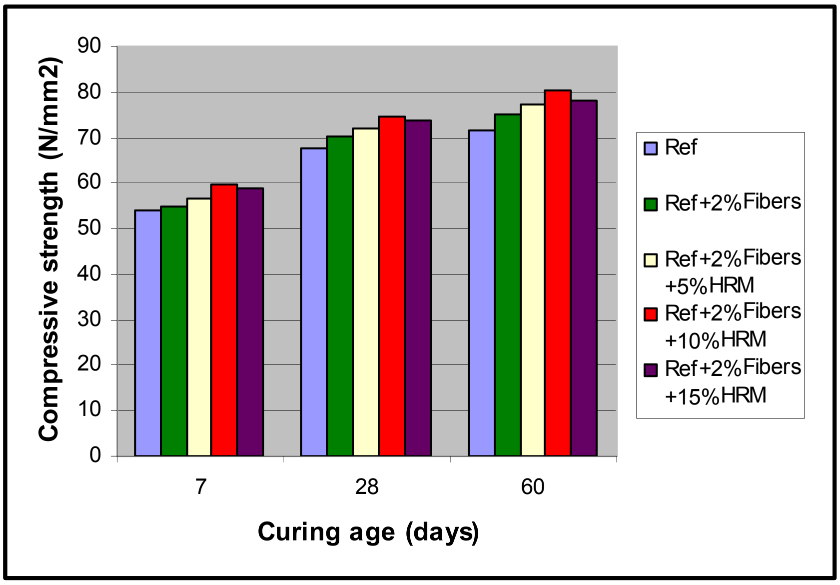

Fig. (1) Compressive strength of concretes cured at different ages.

Splitting Tensile Strength

The splitting tensile strength development at various curing ages for all types of concrete are presented in Table (7) and Fig. (2)

Results demonstrated that the splitting tensile strength of reference concrete improved by the addition of steel fibers . This behavior is attributed to the mechanism of steel fibers in arresting crack progression . The percentage increase in splitting tensile strength of 60 – day curing due to the presence of steel fibers was 29.6 % for reference concrete reinforced with 2% steel fibers by volume over the reference mix .

HRM concrete indicated superior performance to various types of concrete adopted throughout this study . This behavior may be attributed to the pozzolanic reactivity of HRM which contribute to the densification of the concrete matrix resulting in a considerable increase in strength .

Table (7) Splitting tensile strength of various types of concrete

Mix description	Splitting tensile strength (N / mm^2)	
	28 – day	60 - day
Reference	5.26	5.57
Reference +2% Fibers	6.93	7.22
Reference + 2% Fibers + 5% HRM	7.01	7.86
Reference + 2% Fibers + 10% HRM	7.90	8.29
Reference + 2% Fibers + 15% HRM	7.80	8.18

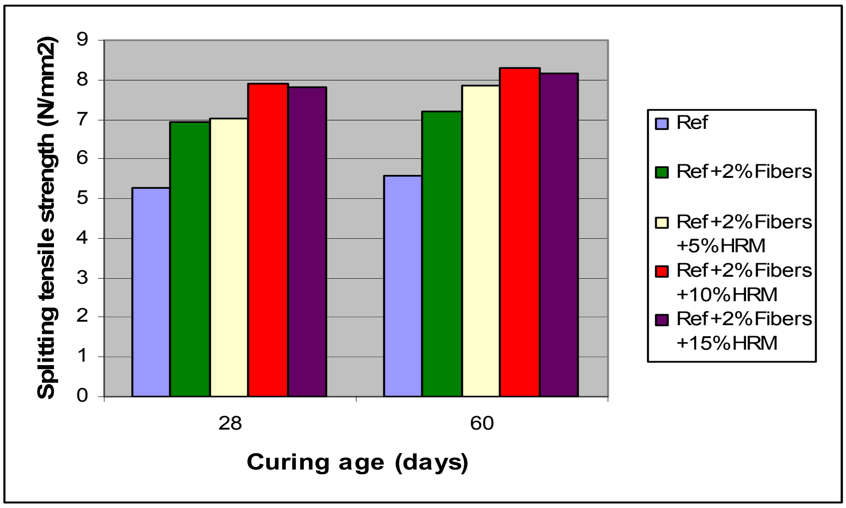

Fig. (2) Splitting tensile strength of concretes cured at different ages

Flexural Strength

Table (8) and Fig. (3) illustrated the values of flexural strength for various types of concrete .

Reference concrete reinforced with steel fibers showed a significant increase in flexural strength compared to the plain concrete . This behavior may be attributed to the role of steel fibers in releasing fracture energy around crack tips which is required to extend crack growing by transferring it from side to another side [23] .

HRM concretes showed improvement in flexural strength over those of concrete without HRM . The percentage increase in flexural strength after 60 – day relative to reference concrete without fibers were 41% , 46.5% , 42.6% for 5% , 10% and 15% replacement by weight of cement respectively .

Table (8) Flexural strength of various types of concrete

Mix description	Flexural strength (N / mm^2)	
	28 – day	60 - day
Reference	7.06	7.20
Reference +2% Fibers	8.92	9.41
Reference + 2% Fibers + 5% HRM	9.73	10.16
Reference + 2% Fibers + 10% HRM	9.90	10.55
Reference + 2% Fibers + 15% HRM	9.81	10.27

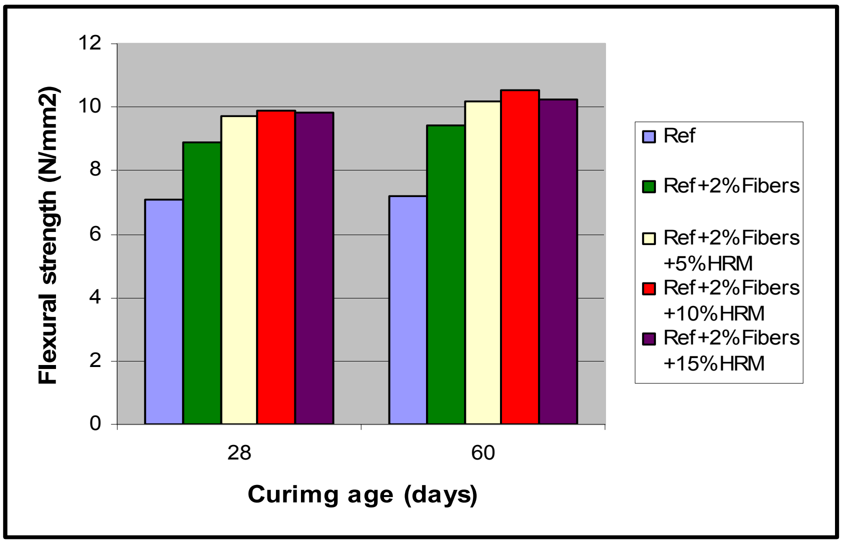

Fig. (3) Flexural strength of concretes cured at different ages

Impact Resistance

60 – day impact resistance for the various mixes is reported in Table (9) . This test is performed in term of the number of blows required to cause initial and ultimate visible crack.

It is clearly noticed from the test results that the impact resistance of reference concrete with 2% steel fibers is higher than the reference concrete . This behavior may be related to the ability of steel fibers in absorbing the energy required to produce failure , where the fiber addition results in more closely – spaced crack , reduced the crack width leading to the absorption of large energy [24] .

At 60 – day curing , the percentage increase in impact resistance for HRM concretes relative to reference mix without HRM were 15.6% , 23.5% , 18% for 5% , 10% , 15% replacement by weight of cement . This may be attributed to the pozzolanic activity of HRM , which reduces the microcracks in the interface between the aggregate and the cement paste .

Table (9) Impact resistance of various types of concrete at 60 - day age

Mix description	Impact resistance , No. of blows	
	First crack	Ultimate failure
Reference	104	210
Reference +2% Fibers	213	587
Reference + 2% Fibers + 5% HRM	250	679
Reference + 2% Fibers + 10% HRM	277	725
Reference + 2% Fibers + 15% HRM	264	693

Absorption

The water absorption test results are given in Table (10) . Results indicated that the water absorption of fiber reinforced metakaolin concrete is decreased , the percentage decrease in water absorption after 60 – day relative to reference concrete were 14.5% , 23.6% and 22.2% for 5% , 10% and 15% replacement by weight of cement respectively . This is mainly due to the highly active pozzolans lead to the reduction in permeability of the matrix .

Table (10) Absorption of various types of concrete

Mix description	Absorption %	
	28 – day	60 - day
Reference	1.61	1.10
Reference +2% Fibers	1.52	1.03
Reference + 2% Fibers + 5% HRM	1.40	0.96
Reference + 2% Fibers + 10% HRM	1.34	0.89
Reference + 2% Fibers + 15% HRM	1.34	0.90

Conclusions:

Based on the test results , the following conclusions can be drawn :-

1) Reference concrete with 2% steel fibers showed slight improvement in compressive strength and absorption at all ages curing compared to the reference concrete .

2) Reference concrete with 2% steel fibers indicated a significant increase in splitting tensile strength , flexural strength and impact resistance, the results indicated that the number of blows to final failure greatly increased by addition of steel fiber .

3) The addition of HRM as a partial replacement by weight of cement to the steel fiber

reinforced concrete improvement in all properties up to 10 % replacement by weight of
cement

4) For application where both enhanced durability and high toughness are required , the use
of high reactivity metakaolin concrete with steel fibers may be advantageous .

Recommendation:

1) A research work is needed to investigate the durability of high performance steel fiber reinforced concrete exposed to aggressive solution .
2) A study is required to investigate the corrosion of high performance steel fiber reinforced concrete .
3) An investigation is required to examine the properties of steel fiber reinforced concrete
incorporating different types of mineral admixtures .
4) A study is required to investigate the properties of high performance steel fiber concrete
containing different percentage of steel fibers ,

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