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# Some Properties of Modified Reactive Powder Concrete

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## Abstract:

***The term reactive powder concrete (RPC) has been used to describe a fibre reinforced , superplasticized, silica fume- cement mixture with very low water-cement ratio, characterized by the presence of very fine quartz sand (0.15-0.4mm) instead of ordinary aggregate. Fibres are incorporated in RPC in order to enhance the fracture properties of the composite material. In this investigation modified RPC with crushed graded natural aggregate (maximum size 12.5mm) has been produced. High compressive strength of 150 MPa can be achieved by using crushed coarse aggregate; this result is in contrast with the model proposed to relate the high compressive strength level of RPC to the absence of coarse aggregate. Modified RPC reinforced with different types (crimped and hooked) and volume fractions (0%, 0.5%, and 1%) of steel fibres has a good performance in terms of high strength (Compressive strength, splitting tensile strength, modulus of rupture, impact strength) and static modulus of elasticity.***

***Keywords:*** ***Modified reactive powder concrete, steel fibers, Volume fraction, Crimped, Hooked***

## الخلاصة

*استخدم مصطلح خرسانة المساحيق الفعالة لوصف الخرسانة ذات الخليط الاسمنتي المسلح بالألياف والحاوي على الملدن المتفوق وأبخرة السليكا المكثفة وبنسبة ماء /اسمنت منخفضة جدا والتي تتميز باحتوائها على الرمل الناعم جدا (0.15-0.4 مم) كبديل عن الركام الخشن الاعتيادي و تضاف الألياف الى خرسانة المساحيق الفعالة وذلك لتحسين خواص المادة المركبة. تتضمن هذه الدراسة تحضير خرسانة مساحيق ناعمة معدلة تحتوي على ركام مكسر خشن طبيعي (بمقاس أقصى 12.5 مم). تم الحصول على خرسانة بمقاومة انضغاط عالية تصل الى 150 نيوتن/مم$^{2}$ بإستخدام الركام الخشن المكسر وهذه النتيجة تناقض الموديل المقترح الذي يبين بأن مقاومة الانضغاط العالية لخرسانة المساحيق الفعالة تعود الى عدم وجود الركام الخشن في الخليط الخرساني. أظهرت النتائج بأن خرسانة المساحيق الفعالة المعدلة المسلحة بأنواع مختلفة ( مجعد و معقوف) ونسب حجمية مختلفة (0%, 0.5% , 1%) من الألياف الفولاذية لها أداء جيد من ناحية المقاومة العالية (مقاومة الانضغاط, مقاومة الشد الانشطاري, معاير الكسر, مقاومة الصدمة) ومعامل المرونة الستاتيكي.*

## 1-Introduction

Original RPC, otherwise known as ultra high performance concrete (UHPC), was developed through microstructural enhancement techniques for cementitious materials [1]. RPC term has been used to describe a fiber- reinforced, superplasticized, silica fume- cement mixture with very low water-cement ratio, characterized by the presence of very fine quartz sand (0.15-0.4mm) instead of ordinary aggregate. In fact, it is not a concrete because there is no coarse aggregate in the cement mixture [2]. Fibers are incorporated in RPC in order to enhance the fracture properties of the composite material. The advantages of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) include higher durability, ductility and strength in comparison with normal concrete and fiber reinforced concrete due to its extremely low porosity, dense matrix, high tensile/compressive strength, and ductile tensile behavior. In comparison with normal steel reinforced concrete, the application of UHPFRC is expected to improve the resistance of buildings and infrastructures under extreme mechanical and environmental loads [3]. In fact there are limited studied on UHPC or RPC.

Ma and Schneider [4] modified UHPC through partial replacement of cement or silica fume by fine quartz powder. The compressive strength and modulus of elasticity were determined for concretes at ages of 3, 7, 14, 28 and 90 days. A self compacting UHPC with a cylinder compressive strength of 155MPa can be produced without heat treatment or any other special measures. The mechanical properties and the autogenous shrinkage of modified UHPC were studied. They conclude that the relationship between compressive strength and elastic modulus of UHPC is quite different from that in conventional high strength concrete. A new empirical equation was suggested to predict E- modulus of UHPC. They also found that the autogenous shrinkage for UHPC is higher than conventional high performance concrete because of high binder (cement and silica fume) content and low water to binder ratio.

Hoagn et al. [5] investigated the influence of types of steel fiber on properties of UHPC. Self compacting UHPC has been manufactured and short steel fiber (straight fiber) with aspect ratio 85 and long steel fiber (hooked ends) with aspect ratio 70 have been added in order to improve ductility. The results indicate that a reasonable combination of two steel fiber types guarantee for high flowability , flexural strength of over 20 MPa and compressive strength of over 150 MPa. Generally in concrete the high viscosity of the cement paste made compaction very necessary. To improve the compaction characteristics of the concrete the idea of adding coarse aggregate was developed [6]. Very few researchers try to produce RPC with coarse aggregate. Ma and Orgass [1] studied the properties of UHPC with and without coarse aggregate. They found that the compressive strength of UHPC with coarse aggregate has reached the same magnitude as UHPC without coarse aggregate. UHPC with coarse aggregate was easier to be fluidized and homogenized and the mixing time can be shorter than that of UHPC without coarse aggregate.

Collepardi et al.[2] studied the original RPC in form of a superplasticized cement mixture with silica fume, steel fibers and ground fine sand (150-400μm) in comparison with a modified RPC where a graded natural aggregate (maximum size 8mm) was used to replace the fine sand and/or part of the cementitious binder. Original and modified RPC were cured at room temperature, steam curing at $90°C$ and high pressure steam curing at $160°C$. The results indicate that the addition of the graded aggregate dose not reduce the compressive strength provided that the quality of the cement matrix, in terms of its water-cement ratio, is not changed. Both the original and modified RPC perform better in terms of higher strength and lower drying shrinkage or creep strain, when they are steam cured rather than cured at room temperature.

Xiao et al. [7] investigated the fracture behavior of different kinds of UHPC, with or without steel fiber, with or without coarse aggregate. The primary conclusion is that the fracture energy of UHPC with coarse aggregate is 1.67 times of UHPC without coarse aggregate; while for UHPC mixed with steel fiber, its fracture energy is about 75 times of UHPC without steel fiber and coarse aggregate.

The main purpose of the present investigation is to modify RPC by including coarse aggregate in the mixture (maximum size 12.5mm) and to study the influence of coarse aggregate on properties of RPC in terms of compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and impact strength.

## 2-Experimental Work

### 2-1 Materials

#### 2-1-1 Cement

Ordinary Portland cement from Tasuga factory was used. The chemical composition and physical properties of the cement are presented in Table (1) and (2) respectively. The results conform to the Iraqi specification No.5/1984.

#### 2-1-2 Fine Aggregate

Natural sand brought from Al-Ukhaider region was used in this investigation. The results of the tests show that it’s grading and sulfate content conform to Iraqi specification No.45/1984 as shown in Table (3) and (4) respectively, it lies in the second grading zone.

### 2-1-3 Coarse Aggregate

Crushed aggregate of maximum size 12.5mm brought from Al- Nibaee region was used in this investigation. The test results show that the coarse aggregate characteristics are within the limit specified by Iraqi standard specification No.45/1984 as shown in Table(5) and (6).

*Table (1) Chemical composition and main components of cement*

| Oxide Composition | Chemical Symbol | Content | Limit of Iraqi Specification N0.5/1984 | |
|---|---|---|---|---|
| | | | Minimum | Maximum |
| Calcium Oxide | CaO | 62.98% | | |
| Silicon Dioxide | $SiO_2$ | 20.24% | | |
| Aluminum Trioxide | $Al_2O_3$ | 4.61% | | |
| Ferric Oxide | $Fe_2O_3$ | 2.74% | | |
| Potassium Oxide | $K_2O$ | 0.27% | | |
| Sodium Oxide | $Na_2O$ | 0.13% | | |
| Magnesium Oxide | MgO | 2.39% | | 5% |
| Sulphate | $SO_3$ | 2.24% | | 2.8% |
| Loss of Ignition | L.O.I | 3.29% | | 4% |
| Insoluble Residue | Ins.Res. | 0.86% | | 1.5% |
| Lime Saturation Factor | LSF | 96.12% | 66 | 102 |
| Free Lime | FL | 1.3 | | |
| Silica Ratio | SM | 2.75 | | |
| Alumina Ratio | AM | 1.68 | | |
| **Main Compounds (Bogues Equations)** | | | | |
| Tricalcium Silicate | $C_3S$ | 61.23% | | |
| Dicalcium Silicate | $C_2S$ | 11.92% | | |
| Tricalcium Aluminates | $C_3A$ | 7.59% | 5% | |
| Tetra Calcium Alminoferrate | $C_4AF$ | 8.33% | | |

### 2-1-4 Mixing Water

Potable water was used for mixing and curing all concrete mixes.

*Table (2) Physical properties of cement*

| Physical properties | | Test results | Limit of Iraqi Specification N0.5/1984 | |
|---|---|---|---|---|
| | | | Minimum | Maximum |
| Compressive Strength | 3 days (MPa) | 29.3 | 15 MPa | |
| | 7 days (MPa) | 39.71 | 23 MPa | |
| Setting Time, Vicat´s method | Initial Time, hr:min | 1:55 | 0:45 | |
| | Final Time, hr:min | 3:05 | | 10:00 |
| Soundness, Le-chatielier method, mm | | 1 | | 10 |
| Specific surface area, Blaine method, $m^2/kg$ | | 346 | 230 | |

### 2-1-5 Admixtures

Two types of admixtures were used throughout this investigation, high range water reducing admixture (HRWRA) which is commercially known as Flocrete SP95 and silica fume. The technical properties of HRWRA, the physical requirement and chemical composition of the silica fume are given in Tables (7), (8) and (9) respectively.

*Table (3) Grading of fine aggregate*

| Sieve size (mm) | % Passing | Limit of Iraqi Specification N0.45/1984 Zone (2) |
|---|---|---|
| 4.75 | 100 | 90-100 |
| 2.36 | 98.2 | 75-100 |
| 1.18 | 71.1 | 55-90 |
| 0.60 | 51.7 | 35-59 |
| 0.30 | 23.3 | 8-30 |
| 0.15 | 8.6 | 0-10 |

*Table (4) Physical and chemical properties of fine aggregate*

| Properties | Test results | Limit |
|---|---|---|
| Apparent specific gravity | 2.68 | |
| Saturated and surface dry specific gravity | 2.64 | |
| Absorption, % | 0.93 | |
| Void ratio, % | 23 | |
| Sulfate content ($SO_3$), % | 0.016 | ≤ 0.5 |
| Soluble salts, % | 0.07 | ≤0.1 |

***Table (5) Grading of coarse aggregate***

| **Sieve size (mm)** | **% Passing** | **Limit of Iraqi Specification N0.45/1984** |
|---|---|---|
| 12.5 | 100 | 95-100 |
| 9.5 | 91.19 | 85-100 |
| 4.75 | 7.82 | 0-25 |
| 2.36 | 0 | 0-5 |

***Table (6) Physical and chemical properties of coarse aggregate***

| **Properties** | **Test results** | **Limit** |
|---|---|---|
| Apparent specific gravity | 2.69 | |
| Saturated and surface dry specific gravity | 2.66 | |
| Absorption, % | 0.75 | |
| Dry rodded bulk density, $kg/m^3$ | 1541 | |
| Void ratio, % | 35.5 | |
| Sulfate content ($SO_3$), % | 0.12 | $\leq 0.5$ |
| Soluble salts, % | 0.04 | $\leq 0.1$ |

### 2-1-6 Steel Fibers

Two types of steel fibers (hooked and crimped) were used. Table (10) indicates the mechanical properties of the steel fibers.

***Table (7) Technical properties of the HRWRA (Flocrete SP95)***

| Properties | Description |
|---|---|
| Color | Brown |
| Freezing point | -2 ℃ approximately |
| Form state | liquid |
| Specific gravity | 1.17+0.01 at 25℃ |
| Chloride content | Nile |
| Air entrainment | Typically less than 2% |

***Table (8) Physical requirements for silica fume***

| Properties | Results | ASTM$_{C1240-05}$ specification | |
|---|---|---|---|
| | | Minimum | Maximum |
| Accelerated pozzolanic activity (7days) | 115 | 105 | |
| Oversize on 45μmm% | 0.77 | | 10 |
| Specific density, $kg/m^3$ | 1780 | | |
| Loose bulk density, $kg/m^3$ | 638.2 | | |
| Specific surface area, $m^2/kg$ | 23800 | | |

***Table (9) Chemical composition for silica fume***

| Chemical composition | % by weight | ASTM C1240-05 specification | |
|---|---|---|---|
| | | Min. | Max. |
| $SiO_2$% | 91.8 | 85 | |
| Moisture content, % | 1 | | 3 |
| LOI (includes carbon), % | 2.1 | | 6 |
| Alkalis like $Na_2O$, % | 1.24 | | |
| $AL_2O_3$, % | 1.1 | | |
| $Fe_2O_3$, % | 1.35 | | |
| CaO, % | 0.37 | | |
| MgO, % | 1.65 | | |
| $SO_3$, % | 0.52 | | |

***Table (10) Mechanical properties of steel fibers***

| Length (mm) | Diameter (mm) | Aspect ratio | Tensile strength (MPa) | Modulus of elasticity (GPa) | Surface |
|---|---|---|---|---|---|
| 30 | 0.6 | 50 | 2000 | 210 | galvanized |

### 2-2 Mixing of Concrete

Mixing process was carried out by using revolving drum tilting mixer of 0.1m$^3$ capacity. Coarse aggregate, sand and silica fume were first placed in the mixer and they were dry mixed for about one minute. The water and HRWRA were mixed apart to each other, and then they were added to the mixed dry materials and mixed for about 30 seconds. Cement was loaded to the mixer and mixed for about 5 minutes, finally the steel fibers is added by spreading over the mix and mixed for about two minutes. This method of mixing is recommended in the ACI committee report 544 [8].

## 3- Results and Discussion

### 3-1 Concrete Mix

Many trial mixes were carried out in order to produce modified RPC using silica fume and HRWRA in the mix. Two types of high strength steel fibers (hooked and crimped) were also used. The mix was designed according to ACI committee 211[9] to have a compressive strength greater than 60 MPa without the addition of admixture (silica fume and HRWRA). The mix proportions are 1:0.8:1.41 by weight with cements content 730 kg/m$^3$ and water- cement ratio

0.27. Since a moderately workable mix with slump value of about 70±5mm was desired and the coarse aggregate used was crushed aggregate, so the water-cement ratio used in the trial mix was increased from 0.27to 0.41.

## 3-2 Effect of HRWRA on Compressive Strength of Concrete

Three different types of HRWRA with different dosages were used as shown in Table (11). The water- cement ratio was adjusted to obtain the same workability of reference mix (slump value 70±5mm).The results show that HRWRA which is commercially known as Flocrete SP95 give the best results. It leads to an improvement in both early and later compressive strength and cause a reduction in water- cement ratio in comparison with reference mix (1:0.8:1.41 w/c ratio 0.41). This attributed to the ability of HRWRA in dispersing cement particles, thereby, greatly enhancing the fluidity of the mix and consequently reducing the water requirements by up to 30%, thus increasing concrete compressive strengths [10]. Table (11) shows that the compressive strength at 7 and 28 days reaches its maximum value at dosage 3% by weight of cement and the reduction in water content at this dosage is about 44% relative to the reference mix (without HRWRA). When the dosage of HRWRA increased from 3% to 4% or 5% by weight of cement, the mix changed to a very cohesive state and the workability considerably decreases and more water is required to have the same slump (70±5mm). This leads to reduction in compressive strength, so the optimum dosage of HRWRA is 3% by weight of cement.

***Table (11) Effect of type of HRWRA on compressive strength of concrete***

| Mix proportions | Type of HRWRA | % of HRWRA by weight of cement | w/c ratio | Slump (mm) | Reduction in w/c ratio (%) | Compressive strength (MPa)( 100mm cube) | |
|---|---|---|---|---|---|---|---|
| | | | | | | 7 days | 28 days |
| 1:0.8:1.41 | Sikament-163N | 0 | 0.41 | 75 | - | 39.95 | 53.31 |
| | | 1 | 0.36 | 70 | 12.2 | 43.11 | 61.90 |
| | | 2 | 0.31 | 75 | 24.4 | 51.67 | 73.19 |
| | | 3 | 0.28 | 70 | 31.7 | 54.50 | 75.30 |
| 1:0.8:1.41 | SP2000 | 1 | 0.35 | 65 | 14.6 | 45.90 | 58.23 |
| | | 2 | 0.32 | 70 | 21.9 | 48.43 | 64.96 |
| | | 3 | 0.29 | 70 | 29.3 | 51.83 | 70.07 |
| 1:0.8:1.41 | SP95 | 1 | 0.33 | 71 | 19.5 | 46.35 | 60.83 |
| | | 2 | 0.28 | 73 | 31.7 | 59.63 | 79.56 |
| | | 3 | 0.23 | 75 | 43.9 | 72.72 | 90.90 |
| | | 4 | 0.29 | 65 | 29.3 | 53.23 | 64.82 |
| | | 5 | 0.35 | 70 | 14.6 | 43.29 | 56.65 |

## 3-3 Effect of Cement Content on Compressive Strength of Concrete

Modified RPC is characterized by very high cement content and there is an optimum cement content beyond which little or no additional increase in strength is achieved [9], so an optimization for cement content in the design mix is needed. It can be found from the results in Table (12) that the compressive strength of concrete mix increases with the increase of cement content up to 900 kg/m$^3$ and when the cement content is more than 900kg/m$^3$, no significant increase in compressive strength was achieved, so the concrete mix with mix proportion 1:0.65:1.14 by weight with cement content 900kg/m$^3$, HRWRA 3% by weight of cement was used in the other trails.

*Table (12) compressive strength of mixes with different cement content*

| Mix proportions by weight | Cement content (kg/m$^3$) | HRWRA (%) by weight of cement | w/c ratio | Slump (mm) | Compressive strength (MPa)(100mm cube) | |
|---|---|---|---|---|---|---|
| | | | | | 7 days | 28 days |
| 1:0.8:1.41 | 730 | 3 | 0.23 | 75 | 72.72 | 90.90 |
| 1:0.73:1.29 | 800 | 3 | 0.23 | 72 | 80.54 | 99.63 |
| 1:0.65:1.143 | 900 | 3 | 0.23 | 70 | 96.22 | 109.62 |
| 1:0.61:1.08 | 950 | 3 | 0.23 | 65 | 97.52 | 111.22 |
| 1:0.58:1.03 | 1000 | 3 | 0.23 | 65 | 98.12 | 112.55 |

## 3-3 Effect of Silica Fume Content on Compressive Strength of Concrete

In this investigation, silica fume was initially used as a replacement by weight of cement with different percentage from 5% up to 20%. Silica fume as addition by weight of cement was also used. Table (13) shows that there is a slump loss of about 5mm with the addition of silica fume to each mix. This attribute to the high surface area of silica fume which causes more water demand for wetting its fine particles [11]. Generally the results in Table (13) indicate that the replacement of cement by silica fume increases the compressive strength of concrete at 7 and 28 days, but when the proportion of silica fume is greater than 15% by weight of cement there is a decrease in the compressive strength. It was found that the optimum content of silica fume is 15% as a partial replacement by weight of cement, which causes an increase of about 14% in 28 days compressive strength relative to reference concrete mix (without silica fume). Table (13) also shows that the compressive strength at 28 days of the concrete mix (1:0.65:1.143 by weight, w/c ratio 0.23, 3% HRWRA, 15% silica fume as partial replacement by weight of cement) increases due to the addition of silica fume of 5% and 10% by weight of cement. It was decided to choose the concrete mix which has mix proportions, 1:0.65:1.143 by weight, w/c ratio 0.23, 3% HRWRA, 15% and 5% silica fume as partial replacement and addition by weight of cement respectively. The compressive strength of this mix at age 28 days is 128.5 MPa.

## 3-4 Effect of Curing Procedure on Compressive Strength of Concrete

It was found that using steam or heat accelerated curing significantly improve the compressive strength of silica fume concrete. Application of heat too early may have a detrimental effect on the long- term strength gain and durability of the concrete. AASHTO standard specifications for highway bridges [12] state that the first application of steam or heat should be applied for 2 to 4 hours after final placement of concrete, in order to allow the initial set of the concrete to take place. The ambient temperature within the curing enclosure must be increased at an average rate not exceeding $22°C$ per hour and the maximum temperature should not exceed $71°C$. In this investigation curing of specimens in hot water for different durations of time was done, all specimens were demoulded after 24 hours and then cured in cold water for 24 houres, then in hot water for different periods as shown in Table (14). The specimens were immersed in hot water after 48 hours of casting and the rate of heating was relatively slow of $20°C$ per hour. The temperature of curing water remained constant of about $60°C$ during the curing period. From Table (14), it can be noted that using hot water curing process improves the compressive strength of concrete; this may be due to the acceleration in the hydration process of cementitious materials. The increase of hot water curing period slightly enhanced the compressive strength of the specimens, the percentage increase in compressive strength for 3 and 20 days hot water curing is about 8% and 13% respectively relative to normally cured concrete. It can be concluded that increasing hot water curing period more than 3 days has no significant effect on the compressive strength of concrete, while it increases the cost and the time required to produce the concrete.

From the previous results it can be concluded that the selected concrete mix to produce modified RPC has the following materials:

- Mix proportion 1:0.65:1.143 by weight, 900kg/m$^3$ cement, 585 kg/m$^3$ sand, 1029 kg/m$^3$ crushed aggregate with maximum size 12.5mm.
- Water/cementitious ratio 0.23.
- HRWRA dosage 3% by weight of cement.
- Silica fume 15% and 5% by weight of cement as a replacement and addition of cement content respectively.

The compressive strength is about 139MPa after 3 days of hot water curing.

*Table (13) Relationship between compressive strength of concrete and silica fume (SF) proportions as a replacement and addition by weight of cement*

| Mix proportions by weight | SF (%) replacement of cement | SF (%) as addition by weight of cement | HRWRA (%) by weight of cement | W/C ratio | Slump (mm) | Compressive strength (MPa)(100mm cube) | |
|---|---|---|---|---|---|---|---|
| | | | | | | 7days | 28 days |
| 1:0.65:1.143 | 0 | 0 | 3 | 0.23 | 70 | 96.22 | 109.62 |
| | 5 | 0 | 3 | 0.23 | 70 | 96.90 | 110.90 |
| | 10 | 0 | 3 | 0.23 | 65 | 97.80 | 121.20 |
| | 15 | 0 | 3 | 0.23 | 65 | 111.0 | 125.20 |
| | 18 | 0 | 3 | 0.23 | 65 | 116.7 | 124.20 |
| | 20 | 0 | 3 | 0.23 | 65 | 108.9 | 122.70 |
| | 15 | 5 | 3 | 0.23 | 65 | 112.4 | 128.50 |
| | 15 | 10 | 3 | 0.23 | 60 | 105.0 | 129.10 |

*Table (14) Effect of hot curing period on the compressive strength of concrete*

| Mix proportions by weight | Air curing period before demoulding (days) | Cold water curing period (days) | Hot water curing period (days) | Compressive strength (MPa)(100mm cube) | Increase in compressive strength (%) |
|---|---|---|---|---|---|
| 1:0.65:1.143 | 1 | 27 | 0 | 128.5 | - |
| | 1 | 1 | 3 | 138.7 | 7.9 |
| | 1 | 1 | 5 | 139.5 | 8.5 |
| | 1 | 1 | 10 | 140.5 | 9.3 |
| | 1 | 1 | 15 | 143.6 | 11.8 |
| | 1 | 1 | 20 | 144.7 | 12.6 |
| | 1 | 1 | 26 | 144.9 | 12.8 |

## 3-5 Effect of Steel Fiber on the Mechanical Properties of Modified RPC

### 3-5-1 Compressive Strength

Hooked and crimped steel fibers with different volume fractions of 0.5%, 0.75% and 1% were added to the selected mix. The results shown in Table (15) and Fig(1) indicate that the compressive strength of concrete (100mm cube) is only slightly affected by the addition of the two types of steel fibers, The maximum increase in compressive strength is about 9% for modified RPC containing 1% crimped steel fibers. This is attributing to the fact that adding steel fibers to concrete increases its strainability in compression failure and so the compressive strength of concrete containing steel fibers increases [13].

***Table (15) Effect of type and volume fraction of steel fibers on the compressive strength of modified RPC***

| Mix proportions | Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | Slump (mm) | Compressive strength (MPa) | Increase in compressive strength (%) |
|---|---|---|---|---|---|
| 1:0.65:1.143<br>- w/c =0.23<br>- 3% HRWRA by weight of cement<br>- SF-15% replacement + 5% addition by weight of cement | - | 0 | 65 | 138.7 | 0 |
| | Crimped | 0.5 | 62 | 139.9 | 0.87 |
| | Hooked | 0.5 | 62 | 141.1 | 1.73 |
| | Crimped | 0.75 | 60 | 145.6 | 4.97 |
| | Hooked | 0.75 | 60 | 144.9 | 4.47 |
| | Crimped | 1 | 55 | 151.3 | 9.08 |
| | Hooked | 1 | 50 | 148.9 | 7.35 |

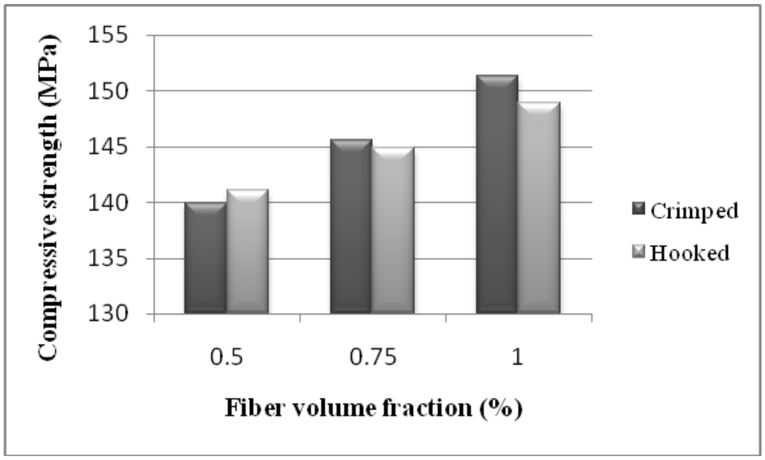

***Fig.(1) Effect of volume fraction and type of steel fibers on the compressive strength of modified RPC***

### 3-5-2 Splitting Tensile Strength

Splitting tensile strength (tested according to ASTM C496-07) results of modified RPC with different types and contents of steel fibers are shown in Table (16) and Fig. (2). It can be concluded that the inclusion of steel fibers in concrete mix cause a considerable increase in splitting tensile strength relative to reference mix (without fibers). Splitting tensile strength increases as the fiber volume fraction increases. The percentage increase in splitting tensile strength is about 35 % and 39% for concrete mix containing 1% crimped and hooked steel fibers respectively. It can be observed that all mixes with hooked steel fibers have slightly higher splitting tensile strength than those containing crimped steel fibers; this may be due to the excellent mechanical anchorage of hooked steel fibers at their ends which leads to high bond strength between the fibers and the matrix [14,15].

***Table (16) splitting tensile test results for modified RPC with different types and contents of steel fibers***

| Mix proportions | Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | splitting tensile strength (MPa) | Increase in splitting tensile strength (%) |
|---|---|---|---|---|
| 1:0.65:1.143<br>- w/c =0.23<br>- 3% HRWRA<br>by weight of cement<br>- SF-15% replacement<br>+<br>5% addition<br>by weight of cement | - | 0 | 7.52 | 0 |
| | Crimped | 0.5 | 8.33 | 10.77 |
| | Hooked | 0.5 | 8.63 | 14.76 |
| | Crimped | 0.75 | 9.11 | 21.14 |
| | Hooked | 0.75 | 9.31 | 23.80 |
| | Crimped | 1 | 10.13 | 34.71 |
| | Hooked | 1 | 10.42 | 38.56 |

### 3-5-3 Flexural Strength (Modulus of Rupture)

Flexural strength test results (tested according to ASTM C78-07 under two point loading) of modified RPC reinforced with different types and fiber volume fraction are presented in Table (17) and Fig. (3). The results demonstrate that using steel fibers causes a considerable increase in flexural strength in comparison with the plain concrete and the flexural strength increases with the increase in fiber volume fraction. Generally it can be seen that the flexural strength of all specimens reinforced with hooked steel fiber have slightly higher flexural strength than that reinforced with crimped steel fibers. It can be noticed from the experimental test that plain concrete specimen suddenly failed in a brittle manner and separated into two parts, while fiber concrete specimens have many cracks before the failure.

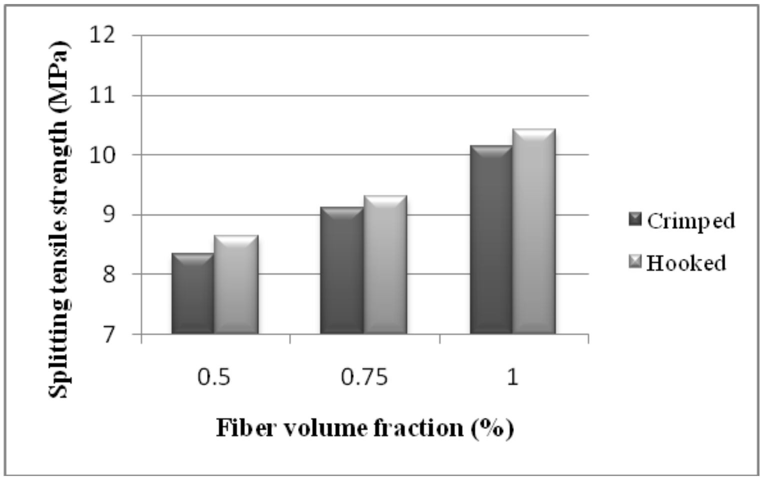

***Fig.(2) Effect of volume fraction and type of steel fibers on the splitting tensile strength of modified RPC***

This is attributed to the role of the action of fibers in matrix in which arresting both the initiation of randomly oriented micro-cracks and its propagation, lead to improving the strength and ductility [16,17]. ACI-544 [18] reported that ultimate flexural strength of fiber reinforced concrete (FRC) generally increases in relation to the product of fiber volume fraction ($Vf$) and aspect ratio of fiber $l_f/d_f$. The equation for the ultimate composite flexural strength is:

$$\sigma cu = 0.97 frVm + 494Vf\,( {}^{lf}/_{df} ) \ldots (1)$$

Where:

$f_r$: stress in the matrix (modulus of rupture of the plain , mortar or concrete), psi.

$V_m$: volume fraction of the matrix =1-$V_f$.

$V_f$ : volume fraction of the fiber =1-$V_m$.

$l_f/d_f$: ratio of the length to diameter of the fibers (aspect ratio).

Crimped fibers, surface- deformed fibers, and fibers with end anchorage produce strengths above those for smooth fibers of the same volume concentration. This may be due to high bond efficiency for these types of fibers relative to smooth fibers. Bond efficiency of the fiber varies from 1.0 to 1.2 depending up to fiber characteristics. It can be seen from Table (18) that the values of flexural strength calculated from equation (1) are underestimated by an average percentage of 8.7%. This may be raised from the higher bond efficiency factor for hooked and crimped steel fibers which is considered to be (1) in equation (1) and according to ACI-544, so for hooked and crimped steel fiber it is suggested to use bond efficiency factor of 1.2 in equation (1). The equation will be as following:

$$\sigma cu = 0.97 frVm + (494 \times 1.2) Vf \left( {}^{lf}/{}_{df} \right) \text{……….(2)}$$

Generally it can be concluded that the calculated flexural strength are underestimated in comparison to the experimental values. This may be because the equation proposed in the ACI-544 is applied for normal strength FRC.

***Table (17) Flexural strength results for modified RPC reinforced with different types and contents of steel fibers***

| Mix proportions | Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | Flexural strength (MPa) | Increase in flexural strength (%) |
|---|---|---|---|---|
| 1:0.65:1.143<br>- w/c =0.23<br>- 3% HRWRA by weight of cement<br>- SF-15% replacement + 5% addition by weight of cement | - | 0 | 8.31 | 0 |
| | Crimped | 0.5 | 9.61 | 15.64 |
| | Hooked | 0.5 | 9.91 | 19.25 |
| | Crimped | 0.75 | 9.94 | 19.61 |
| | Hooked | 0.75 | 10.32 | 24.19 |
| | Crimped | 1 | 10.40 | 25.15 |
| | Hooked | 1 | 10.76 | 29.48 |

***Table (18) Details of experimental and calculated flexural strength for modified RPC***

| Mix proportions | Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | Experimental flexural strength (MPa) | Calculated flexural strength (MPa) | | Ratio of cal./exp. Flexural strength | |
|---|---|---|---|---|---|---|---|
| | | | | Equ. (1) | Equ. (2) | Equ. (1) | Equ. (2) |
| 1:0.65:1.143<br>- w/c =0.23<br>- 3% HRWRA by weight of cement<br>- SF-15% replacement + 5% addition by weight of cement | - | 0 | 8.31 | | | | |
| | Crimped | 0.5 | 9.61 | 8.88 | 9.04 | 0.92 | 0.94 |
| | Hooked | 0.5 | 9.91 | 8.88 | 9.04 | 0.90 | 0.91 |
| | Crimped | 0.75 | 9.94 | 9.28 | 9.53 | 0.93 | 0.96 |
| | Hooked | 0.75 | 10.32 | 9.28 | 9.53 | 0.90 | 0.92 |
| | Crimped | 1 | 10.40 | 9.68 | 10.02 | 0.93 | 0.96 |
| | Hooked | 1 | 10.76 | 9.68 | 10.02 | 0.90 | 0.93 |

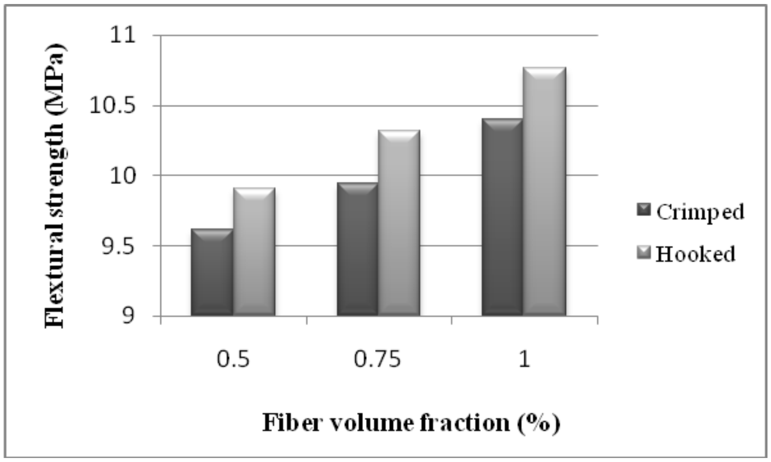

***Fig.(3) Effect of volume fraction and type of steel fibers on the Flextural strength of modified RPC***

### 3-5-4 Static Modulus of Elasticity

Table (19) and Fig.(4) show the results of static modulus of elasticity(tested according to ASTM C469-07) for modified RPC containing different types and content of steel fibers. Generally the results indicate that the modulus of elasticity increases with the increase in fiber volume fraction. Many researchers have performed work to find relationship between the compressive strength of concrete ($f'c$) and its elastic modulus ($Ec$). ACI-318[19] provided the following equation for plain normal strength concrete:

$$Ec = 4700 f'c^{1/2} \quad \text{(MPa)} \ldots\ldots (3)$$

Modulus of elasticity of high performance concrete can be estimated from the compressive strength according to CEB [20] as following:

$$Ec = 9515 f'c^{1/3} \quad \text{(MPa)} \ \ldots\ldots.. (4)$$

ACI-363 [21] present a relationship between the compressive strength and the modulus of elasticity for high strength concrete with compressive strength up to 83 MPa :

$$Ec = 3320 f'c^{1/2} + 6900 \ \text{(MPa)}\ldots.. (5)$$

Thomas and Ramaswamy[22]show the relationship between modulus of elasticity and compressive strength for fiber reinforced high strength concrete with $f'c \leq 85$ MPa as following:

$$Ec = 4580f'c^{0.5} + 0.42(f'c)RI + 390RI \ldots \quad (6)$$

Where:

*RI*: reinforced index of fiber [*Vf (lf/df )*]

Ma and Schneider [4] suggested the following equation for ultra high performance concrete:

$$Ec = 16364\ln(f'c) - 34828 \quad \text{(MPa)} \ldots . (7)$$

The results show that calculated modulus of elasticity using equations (3) and (6) are overestimated in comparison to the experimental values, while the results of the calculated modulus of elasticity using the other equations are underestimated. It can be observed that modulus of elasticity calculated by using equation (4) is the best, but the equation proposed by Thomas and Ramswamy [equation (6)] is more suitable; this is because that they tack the fiber index into consideration. The average ratio between the measured and calculated modulus of elasticity is 0.944.

***Table (19) Details of measured and calculated modulus of elasticity for modified RPC***

| Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | Experimental modulus of elasticity (GPa) | Compressive strength (MPa) | Modulus of elasticity (GPa) calculated according to: | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | ACI-318 | Ma and Schneider | CEB | Thomes and Ramswamy | ACI 363 |
| - | 0 | 50.21 | 138.7 | 55.35 | 45.90 | 49.25 | 53.94 | 46.00 |
| Crimped | 0.5 | 51.75 | 139.9 | 55.59 | 46.03 | 49.39 | 54.28 | 46.17 |
| Hooked | 0.5 | 51.53 | 141.1 | 55.83 | 46.17 | 49.54 | 54.52 | 46.34 |
| Crimped | 0.75 | 52.92 | 145.6 | 56.71 | 46.68 | 50.06 | 55.43 | 46.96 |
| Hooked | 0.75 | 51.95 | 144.9 | 56.58 | 46.60 | 49.98 | 55.30 | 46.86 |
| Crimped | 1 | 53.05 | 151.3 | 57.81 | 47.31 | 50.70 | 56.56 | 47.74 |
| Hooked | 1 | 53.15 | 148.9 | 57.35 | 47.05 | 50.43 | 56.11 | 47.41 |

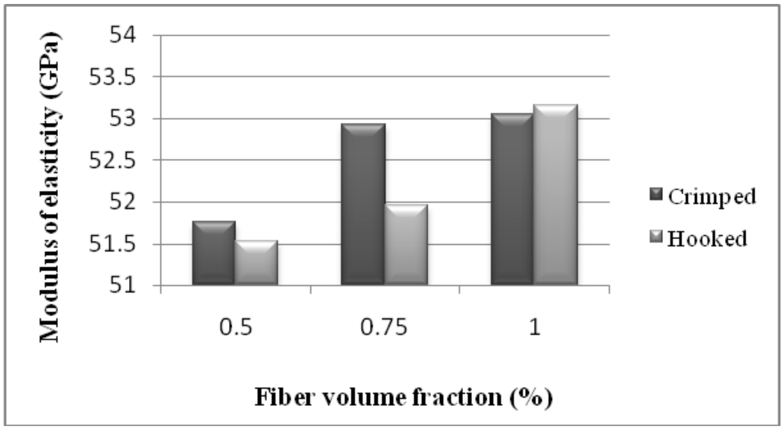

***Fig.(4) Effect of volume fraction and type of steel fibers on the modulus of elasticity of modified RPC***

### 3-5-5 Impact strength

Improved impact resistance is one of the important attributes of FRC. Several types of test have been used to measure the impact resistance of FRC; the simplest test according to ACI-544.2R [23] is the “repeated impact”, drop weight test. This test yields the number of blows necessary to cause prescribed levels of distress in the test specimen. This number serves as a qualitative estimate of the energy absorbed by the specimen at the levels of distress specified. The test can be used to compare the relative merits of different fiber concrete mixtures and to demonstrate the improved performance of FRC compared to plain concrete (without fibers). The number of blows required to cause first crack and ultimate failure for reference (without fibers) and modified RPC reinforced with different types and volume fraction of steel fiber are summarized in Table (20) and plotted in Fig.(5). The test results illustrate that the number of blows or the energy required causing initial crack and ultimate failure for modified RPC specimens reinforced with different types and volume fraction of steel fibers is higher than that of reference concrete. The number of blows causing first crack and ultimate failure significantly increase as the fiber content increases. The percentage increase in number of blows causing first crack range from about 24% to 73%, while for ultimate failure is between 55% to 148%. The type of steel fiber also affects the results of number of blows for both first crack and ultimate failure. Generally hooked steel fibers show higher impact strength (number of blows) at both first crack and ultimate load, this may be due to the excellent mechanical anchorage of hooked steel fibers at their ends which cause high bond strength between the fibers and the matrix [14,15].

***Table (20) Details of the number of blows for modified RPC***

| Type of steel fibers | Volume fraction of steel fibers $V_f$ (%) | No. of blows causing first crack | (%) increase in first crack blows | No. of blows causing ultimate failure | (%) increase in ultimate failure blows |
|---|---|---|---|---|---|
| - | 0 | 55 | - | 445 | - |
| Crimped | 0.5 | 68 | 23.6 | 689 | 54.8 |
| Hooked | 0.5 | 71 | 29.0 | 717 | 61.1 |
| Crimped | 0.75 | 74 | 34.5 | 854 | 91.9 |
| Hooked | 0.75 | 89 | 61.8 | 893 | 100.7 |
| Crimped | 1 | 86 | 56.4 | 1027 | 130.8 |
| Hooked | 1 | 95 | 72.7 | 1102 | 147.6 |

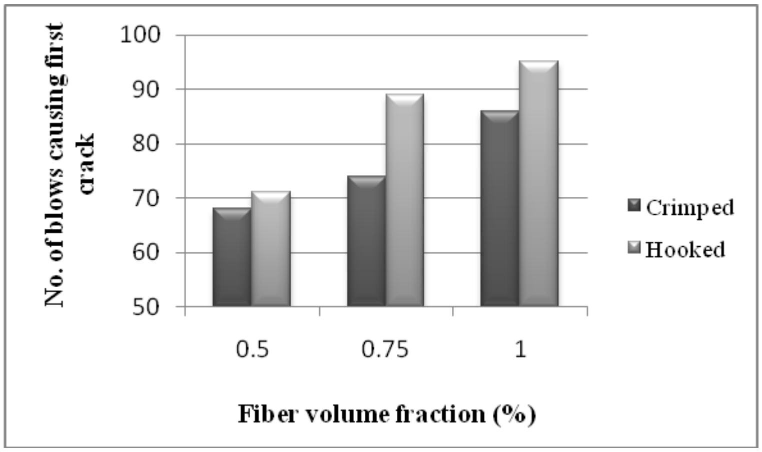

***Fig.(5) Effect of volume fraction and type of steel fibers on the number Of blows causing first crack of modified RPC specimens***

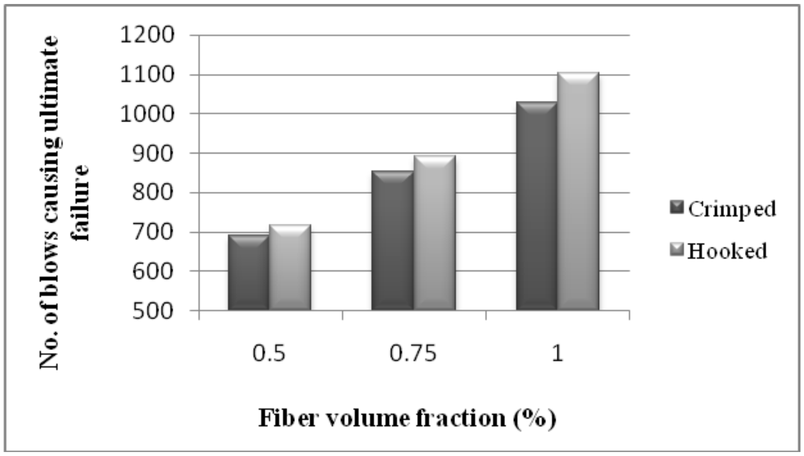

***Fig.(6) Effect of volume fraction and type of steel fibers on the number of blows Causing ultimate failure of modified RPC specimens***

## 4- Conclusions

From the experimental results presented in this investigation, the following conclusions can be drawn:

1- High compressive strength of 150 MPa can be achieved by using crushed coarse aggregate in RPC; this result is in contrast with the model proposed to relate the high compressive strength level of RPC to the absence of coarse aggregate.

2- Hot water curing (rate of heating $20°C$ per hour with temperature $60°C$) process improves the compressive strength of modified RPC; the optimum period of hot water curing is 3 days after 24 hours curing in mould and 24 hours curing in cold water.

3- The inclusion of both hooked and crimped steel fibers considerably increase the splitting tensile and flexural strengths relative to plain modified RPC, these strengths increase as the fiber content increase. The percentage increase in splitting tensile strength is about 35% and 39%, while the percentage increase in flexural strength is about 25% and 29% for modified RPC reinforced with crimped and hooked steel fibers of volume fraction 1% respectively.

4- Static modulus of elasticity of steel fiber modified RPC slightly increases relative to plain modified RPC, as fiber content increase the modulus of elasticity improved. The percentage increase in modulus of elasticity is about 6% for crimped and hooked steel fibers with volume fraction 1%.

5- The energy required causing initial crack and ultimate failure for modified RPC reinforced with different types and contents of steel fibers is significantly increase in comparison to plain modified RPC, as the volume fraction of fiber increases the energy causing first crack and ultimate failure increase.

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