# Studying of Some Mechanical Properties of Reactive Powder Concrete Using Local Materials

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## ABSTRACT

This research aims to investigate and evaluate a reactive powder concrete (RPC) cast using economical materials. Its mechanical properties were investigated and evaluated by studying the effects of using different cement and silica fume contents and locally steel fibers aspect ratios as reinforcement for this concrete. A compressive strength of about 155.2MPa, indirect tensile strength of 16.0MPa, modulus of elasticity of 48.7GPa, flexural strength of 43.5MPa, impact energy of 3294.4kN.m and abrasion loss 0.59% have been achieved for reinforced RPC contains 910 kg/m$^3$ cement content, silica fume content 185 kg/m$^3$ of cement weight and fiber volume fraction 2%. The water absorption values were 1.5 times higher for the normal strength concrete in comparison with the reactive powder concrete.

**Keywords:** reactive powder concrete, mechanical properties, abrasion, impact strength, steel fibers

# دراسة بعض الخواص الميكانيكية لخرسانة المساحيق الفعالة باستخدم مواد محلية

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## الخلاصة

يهدف هذا البحث لتحري وتقييم خرسانة المساحيق الفعالة المصنوعة من استخدام مواد اقتصادية. تم دراسة وتقييم خواصها الميكانيكية باستخدام انواع مختلفة من السمنت وغبار السيلكا والياف الحديد المحلية الصنع. من النتائج العملية المستحصلة لوحظ بان مقاومة الانضغط للخرسانة كانت 155,2 ميكاباسكال، 16,0 ميكاباسكال مقاومة الشد الغير مباشرة، 48,7 ميكاباسكال معامل المرونة الاستاتيكي، 43,5 ميكاباسكال لمقاومة الانثناء، 3294,4 كن.م و 0.59% فقدان الاحتكاك وهذه القيم تحققت لخرسانة المساحيق الفعالة المسلحة بالالياف بنسة حجمية 2% والحاوية على سمنت 910 كغم/م$^3$ ومحتوى السيلكا 185 كغم/م$^3$ من وزن السمنت. اما مقدار الامتصاص فقد سجل من الشغل العملي 1.5 مرة اكثر للخرسانة الاعتيادية مقارنة بخرسانة المساحيق الفعالة.

الكلمات الرئيسية: خرسانة المساحيق الفعالة, الخواص الميكانيكية, الاحتكاك,مقاومة الصدم, الالياف الحديدية

# 1. INTRODUCTION

## 1.1 Background

The development of concrete material may be divided into several stages. The first is the traditional normal strength concrete (NSC). The second is the high strength concrete (HSC) that is considered to be the strongest and stiffest cement based material. HSC has a compressive strength of approximately 70 MPa, a flexural strength of about 10 MPa and a Young's modulus of 14 to 42 GPa. Now, given the improvements on a microscopic scale, the technology of the Reactive Powder Concrete (RPC) is covered by one of many patents in a range known as Ultra High Performance Concretes **,Xiaoa, et al., 2004.**

Reactive powder concrete (RPC) is a new generation concrete with ultra-high performance and it was developed through microstructure enhancement techniques for cementitious materials **,Richard and Cheyrezy, 1995.** As eliminated the coarse aggregates, reduced the water-cementitious material ratio, lowered the CaO to $SiO_2$ ratio by introducing the silica components, and incorporated steel micro-fibres **,Chan and Chu, 2004.** RPC has a remarkable strength and very high ductility. Its ductility is about 250 times higher than that of conventional concrete **,Shaheen, and Shrive, 2006.** Nowadays, RPC seems to be a promising material for special pre-stressed and precast concrete members. Due to ultra-high mechanical performance of RPC, the thickness of concrete elements can be reduced **, Aïtcin, 2003.**

RPC represents one of the most recent technological leaps witnessed by the construction industry. It lies at the forefront in terms of innovation, aesthetics and structural efficiency, **Prabha, et al., 2010.** This new family of materials has compressive strengths of 170 to 230 MPa and flexural strength of 30 to 50 MPa, depending on the type of fibers used **,Moallem 2010 and AL-Hassani, 2014.** Additionally, it has a tensile strength of between 6 and 13 MPa that is maintained after first cracking. The traditional concrete has tensile strengths on the order of 2 to 4 MPa that is lost when cracking occurs **,Washer, et al., 2003.** It has also an increased resistance to abrasion, erosion, corrosion and greatly reduced permeability to moisture, chlorides and chemical attack **,Moallem 2010 and Abdelrazig, 2008.** In order to achieve ultra-high strength and ductility, RPC should contain some steel micro-fibres and has a very low water-cementitious material ratio **,Talebinejad, et al., 2004.** When cracking appears on a very small scale, the fibres intervene to prevent the microscopic crack from being propagated and causing the ruin of the structure. During multi-cracking of material, action known as of "bridging" of cracks by fibres involves many micro-mechanisms.

One of the most significant assets of RPC is the improvement in compressive strength; RPC has been demonstrated to achieve compressive strengths ranging from 23-33 ksi (158-228MPa) **,Perry and Zakariasen, 2003.** This improvement in compressive strength has far exceeded the results achieved with conventional concretes and may allow for the possibility of RPC to be more competitive in markets that have been typically dominated by steel construction **,Harris, 2004.** The significant improvements in compressive strength are complimented by the fact that RPC also exhibits tensile strength that has not been demonstrated in conventional concretes. This tensile strength allows the material to support both pre-cracking and post-cracking loads without experiencing the brittle failure that would be common in a conventional concrete. RPC has demonstrated tensile strengths ranging from 0.9-1.7ksi (6-12) MPa with various curing regimes and standard ASTM testing methods **,Kjellsen** and **Atlassi, 1999.** These tensile strengths were achieved as a result of the interaction of the steel fibers on the microscopic level and their ability to sustain load after the onset of cracking **,Harris, 2004.**

In addition to the improvements in tensile strength, UHPC can also achieve flexural strengths ranging from 5,000–7,200 psi (35-50 MPa) **,Perry** and **Zakariasen, 2003.** This combination of the tensile and flexural strength makes UHPC an extremely ductile material, capable of supporting significant loads beyond cracking **,Harris, 2004.**

Experimental study carried out on the tensile behaviour of different Ultra High Performance Fiber Reinforced Concrete (UHPFRC) mixes using four types of high strength steel fibers; straight with aspect ratio 65, hooked with aspect ratio 79, high twisted with aspect ratio 100, and low twisted with aspect ratio 100 with different volume fractions (1%, 1.5%, 2% and 2.5%). The results showed that both the tensile strength and the maximum post-cracking strain are significantly improved by using deformed steel fibers instead of smooth fibers. Moreover the path of the stress strain curves of UHPFRC reinforced with hooked steel fibers and UHPFRC reinforced with twisted steel fibers are similar up to the peak load of UHPFRC reinforced with hooked steel fibers. While UHPFRC reinforced with hooked steel fibers begins softening at post cracking strain $\varepsilon tp = 0.46\%$, UHPFRC reinforced with twisted steel fibers keeps increasing the tensile stress up to post cracking strain $\varepsilon tp \approx 0.6\%$ **,Wille, et al., 2011.**

The mechanical properties and impact resistance of RPC containing silica fume and ground granulated blast furnace slag (GGBFS) and fly ash as a replacement by weight of cement were studied. To improve ductility, steel fibers with polypropylene fibers in hybrid were used. All specimens were cured in 20°C and 90°C for 7, 14 and 28 days. The test results showed that the modulus of elasticity is 50 to 60GPa. Initial results from simple impact load test on 1000 mm square, and 100mm thick unreinforced slab supported on all sides, were very encouraging. The concrete on the top was powdered under repeated impacts but there was no indication of tensile cracking. After 70 impacts, a cone of concrete sheared off from the underside of the slab when the thickness of the slab had been reduced by the powdering on the top surface **,Marios, et al., 2003.** The mechanical properties and impact resistance of RPC were investigated. Tests on the mechanical properties indicated that RPC has enhanced tensile strength and ductility; i.e. Flexural strength values are likely to be between (30-60) MPa and fracture energies above 10000 J/m$^2$.It has been shown that concrete with compressive strength as high as 200 MPa and flexural strength as high as 40 MPa can be produced in the laboratory and the addition of steel fibers to the RPC mixes increase not only the flexural strength and ductility but also increase the compressive strength **,Soutsos, et al., 2001.**

## 1.2 Research Objectives

In this context, the present study is devoted to investigate the feasibility of manufacturing reactive powder concrete RPC mixtures with its ultra mechanical properties using locally available materials in Iraq. The main variables are; cement content, silica fume content and steel fibers. In this research, the available sand with its suitable size for this type of concrete and two types of cement ordinary Portland and sulphate resisting Portland cement are used instead of using expensive materials such as quartz powder and steel aggregates to produce comparable mixtures as most researchers do. The experimental test program is performed to study the behaviour of the RPC under the previous variables in compressive strength, modulus of elasticity, indirect tensile strength, flexural strength, water absorption and impact strength. In this research, the effect of compressive strength and number of blows on abrasion loss of normal and reactive powder concrete was taken into consideration. This research provides data for the researchers concerning main properties of RPC manufacturing using economical (local) available materials.

## 2. EXPERIMENTAL SET-UP

All tests in this research were carried out in the Construction Materials Laboratory in Civil Engineering Department, College Engineering, Babylon University. The materials used, preparing, casting, curing of test specimens and testing procedures were discussed in this section.

### 2.1 Materials

2.1.1 Cement

Two types of Portland cement, conforming to the IQS 5/1984 are used. The first type is ordinary Portland cement (OPC) and the other sulphate resistant Portland cement (SRPC) (ASTMC150- type I and type V) manufactured by united cement company commercially known (TASLUJA-BAZIAN). The chemical and physical properties of these types of cement are presented in **Table 1**. Test results indicate that the adopted cement conforms to Iraqi specifications **(IQS No.5/ 1984)**.

2.1.2 Silica fume

Silica fume has been used as a mineral admixture added to the RPC mixes of this study. It is a waste by-product of silicon and silicon alloys industry consisting mainly of non-combustible amorphous silica ($SiO_2$) particles. It was produced by Iraq Ferro Alloys Corporation. Silica fume is used with (20%) as replacement of cement. The chemical composition and physical requirements show that the silica fume conforms to the chemical and physical requirements of **ASTM C1240-05** specifications see **Table 2**.

2.1.3 Fine aggregate

Al-Ekhaider natural sand of 4.75mm was used as fine aggregate. The grading of original fine aggregate is shown in **Table 3**. The sand was washed and cleaned by water several times, later it was speared out and left in air to dry before use. Results indicate that fine aggregate grading is within the requirements of the Iraqi Specification No.45/1984. For RPC, very fine sand with maximum size 600μm was used. This sand was separated by sieving, its grading satisfied the fine grading in accordance with the Iraqi Specification No.45/1984. **Table 4** illustrates the sieve analysis of the separated fine sand. **Table 5** shows the specific gravity, sulfate, and absorption content of fine aggregate, the latter being within the requirements of the Iraqi specification No.45/1984.

2.1.4 Water

Clean, drinkable, fresh and free from impurities tap water used for both making and curing the tested specimens.

2.1.5 Admixtures superplasticizer: high range water reducing admixture

The high range water reducing admixture used in this study is a third generation super plasticizer for concrete and mortar, it is Aqueous solution of modified Polycarboxylates, which is known commercially as SikaViscocrete-5930.Itis High Performance Super plasticizer Concrete Admixture, It is imported from Sika company in Egypt. SikaViscocrete-5930 has been primarily developed for applications where the highest durability and performance are required.SikaViscocrete-5930 is free from chlorides and complies with **ASTM C494-99** type G and F. The technical description is shown in **Table 6**.

#### 2.1.6 Steel fibers

Short discrete iron wire used as alternative of standard fiber which used at different volume fraction with aspect ratio (l/d = 37.5). The fibers are used to increase tensile capacity and improve ductility. The steel fibers used in this investigation are clean of rust or oil of straight steel wire fibers. The used steel fibers are chopped or cut from steel wires that locally used to link the reinforcement bar to the stirrups. The steel wires are cut into the desired length which was 30 mm omit. The fibers used are of diameter 0.8 ±0.02 mm where as the diameter that usually used in nearly all the research in producing RPC which was 0.2 mm. This type of fiber is very cheap in comparison with the other types of steel fibers and is available in all markets in Iraq. The fiber use confidence with **ASTM E 882** and the tensile test were done in laboratory of materials at the University of Babylon. The properties of the steel fibers used are shown in **Table 7**.

### 2.2 Determination of the Workability of Concrete Mixtures

The flowability was tested by the flow table test in accordance with ASTM C-1437. **Fig. 1** shows flow table device and workability test. The flow is the resulting increase in average base diameter of the mortar mass, expressed as a percentage of the original base diameter of flow table cone (100 mm), i.e.:

$$Flow, D_{flow} = \frac{D - 100}{100} \times 100$$

Where:

D: Average diameter of the spread mix measured in four directions, (mm).

### 2.3 Strength Activity Index for Mineral Admixture

Reference and high performance mortars were prepared for pozzolanic activity. All mortars consist of 1 part of cement or cementitious materials and 2.75 parts of graded standard sand by weight in accordance with ASTMC311-05. **Table 8** shows w/c or w/cm ratio and pozzolanic activity index. The pozzolanic activity index (P.A.I.) with Portland cement was determined as follows, according to **ASTM C311-05**.

P.A.I. = (A/B) ×100

Where:

A: average compressive strength of test mix cube.

B: average compressive strength of reference mix cube.

### 2.4 Mixing Procedure

All trial mixes were performed in a small rotary mixer of 0.01m$^3$capacity, while the mixes of RPC specimens were performed in a rotary mixer of 0.09 m$^3$ for RPC concrete. Before using the mixer, any remaining concrete from previous batch was cleaned off. A damp cloth was used to wipe the pan and the blades of the mixer. The silica fume powder was mixed in dry state with the required quantity of cement for 5 minutes to ensure uniform dispersion of the reactive powder particles throughout the cement particles. Then, fine sand was loaded into the mixer and mixed for 5 minutes. The required amount of tap water was added to the rotary mixer within 1 minute. Then all the super plasticizers were added and mixed for an additional 5 minutes. When steel fibers were used, they were introduced, and dispersed uniformly. These were added slowly to the rotary mixer after the rest of the materials had been properly mixed and the concrete had a wet appearance and mixed for an additional 2 minutes. The same mixing procedure, schematized in

**Fig. 2**, was rigorously applied for each batch. The mixing of one batch requires approximately 20 minutes from adding water to the mix.

## 2.5 Mixtures Proportions

The mixture ratios were based on guidelines and specifications given in several different approaches presented in literature. The composition of normal weight concrete (NC) with water-to-cement ratio (W/C) of 0.35 is given in Table 8. Cement dosage of RPC is generally higher than 1000 kg/m$^3$ to achieve ultra-high strength under very low water/cement ratios. A high amount of cement not only affects the production costs, but also has negative effects on the heat of hydration and may cause shrinkage problems. Mineral admixtures can be a feasible solution to overcome these problems in RPC. **Table 9** summarizes the mixture designs of RPC produced in this study; the water-cementitious material ratio of 0.175 used in this study is also included in this table.

## 2.6 Concrete Samples

Samples were divided into four groups. (i) standard cubes of dimensions 50×50×50 mm for measuring the compressive strength and water absorption, (ii) cylinders of 100 mm diameter and 200 mm height for measuring the indirect tensile strength and the modulus of elasticity and (iii) prisms of 50×50×300 mm to measure the flexural strength and (iv) cylinders of 150 mm diameter × 65 mm height for measuring the impact strength. All tests in this research were carried out to investigate the main properties of RPC samples as reported in this section.

## 2.7 Compressive Strength and Water Absorption Test

The compressive strength test was carried out according to **B.S: 1881: part 116** using a digital testing machine with a capacity of 2000 kN. Three cubs were cast for each mix at each age, for determination of compressive strength. Cubes were removed from curing solution at age of 3, 28 and 56 days.

In general, either the **ASTM C642 or BS1881:122** standards can be used for the water absorption test of RPC specimens. In this study, the latter was referred to. The cylindrical specimens were dried in oven for 24 hours first and then its oven-dried weight was measured denote by WD. Then the dried specimens were saturated completely in water for one hour, one day, three days and seven days, respectively. Then the specimens were taken out of water, wiped out the excessive water on the surface of specimen with cloth and measured its saturated weight denoted as WW. The water absorption ratio Ra is simply defined as

$$R_a = \frac{W_W - W_D}{W_D} \times 100\% \tag{1}$$

1) Prism Flexural Test: The concrete modulus of rupture was determined by testing prism specimens in conformity with **ASTM C 78-02**. Each prism was simply supported and subjected to a two point loading using an electrical testing machine with a capacity of 2000 kN.

2) Tension Test: Indirect tension test (splitting method) has been determined by testing standard cylinders for every mix depending on **ASTM C496-05** specification. A 2000 KN capacity compression testing machine was used.

3) Modulus of Elasticity Test: This test was carried out on cylindrical specimens. The 40% of ultimate compressive strength of concrete specimen was applied on the concrete cylinders to perform the elastic modulus test as specified by **ASTM C-469**. The specimens were tested at age

28 days and the average of three specimens was adopted. A 2000 kN capacity compression testing machine was used to apply a compressive axial load and compress meter (dial gauge with accuracy 0.01 mm and a maximum capacity of 10 mm) was used.

4) Impact Strength Test: The impact resistance (dynamic energy absorption as well as strength) is one of the important attributes of RPC and there are several methods to find impact resistance, the test done according **ACI 544.2R**, using drop-weight test which is modified according CBR hummer test using three cylinders at 28 days age. **Fig. 3** states the device and specimen tested. The test measure the impact resistance depending on number of blows necessary to cause prescribed levels of distress in the test specimen. The hammer is dropped repeatedly, and the numbers of blow cause first visible crack on the top and cause ultimate failure are both records.

The test specimen is supported by a rigid base. In practice both supports and boundary conditions of a fiber concrete element may be quite different from those adopted in the test. The manual application of the impact load tends to be tedious and inconvenient particularly if several hundreds of blows are required to produce final failure. Nevertheless the falling weight test method appears to take into account the properties of the matrix, the nature of the fiber, the nature of interfacial zone between particles of the matrix as well as between fiber surface and matrix. Impact toughness of RPC was measured by number of blows for first crack and failure, using the equation blow:-

$$W=n\times m\times g\times h \tag{2}$$

Where,
W: impact energy (Joule (J) or kN.m);
n: impact number;
h: the height hammer drops (457mm);
g: accelerating velocity (9.81m/s$^2$);
m: weight of hammer (4.536kg).

5) Abrasion Test: The abrasion resistance of NSC and RPC was measured through testing according to **ASTM C944**, in which a rotating abrading wheel bears on and wears away the concrete surface for a period of two minutes. One modification to the standard test method was made in this program. The reported test results are the product of 10 total minutes of abrasion representing five two-minute cycles completed on each specimen. The abrasion testing was performed on three specimens from each of the NSC and RPC. However, as abrasion resistance is highly dependent on the surface condition of the concrete, each specimen was tested on three different surfaces. First, all specimens were tested on the surface formed by casting NSC and RPC against the steel mould in which they were produced. Following these tests, the cast (and now abraded) surface was sandblasted until it displayed a uniform texture. The testing was then repeated for this sandblasted surface. Finally, the testing was again repeated for all the specimens subsequent to having the test surface ground plane using a cylinder end grinder. The weight loss due to abrasion was measured.

## 3.TEST RESULTS AND DISCUSSION

### 3.1 Mechanical Properties

The test results for mechanical properties in this study are summarized in **Table 10**. The compressive strength is one of the important properties of hardened RPC, and in general, is the characteristic material value for the classification of concrete in national and international codes. To study the effect of different types of cement and fiber contents on compressive strength of RPC and NC, several mixes were tested at ages of (3, 28 and 56) days to determine strength development as a function of age, three cubes are used within this test. The highest measured 28-day compressive strength values for the mixes of the NC and RPC specimens are shown in **Fig. 4.**

It is obvious from the results slight increment compressive strength of concrete by (7.4, 11.1, 17.0 and 23.6) % from mixes contain steel fibers (0.5, 1, 1.5, 2) % volume fraction respectively relative to the control (RPC without steel fiber) for both types of cement approximately at the age of test 28 days. The development of compressive strength for RPC may be come from the effect of high performance superplasticizer (visco crete 5930) as a water reduction on compressive strength, and because the low water cementitious ratio used in RPC mixes. Over and above the chemical reaction of (pozzolanic materials) micro silica fume with calcium hydroxide released from cement hydration leading to improve compressive strength, reduce the micro cracking, reduce voids and strengthen the microstructure. The chemical reaction starts at early ages 3days, and increases till the age of 28 days. It is noted that, unlike the normal weight concrete specimens with the failure modes of either in crushed state or two separated pieces, these failed RPC specimens are still kept together by the steel fibers

The flexural strength, expressed as the modulus of rupture. The values of flexural strength of the specimens considered in the present investigation are summarized in **Table 10** and plotted in **Fig. 5**. It is worthwhile to note that the fibrous concrete mixes really standout higher in the flexural strength when compared to the non-fibrous concrete mixes for both concrete NC and RPC. Results presented in Table above indicated that for mixes which contain steel fiber of volumetric ratio (0.5, 1, 1.5, and 2) % respectively, the modulus of rupture after 28 days of curing increased by (38.3, 58.7, 100.4 and 109.6) % and (38, 57.6, 96.2 and 107.1) % for ordinary Portland cement and sulfate resisting cement respectively relative to the reference concrete mix that is without fibers. RPC also shows significant increase in flexural tensile strength in comparison with normal concrete, where this increment is about five times that for the normal concrete. It is obvious from the results that the addition of steel fibers to normal concrete increased flexural strength, where this increment is about 1.5 times that for the normal concrete.

The tensile strength of NC and RPC is much lower than the compressive strength, because of the ease with cracks which propagate under tensile loads, and is usually not considered in design. However, it is an important property, since cracking in concrete is most generally due to the tensile stresses that occur under load, or due to environmental changes. The tensile strength increases with age for all mixes as shown in **Fig. 6**. All fibrous mixes demonstrated higher splitting tensile strength relative to plain mix at all curing ages. Splitting tensile strength indicated significant increase in strength due to the inclusion of steel fibers. The split-cylinder loading configuration causes vertical compressive stress and lateral tensile stress in the cylinder. This biaxial stress state has a definite effect on the post cracking behavior while the cylinders with fibers are cracked at failure without separation. The mode of failure in RPC cylinders without micro steel fiber is done by splitting the specimen into two symmetrical parts whereas the mode of failure in specimen with steel fiber was done by splitting the specimen but still as one mass with crack along the specimen. The mode of failure in normal concrete NC without steel fiber was done by splitting the specimen to two parts with crashing some parts of the specimen but the specimen with steel fiber was splitting and stills the parts together and there were lateral side cracks.

The modulus of elasticity is strongly influenced by the concrete materials and their proportions, **MAHDI, 2009**. The static modulus of elasticity results for all mixes is presented in **Table 10** and **Fig. 7**. It can be noticed that the increase in steel fibers ratio show only slight increases in the static modulus of elasticity. This may be because the modulus of elasticity was calculated to the stress corresponding to 40% of the ultimate load, so it is determined prior to concrete cracking; therefore, the fibers were not activated. The highest value of 51.3GPa was measured in the mix (NRPC2). The lowest value of the modulus of elasticity which equalled slightly over 26.2GPa was measured in the case of the mix (SNC0). The types of cement did not have significant effect on the measured values. In general, the modulus of elasticity increased due to the presence of steel fiber and silica fume.

Brittleness factor is the ratios between splitting tensile strength to compressive strength which represent the degree of hardness of fiber reinforce concrete which increased with the increase of volume fraction friction of fiber. The values of the Brittleness factor for all main types of mixes are shown in **Fig. 8**. In this figure, the graph of coefficient of brittleness is increasing by increasing the volume fraction friction of fiber. This result indicates that splitting tensile strength of RPC shows ability well because of tensile performance of fibers. Depending on this experimental result, increase of volume fraction friction of fiber helped rise of ductile behavior of RPC. The ratios of decrease for water absorption are in range of 49.0 to 66.7% imply this test method although is rather simple but seem to properly reflect the function of pozzolanic reaction and type of cement and shown in **Fig. 9**.

In the **Figs. 10 and 11,** the graph of brittleness factor is reducing by increasing the volume fraction of fibers. This result indicates that splitting tensile strength of concrete fibered shows ability well because of tensile performance of steel fibers. Depending on this experimental result, increase of volume fraction of fibers helped rise of ductile behavior of NC and RPC.

### 3.2 Impact Strength and Abrasion Test

Improved impact resistance is one of the important attributes of RPC. The number of blows required causing first crack and ultimate failure for reference and RPC reinforced with different percent of volume fraction of steel fiber are summarized in **Table 11** and plotted in **Fig.12. Fig. 13** reveals the fracture toughness increased with increased fiber volume. This behaviour related to the bond strength between the steel fiber and cement paste. The test results illustrate that the number of blows or the energy required causing initial crack and ultimate failure for RPC specimens reinforced with different volume fraction of steel fibers is higher than that of reference concrete. It is clear that the impact strength or the number of blows causing first crack and ultimate failures significantly increase as the fiber content increases and for different types of cement. Generally using ordinary Portland cement show higher impact strength (No. of blows) at both first crack and ultimate load than sulphate resisting cement for both types of concrete NC and RPC. It can be recognized that the failure surfaces of the fiber reinforced concrete specimens differ clearly from those of the plain concrete through the specimen of non-fiber reinforced dispread to several pieces in less number of blow after the first crack appears while fiber reinforced specimens still almost together after ultimate failure and displayed different modes of failure. Although the falling weight test is a simple, practical test carried out under rather arbitrary conditions and can give an indirect assessment of the

- The test specimen is supported by a rigid base. In practice both supports and boundary conditions of a fiber concrete element may be quite different from those adopted in the test.
- The manual application of the impact load tends to be tedious and inconvenient particularly if several hundreds of blows are required to produce final failure.

Nevertheless the falling weight test method appears to take into account the properties of the matrix, the nature of the fiber, the nature of interfacial zone between particles of the matrix as well as between fiber surface and matrix.

Abrasion resistance can be an important parameter for any concrete that is exposed to contact with other materials. The average weight loss per 2 minute abrading results is shown in **Fig. 14**. The highest value of 3.82% was measured in the SNC0 mix. The lowest value of the abrasion loss which equaled slightly over 0.59% was measured in the case of the NRPC2 mix. The type of cement did not have significant effect on the measured values. In general, the abrasion loss decreased due to the presence of steel fibers and depended on the type of concrete. The addition of steel fiber in the composite produces a denser and stronger surface, which results in a higher resistance to abrasion. It is obvious that particle loss under mechanical abrasion effect is much more difficult in the vicinity of steel fibers. Results indicated that addition of steel fibers (2%) decreased weight loss due to abrasion by 45% and 44% for RPC and NC respectively. RPC demonstrated very low abrasion compared to NC. This result was more pronounced in the case of plain matrices.

**Fig. 15** shows the relationship between compressive strengths and mass losses for NC and RPC. Mechanical properties were compared with abrasion loss values and a good correlation was obtained. The relations follow exponential functions. It is well known that compressive strength is the most important factor governing the abrasion resistance of concrete **(Laplante, et al., 1991)**. Steel fiber reinforcement improves not only flexural performance but also compressive strength in the case of ultra-high performance concrete. Furthermore, relationship between the compressive strength of fiber reinforced RPC and the mass loss is meaningful.

### 3.3 Statistical Evaluation of Test Results

The compressive strength, number of blows and abrasion loss are given in Table 12. A multiple regression analysis was applied to obtain the following relationship among compressive strength, number of blows and loss on abrasion.

The comparison of experimental and estimated loss on abrasion (obtained from Eq. 3) as well as 95 % confidence intervals is shown in **Fig. 16**. The estimated values are in excellent agreement with the experimental values obtained in this study. The coefficient of correlation between estimated and experimental values is 95%. In the other words, with a few exceptions, the differences between calculated and experimentally obtained values are within a range of ±2.45.

$$\mathrm{LOA}=4.67-0.0037\times NB-0.022\times fc \qquad (3)$$

Where,

LOA : 28-day abrasion loss of normal and reactive powder concrete,

fc : 28-day compressive strength of concrete, (MPa),

NB : number of blows.

## 4. CONCLUSION

The presented results showed that it is feasible to produce reactive powder concretes from locally materials applying reactive powder concretes principles and packing density theories. The 28-day compressive strength and the rheology of the normal and of the reactive powder concretes appeared to be comparable. A compressive strength of 172.4MPa, indirect tensile strength of 17.1MPa, modulus of elasticity of 51.3GPa and flexural strength of 48.2MPa were approached for steel fibers reactive concrete samples of 910 kg/m$^3$ cement content and 230 kg/m$^3$ silica fume (NRPC2). The use of fine sand whose grain size is (<600μm) improves the compressive strength due to the more dense microstructure of the cement matrix. RPC without fibers is a brittle material and fails suddenly and violently.

The addition of steel fiber to concrete increases the impact resistance of the composite significantly. The increase in the steel fibers volume fraction and using ordinary Portland cement

led to a good increase in the impact resistance of the normal concrete and RPC specimens. Also addition of steel fibers in discrete forms to RPC changes its brittle mode of failure into a more ductile. It is recommended to use of steel fibers as an enhancing material to RPC. It seems that RPC is a good alternative material under mechanical abrasion exposure due to heavy traffic loads. The abrasion loss of NC and RPC can be estimated from compressive strength and number of blows results. The proposed equation has a sufficient reliability.
Finally, it can produce an economic RPC using locally available materials in Iraq, in order to manufacturing a pre-cast ultra high strength concrete with ultra mechanical properties (RPC). Further improvement of the mechanical properties of normal and reactive powder concretes could be achieved by, for instance, incorporation of locally fibers or non-fibers either in both concretes or only in the transition zone. In this case a more detailed study is needed.

## 5. ACKNOWLEDGMENTS

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**DOI:** 10.1061/ (ASCE) 0899-1561(1991)3:1(19)

**Table 1.** Chemical composition and physical properties of cement.

| **Materials** | **OPC** | **SRPC** | **Limits of Iraqi Specification No.5/1984** | |
|---|---|---|---|---|
| | | | **OPC** | **SRPC** |
| CaO | 62.41 | 62.33 | --- | --- |
| $SiO_2$ | 19.78 | 21.14 | --- | --- |
| $Al_2O_3$ | 4.98 | 3.54 | --- | --- |
| $Fe_2O_3$ | 3.48 | 5.16 | --- | --- |
| $SO_3$ | 2.47 | 2.24 | ≤ 2.8% if $C_3A$ >5% | ≤ 2.5% if $C_3A$ <5% |
| MgO | 2.35 | 2.35 | ≤ 5% | ≤ 5% |
| Alkalis | 1.13 | 1.18 | --- | --- |
| L.O.I. | 3.40 | 2.06 | ≤ 4% | ≤ 4% |
| I.R. | 1.28 | 1.45 | ≤ 1.5% | ≤ 1.5% |
| L.S.F. | 0.95 | 0.90 | 0.66-1.02 | 0.66-1.02 |
| Main Compounds (Bogue's Equation) Percentage by Weight of Cement | | | | |
| Tricalcium Silicate $C_3S$ | 58.20 | 55.47 | --- | --- |
| Dicalcium Silicate $C_2S$ | 12.91 | 18.85 | --- | --- |
| Tricalcium Aluminate $C_3A$ | 7.30 | 0.66 | --- | ≤ 3.5% |
| Tetracalcium Aluminoferrite $C_4AF$ | 10.58 | 15.68 | --- | --- |
| Physical Properties | | | | |
| Fineness, Blain method cm$^2$/gm | 3460 | 3150 | ≥ 2300 | ≥ 2500 |
| Compressive strength, MPa | | | | |
| 3 days | 23 | 19 | ≥ 15 | |
| 7 days | 32 | 27 | ≥ 23 | |
| Setting time(Vicat's method) | | | | |
| Initial, minute | 180 | 130 | ≥ 45 min | |
| Final (hours:minute) | 3:30 | 2:45 | ≤ 10 hours | |

**Table 2.** Chemical composition and physical analysis of silica fume.

| **Oxide Composition** | **Oxide Content** | **ASTM C-1240 Limitations** |
|---|---|---|
| CaO | 1.25 | --- |
| $SiO_2$ | 89.16 | ≥ 85 |
| $Al_2O_3$ | 0.36 | --- |
| $Fe_2O_3$ | 1.16 | --- |
| $SO_3$ | 0.90 | --- |
| MgO | 2.45 | --- |
| $Na_2O$ | 0.05 | --- |
| $K_2O$ | 0.07 | --- |
| L.O.I | 3.80 | ≤ 6.0 |
| Moisture content | 0.80 | ≤ 3.0 |
| Physical Properties | | |
| Percent retained on 45µm (No.325) sieve, max, % | 7 | ≤ 10 |
| Pozzolanic activity index % at 7 days accelerated curing | 147 | ≥ 105 |
| Specific surface, min, (m$^2$lgm) | 21 | ≥ 15 |

**Table 3.** Grading of the fine sand.

| Sieve Size [mm] | Cumulative Passing % | Limits of Iraqi Specification No.45/1984, Zone 3 |
|---|---|---|
| 10 | 100 | 100 |
| 4.75 | 97 | 90-100 |
| 2.36 | 92 | 85-100 |
| 1.18 | 88 | 75-100 |
| 0.600 | 71 | 60-79 |
| 0.300 | 30 | 12-40 |
| 0.150 | 10 | 0-10 |

**Table 4.** Grading of the separated fine sand.

| Sieve Size [mm] | Cumulative Passing % | Limits of Iraqi Specification No.45/1984, Zone 4 |
|---|---|---|
| 10 | 100 | 100 |
| 4.75 | 100 | 95-100 |
| 2.36 | 100 | 95-100 |
| 1.18 | 100 | 90-100 |
| 0.600 | 100 | 80-100 |
| 0.300 | 45 | 15-50 |
| 0.150 | 11 | 0-15 |

**Table 5.** Chemical properties of the fine aggregate.

| Physical Properties | Test Results | Limits of Iraqi Specification No.45/1984 |
|---|---|---|
| Specific gravity | **2.7** | **---** |
| Sulfate content | 0.09 % | ≤ 0.5 % |
| Absorption | 0.75 % | --- |

**Table 6.** Technical description of SikaViscocrete-5930.

| Basis | Aqueous Solution of Modified Polycarboxylate |
|---|---|
| Boiling | 100°C |
| Hazardous Decomposition products (hazardous reactions) | No hazardous reactions known. |
| Odor | None |
| Appearance | Turbid liquid |
| Colour | Turbid liquid |
| Specific gravity | 1.08 kg/lt. ± 0.005 |
| pH | 7-9 |
| Chloride content | None |
| Toxicity | Non-Toxic under relevant health and safety codes. |
| Storage | Protected from direct sunlight and frost at temperatures between + 5°C and + 35°C. |

**Table 7.** Properties of the used steel fibers.

| Property | Specifications |
|---|---|
| Relative density | 7860 Kg/m$^3$ |
| Ultimate straight tensile strength | 670 MPa |
| Form | Straight |
| Average length | 30 mm |
| Diameter | 0.8mm ± 0.02mm |
| Aspect ratio (Lf/Df) | 37.5 |

**Table 8.** Pozzolanic Activity Index and w/c or w/cm Ratios for Test Mortars.

| Index | SF% by wt. of Cement | W/C or WCM to Give Flow 110±15 | P.A.I |
|---|---|---|---|
| M* | --- | 0.50 | --- |
| M - 25SF - HRWRA** | 20 | 0.35 | 147 |

*Mortar with standard sand.

**Mortar with standard sand, 20% silica and 5% super- plasticizer (sika viscocrete 5930) by weight of cementitious.

**Table 9.** Composition of NC and RPC..

| Ingredient | Cement kg/m$^3$ | Water kg/m$^3$ | SP kg/m$^3$ | Sand kg/m$^3$ | Gravel kg/m$^3$ | Silica Fume kg/m$^3$ |
|---|---|---|---|---|---|---|
| NC | 440 | 154 | 60 | 635 | 1045 | - |
| RPC | 910 | 160 | 80 | 960 | - | 185 |

**Table 10.** Mechanical properties of NC and RPC specimens.

| Type of Concrete | Mix | Compressive Strength [MPa] | | | Flexural. 28 Day [MPa] | Splitting. 28 Day [MPa] | Modulus of Elasticity 28 Day [MPa] | Brittleness Ffactor | Water Absorption Ratio [%] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 day | 28 day | 56 day | | | | | 3 day | 28 day |
| Normal concrete | NNC0 | 31.4 | 45.3 | 50.7 | 7.8 | 5.9 | 28.5 | 0.130 | 1.01 | 1.59 |
| | NNC0.5 | 38.3 | 61.4 | 68.8 | 8.9 | 7.9 | 34.0 | 0.129 | 1.01 | 1.61 |
| | NNC1 | 43.7 | 72.6 | 81.3 | 9.6 | 9.1 | 37.9 | 0.125 | 1.02 | 1.62 |
| | NNC1.5 | 51.5 | 77.8 | 87.1 | 10.2 | 10.7 | 39.6 | 0.138 | 1.03 | 1.65 |
| | NNC2 | 55.1 | 82.4 | 92.3 | 10.8 | 11.6 | 41.4 | 0.141 | 1.04 | 1.67 |
| | SNC0 | 28.3 | 42.1 | 47.6 | 7.3 | 5.5 | 26.2 | 0.131 | 1.07 | 1.71 |
| | SNC0.5 | 34.4 | 57.0 | 64.4 | 8.4 | 7.3 | 31.3 | 0.128 | 1.08 | 1.73 |
| | SNC1 | 39.1 | 67.5 | 76.3 | 9.0 | 8.5 | 34.9 | 0.126 | 1.08 | 1.75 |
| | SNC1.5 | 45.8 | 72.4 | 81.8 | 9.6 | 10.0 | 36.4 | 0.138 | 1.09 | 1.77 |
| | SNC2 | 49.9 | 76.6 | 86.6 | 10.2 | 11.0 | 38.1 | 0.144 | 1.10 | 1.78 |
| Reactive powder concrete | NRPC0 | 103.4 | 139.5 | 160.4 | 23.0 | 9.7 | 40.0 | 0.070 | 0.63 | 0.96 |
| | NRPC0.5 | 114.0 | 149.8 | 172.3 | 31.8 | 12.0 | 45.2 | 0.080 | 0.65 | 0.98 |
| | NRPC1 | 120.2 | 155.0 | 178.3 | 36.5 | 13.2 | 47.8 | 0.085 | 0.65 | 1.00 |
| | NRPC1.5 | 131.0 | 163.2 | 187.7 | 46.1 | 16.7 | 49.7 | 0.102 | 0.67 | 1.01 |
| | NRPC2 | 134.8 | 172.4 | 198.3 | 48.2 | 17.1 | 51.3 | 0.099 | 0.69 | 1.02 |
| | SRPC0 | 88.0 | 125.6 | 143.2 | 21.0 | 8.9 | 38.0 | 0.071 | 0.66 | 1.03 |
| | SRPC0.5 | 97.3 | 134.8 | 153.7 | 29.0 | 11.0 | 42.9 | 0.082 | 0.68 | 1.05 |
| | SRPC1 | 102.0 | 139.5 | 159.0 | 33.1 | 12.0 | 45.4 | 0.086 | 0.69 | 1.07 |
| | SRPC1.5 | 111.2 | 146.9 | 167.5 | 41.2 | 15.0 | 47.2 | 0.102 | 0.71 | 1.08 |
| | SRPC2 | 115.6 | 155.2 | 176.9 | 43.5 | 16.0 | 48.7 | 0.103 | 0.72 | 1.08 |

**Table 11.** Impact resistance of NC and RPC specimens.

| Type of Concrete | Mix | AbrasioL loss (% by wt.) | No. of Blows up to | | Average Impact Energy (J or kN.m) for | |
|---|---|---|---|---|---|---|
| | | | First crack | Ultimate failure | First crack | Failure crack |
| Normal concrete | NNC0 | 3.68 | 39 | 63 | 793.1 | 1281.1 |
| | NNC0.5 | 3.25 | 54 | 85 | 1098.1 | 1728.5 |
| | NNC1 | 2.68 | 68 | 97 | 1382.8 | 1972.6 |
| | NNC1.5 | 2.33 | 76 | 106 | 1545.5 | 2155.6 |
| | NNC2 | 2.06 | 81 | 116 | 1647.2 | 2358.9 |
| | SNC0 | 3.82 | 39 | 61 | 793.1 | 1240.5 |
| | SNC0.5 | 3.37 | 51 | 82 | 1037.1 | 1667.5 |
| | SNC1 | 2.75 | 64 | 94 | 1301.5 | 1911.6 |
| | SNC1.5 | 2.40 | 73 | 105 | 1484.5 | 2135.2 |
| | SNC2 | 2.11 | 79 | 113 | 1606.5 | 2297.9 |
| Reactive powder concrete | NRPC0 | 1.07 | 64 | 89 | 1301.5 | 1809.9 |
| | NRPC0.5 | 0.94 | 79 | 113 | 1606.5 | 2297.9 |
| | NRPC1 | 0.77 | 88 | 142 | 1789.5 | 2887.7 |
| | NRPC1.5 | 0.67 | 96 | 151 | 1952.2 | 3070.7 |
| | NRPC2 | 0.59 | 99 | 165 | 2013.2 | 3355.4 |
| | SRPC0 | 1.13 | 61 | 87 | 1240.5 | 1769.2 |
| | SRPC0.5 | 1.00 | 74 | 110 | 1504.8 | 2236.9 |
| | SRPC1 | 0.83 | 84 | 139 | 1708.2 | 2826.7 |
| | SRPC1.5 | 0.72 | 92 | 147 | 1870.9 | 2989.3 |
| | SRPC2 | 0.60 | 90 | 162 | 1830.2 | 3294.4 |

**Table 12.** Measured and estimated abrasion loss values.

| Type of Concrete | Mix | Abrasion Loss (% by wt.) | | No. of Blows up to Ultimate Failure | Compressive Strength [MPa] |
|---|---|---|---|---|---|
| | | Measured | Estimated | | |
| Normal concrete | NNC0 | 3.68 | 3.41 | 63 | 45.3 |
| | NNC0.5 | 3.25 | 2.97 | 85 | 61.4 |
| | NNC1 | 2.68 | 2.67 | 97 | 72.6 |
| | NNC1.5 | 2.33 | 2.52 | 106 | 77.8 |
| | NNC2 | 2.06 | 2.37 | 116 | 82.4 |
| | SNC0 | 3.82 | 3.49 | 61 | 42.1 |
| | SNC0.5 | 3.37 | 3.08 | 82 | 57.0 |
| | SNC1 | 2.75 | 2.79 | 94 | 67.5 |
| | SNC1.5 | 2.40 | 2.64 | 105 | 72.4 |
| | SNC2 | 2.11 | 2.52 | 113 | 76.6 |
| Reactive powder concrete | NRPC0 | 1.07 | 1.18 | 89 | 139.5 |
| | NRPC0.5 | 0.94 | 0.86 | 113 | 149.8 |
| | NRPC1 | 0.77 | 0.63 | 142 | 155.0 |
| | NRPC1.5 | 0.67 | 0.41 | 151 | 163.2 |
| | NRPC2 | 0.59 | 0.15 | 165 | 172.4 |
| | SRPC0 | 1.13 | 1.50 | 87 | 125.6 |
| | SRPC0.5 | 1.00 | 1.21 | 110 | 134.8 |
| | SRPC1 | 0.83 | 1.00 | 139 | 139.5 |
| | SRPC1.5 | 0.72 | 0.80 | 147 | 146.9 |
| | SRPC2 | 0.60 | 0.55 | 162 | 155.2 |

**Figure 1.** Flow table device used.

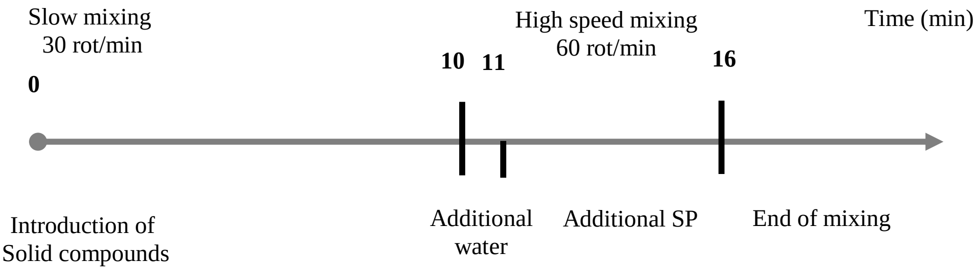

**Figure 2.** Mixing procedure of RPC.

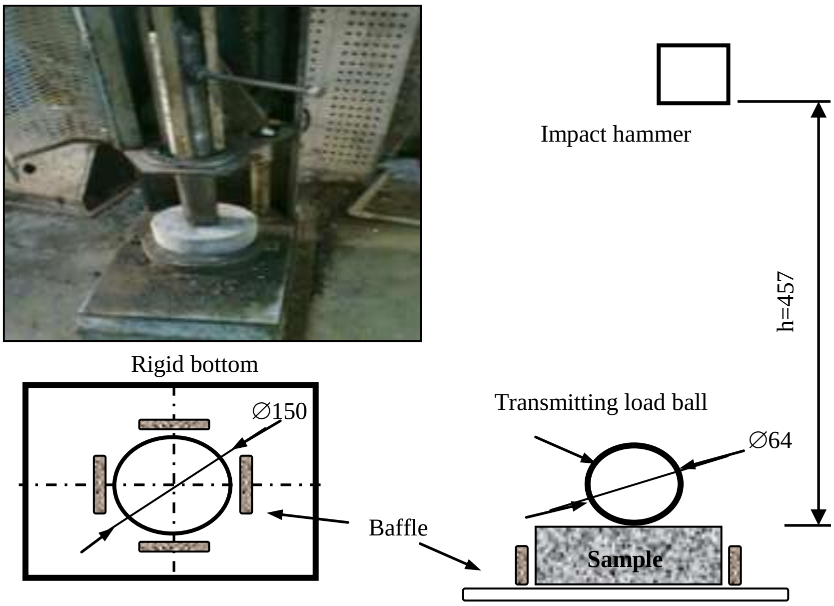

**Figure 3.** Impact test.

This test was conducted in the laboratory of College Engineering-Civil Department- Babylon University.

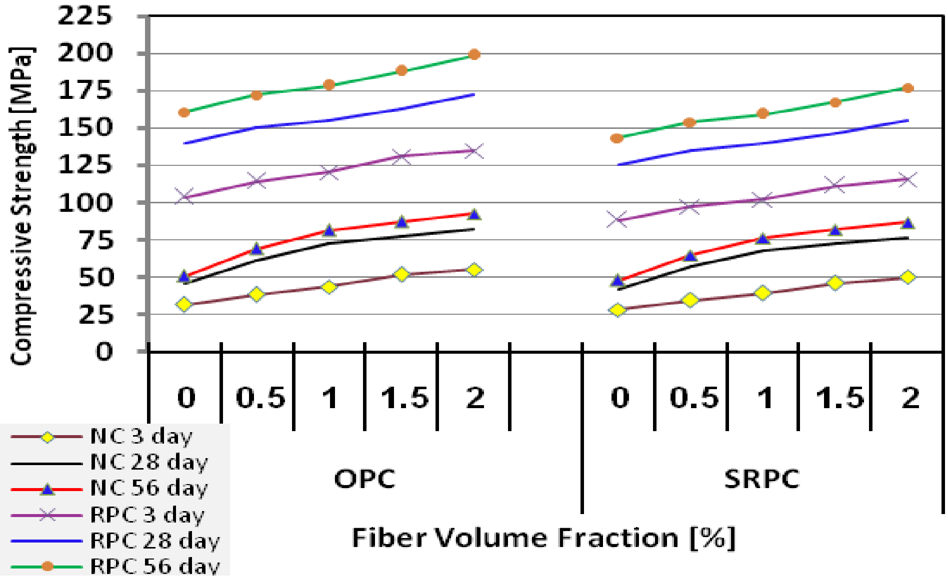

**Figure 4.** Effect of volume fraction and type of cement on the compressive strength.

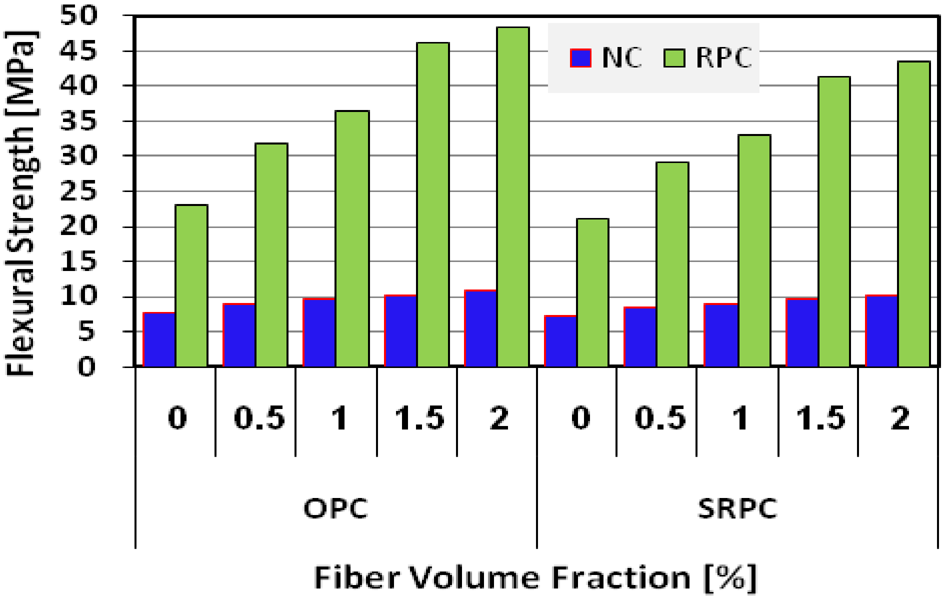

**Figure 5.** Effect of volume fraction and type of cement on the flexural strength.

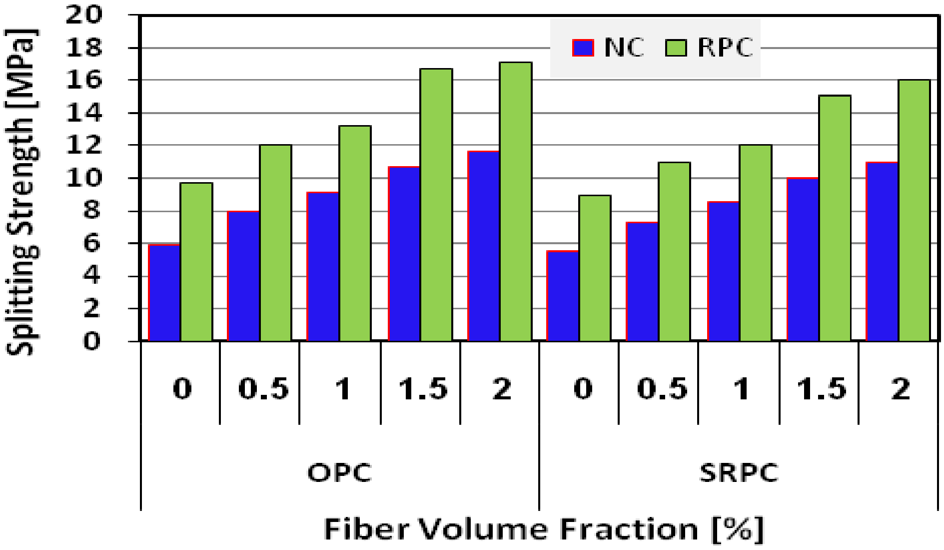

**Figure 6.** Effect of volume fraction and type of cement on the splitting strength.

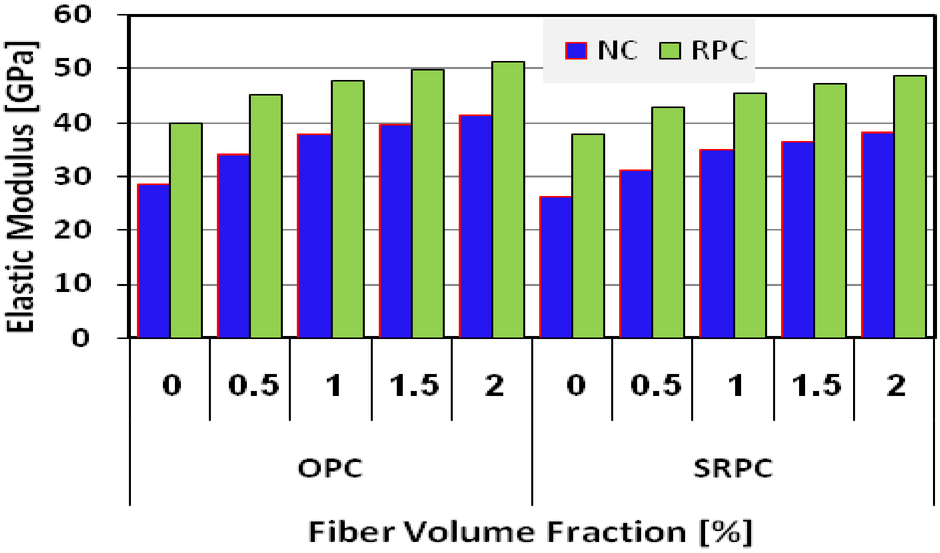

**Figure 7.** Effect of volume fraction and type of cement on the elastic strain.

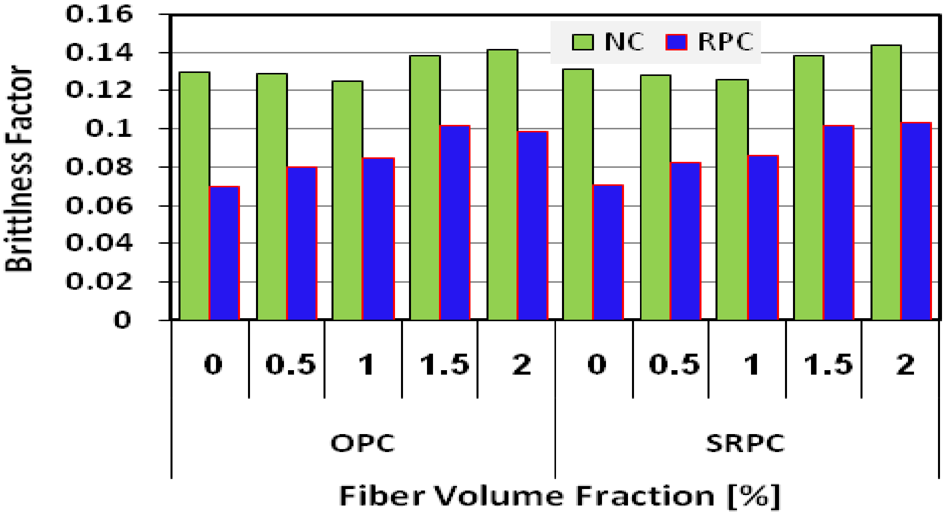

**Figure 8.** Effect of volume fraction and type of cement on the brittleness factor.

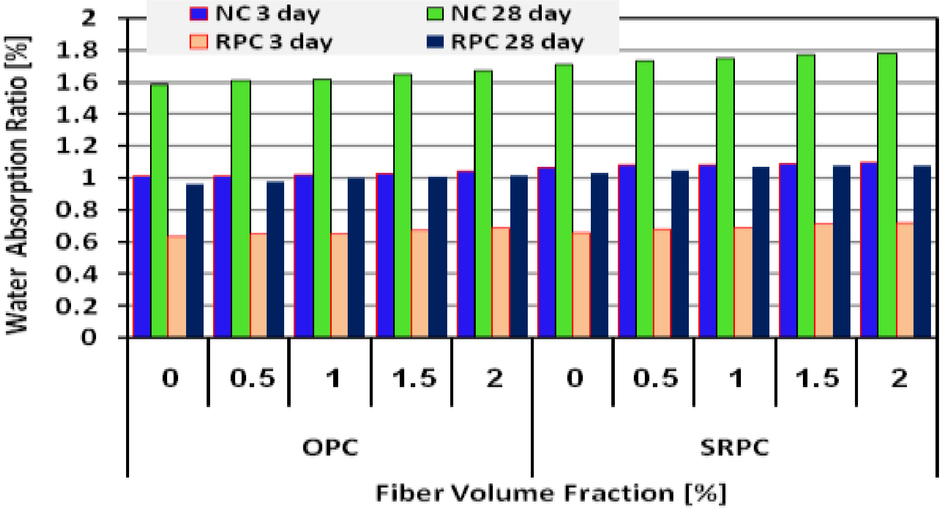

**Figure 9.** Effect of volume fraction and type of cement on the water absorption.

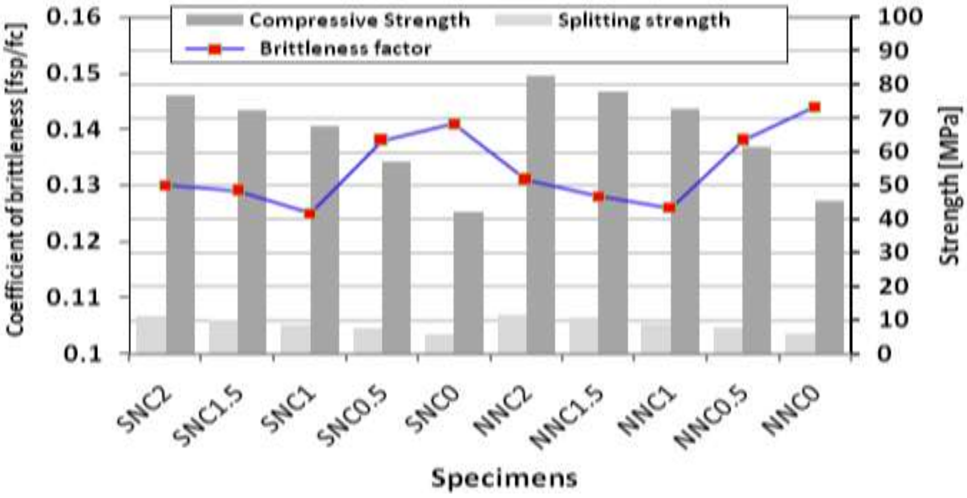

**Figure 10.** Compressive strength, splitting tensile strength and brittleness factor of NC.

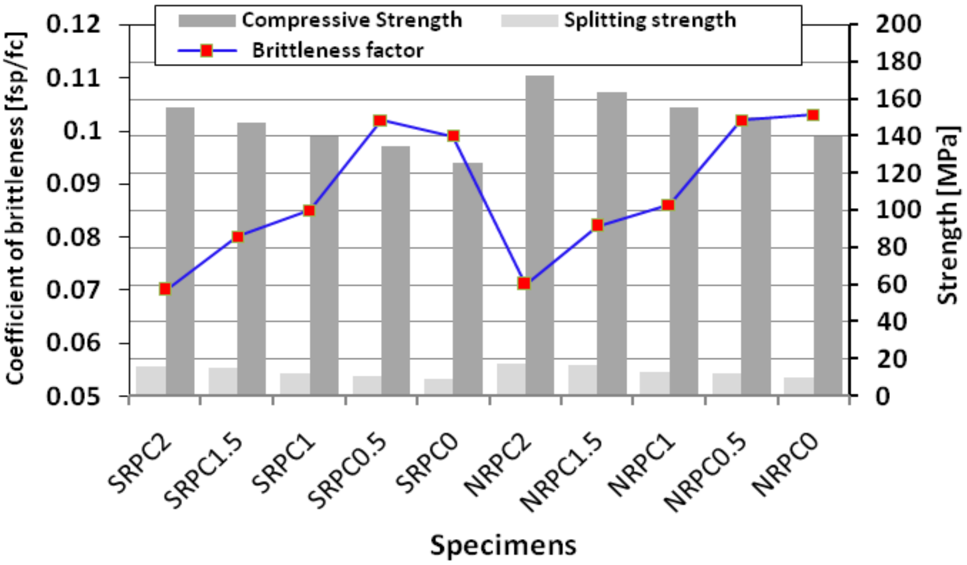

**Figure 11.** Compressive strength, splitting tensile strength and brittleness factor of RPC.

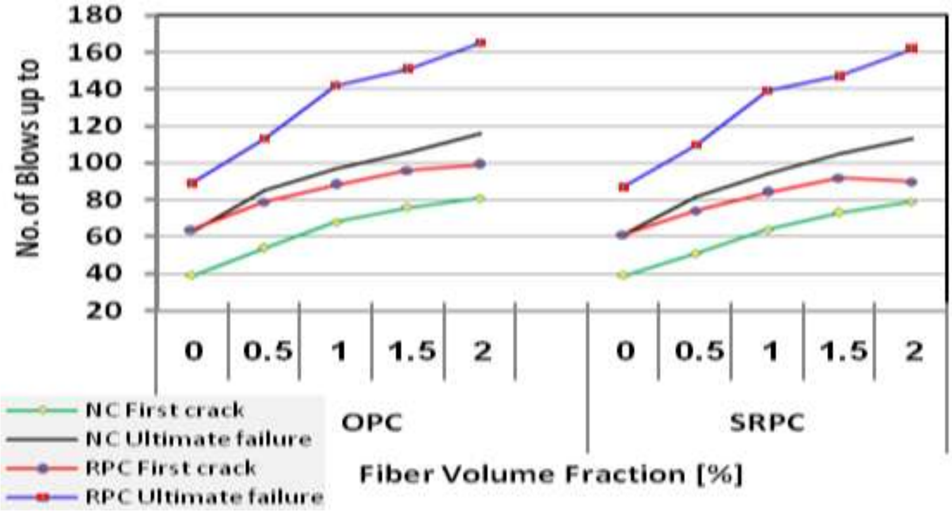

**Figure 12.** Effect of volume fraction and type of cement on the impact strength.

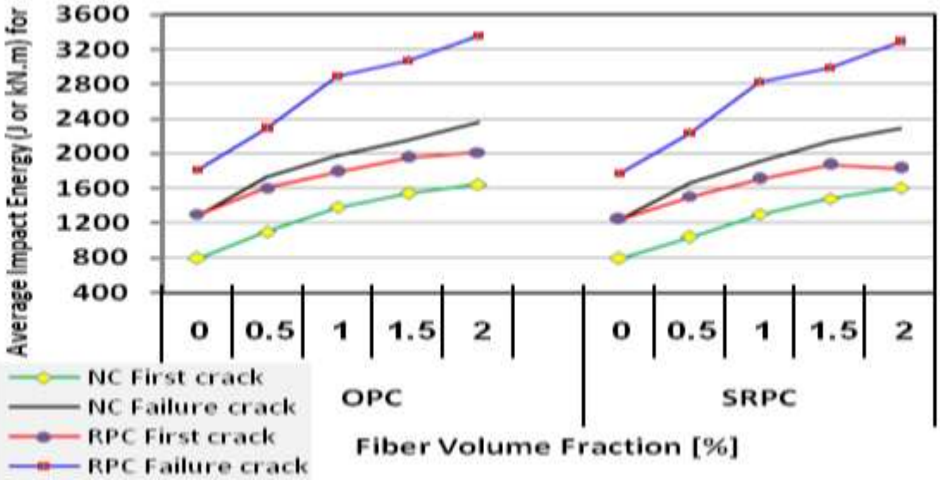

**Figure 13.** Effect of volume fraction and type of cement on the first and failure crack.

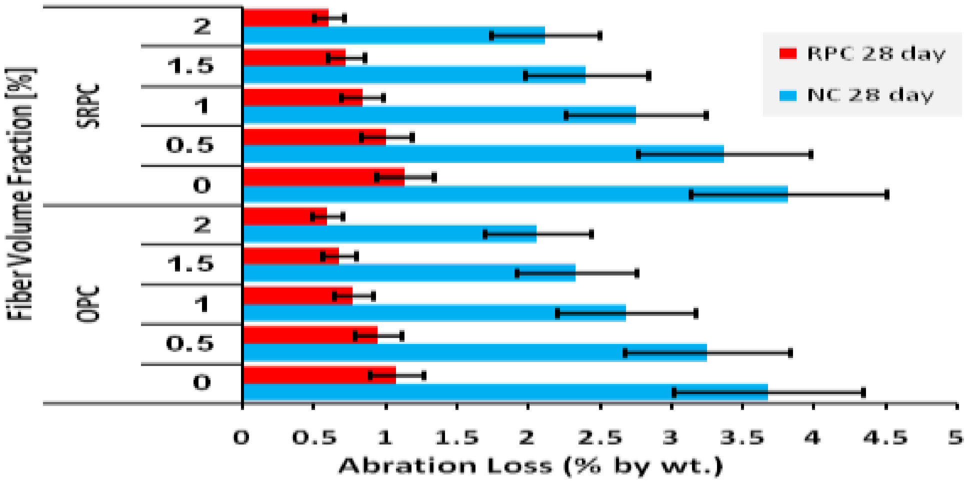

**Figure 14.** Effect of volume fraction and type of cement on the abrasion loss.

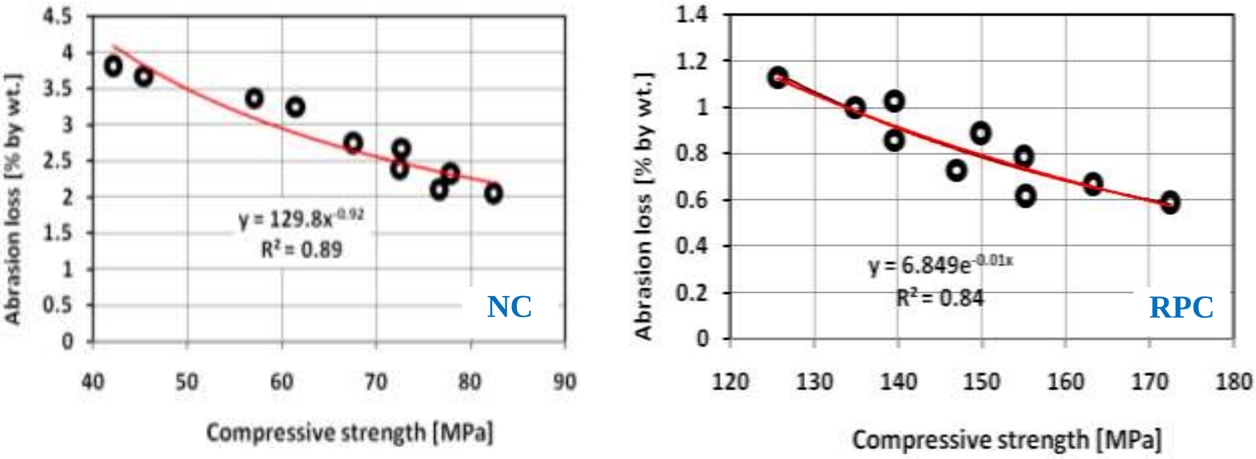

**Figure 15.** Compressive strength vs abrasion loss for NC and RPC.

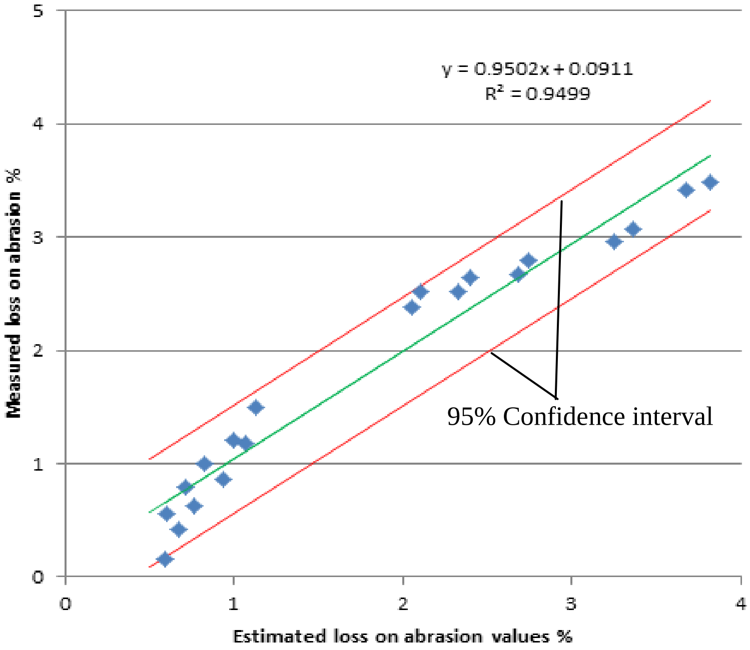

**Figure 16.** Comparison of experimental and theoretical abrasion loss for NC and RPC.