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Enhancement of deformation constant and mechanical properties of concrete using additive materials

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Abstract. The deformation of two bodies touching at one or more points due to collision is based on dynamic loading, and as such, these impacts are very important in dynamic analysis to find the force time history as developed during tests. The deformation constants for the contact surface between a freely dropped steel mass and concrete containing additives used to increase the compressive strength and enhance other mechanical properties such as tensile strength and to produce new concretes such as reactive powder concrete with and without steel plate covers of different thicknesses on the top face of the specimens are investigated. The mechanical properties of reactive powder concrete, including compressive strength, tensile strength, and modulus of rupture, are also explored and compared with those of normal weight concrete with different percentages (12, 15, 20 and 25% by weight) of silica fume. The characteristics of the micro steel fibre mixed with concrete in this investigation are 15 mm length, 0.2 mm diameter, with aspect ratios of 75, added as 1, 1.5 and 2% by volume, while the water cement ratios used are 20 and 22%. All specimens were tested at 7 and 28 days, and results for the deformation constant and mechanical properties at those ages are discussed. A mathematical model is suggested to express compressive strength as a function of percentages of steel fibre, and further mathematical models are suggested for splitting tensile strength and flexural strength as functions of compressive strength based on these experimental tests. The suggested mathematical models were compared with results from other researchers; close agreement of the test results of the present study and other researchers' work were found.

Keywordsژ Deformation constant, Impact loading, Reactive powder, Mechanical properties, Experimental test.

1. Introduction

The contact mechanics between two bodies that touch at a point or points on a contact surface can be used to determine the deformation constant. The dynamic contact is defined as the central normal to the contact bodies at the surface points. The deformation constant is found experimentally by testing a specimen such as a cube of concrete under dynamic load and recording the deformation for each applied loading, then draw the relationship between the applied load and the corresponding deformation.

The use of reactive powder concrete can increase the compressive strength of concrete in the absence of gravel and presence of silica fume and steel fibre, with the help of superplasticizer to reduce the water cement ratio and increase the concrete workability. Few studies have been concerned with the deformation constant of concrete with additives materials, such as reactive powder concrete, though many researchers have investigated the mechanical properties of reactive powder concrete such as its compressive strength, tensile strength, flexural strength, and modulus of elasticity. Reactive powder concrete (RPC) is classified as cementitious composite materials that contain mixed materials that behave as a unity to offer excellent physical properties in terms of strength and ductility.

In 2010, Yaakoub [1] explored the mechanical properties of RPC using a scaled beam under flexural testing. Various parameters were considered, such as fibre steel ratio and silica fume content. A model using a finite element approach (FEA) showed close results to the experimental tests. These results showed that the compressive strength increased as the ratio of steel fibre and silica fume increased. In 2012, Danha [2] investigated the tensile strength of RPC using both experimental and theoretical approaches, examining how to enhance the tensile strength of concrete using different ratios of silica fume up to 30% and steel fibre at not more than 3%. The proposed models were suggested based on test results, and the presence of additive materials enhanced the mechanical properties of the concrete. In 2012, Mahdi [3] investigated reinforced concrete columns using experimental tests and analytical solutions. The study on the strength of concrete in the presence of steel fibres and polypropylene fibres, comparing the results with normal concrete. The main variables were compressive strength, longitudinal, and lateral reinforcement, steel fibre ratio, and type of fibre. The results showed that the addition of steel fibres enhanced the mechanical properties of concrete and thus the full capacity of columns. In 2013, Ghailan [4] studied RPC using experimental and theoretical approaches. A total of twenty-four beams, including modified RPC, were subjected to shear. The results indicated that the use of RPC led to a significant strength increase compared with normal concrete. Similarly, Mohammed [5] tested RPC and normal concrete; twenty-four beam specimens were tested to flexural failure. The main parameters considered wee RPC ratio, steel fibre content, and longitudinal steel ratio. The RPC gave higher loading capacity and decreased deflection. Ismael [6] experimentally and theoretically investigated beam specimens made of RPC under flexural loading. Many parameters such as steel fibre and silica fume content, tensile steel and geometric sections were considered, and the first crack load, strength capacity, maximum deflection, and failure mode of specimens were recorded. The test results indicated that when the RP increased, loading capacity increased based on the steel fibre percentage. In 2013, Ma'roof [7] examined the behavior of RPC by experimental means including tests and numerical approaches using finite element analysis. The main parameters were steel fibres and silica fume. Increases in RPC percentage increased compressive strength, splitting tensile strength, and modulus of elasticity. In 2014, Yousif [8] studied the effects of steel fibre and silica fume ratios on the mechanical properties of RPC. From the test results, an increase in steel fibre caused an increase in ultimate load, while the maximum deflection decreased. In 2015, Al-Hassani et al. [9] investigated the behaviours of RPC and normal concrete. The flexural behavior of reinforced concrete beams was investigated experimentally to check the use of normal concrete strength against RPC. The use of RPC parts enhanced the behaviour of specimens under flexural effects.

In the current paper, the deformation constant of reactive powder concrete, with and without steel plates, is investigated under the effects of dynamic loading, along with a consideration of the mechanical properties of RPC.

2. Materials

Several parameters are adopted here, including silica fume at 12, 15, and 20%, and steel fibre mixed with concrete at 1, 1.5 and 2% by volume, with water to cement ratios of 0.20 and 0.22. All specimens were tested at 7 and 28 days. The materials used are summarised below:

2.1 Cement

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Ordinary Portland cement (OPC) was used. Tables 1 and 2 list the chemical and physical properties of the cement, which conformed to Iraqi Specification (IQS) No. 5/1984[10]. The quantity of cement used . was 900 kg per cubic meter of RPC

Table 1. Chemical composition of cement

Oxide Composition	% by weight	Limit of Iraqi specification No. 5/1984 [10]
SiO_2	19.80	-
CaO	64.53	-
MgO	1.78	5.0 (max)
Fe_2O_3	3.28	-
Al_2O_3	5.11	-
SO_3	2.55	2.8 (max)
Loss on ignition	3.11	4.0 (max)
Insoluble residue	1.06	1.5 (max)
Lime saturation factor	0.98	0.66-1.02
Main compounds		
C_3S	48.55	-
C_2S	22.15	-
C_3A	8.58	-
C_4AF	10.73	-

Table 2. Physical properties of cement

Physical properties	Test result	Limit of Iraqi specification No. 5/1984 [10]
Specific surface area (Blaine Method), m^2/kg	383	230 (min)
Setting time (Vicat's method) Initial setting, hrs: min Final setting, hrs: min	 1:55 4:25	 00:45 (min) 10:00 (max)
Compressive strength, MPa 3 days 7 days	 25.85 28.00	 15.00 (min) 23.00 (min)
Autoclave expansion %	0.01	0.8 (max)

2.2 Fine Aggregate

The type of fine aggregate used is classified as very fine sand with a maximum size of 600 μm. The source of this sand is the Sika company. The specifications of the fine sand match Iraqi specification (IQS) No. 45/1984 [11] as listed in Table 3. The quantity of sand was 990 kg per cubic meter of RPC.

Table 3. Grading of the Fine Sand Compared

Sieve Size (mm)	% Cumulative Passing	Limits of Iraqi specification No. 45/1984 [11], zone 4
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.600	100	80-100
0.300	47	15-50
0.150	12	0-15

2.3 Water

Ordinary tap water was used as being clean and free from injurious quantities of oils, acids, alkalis, salts, and organic materials.

2.4 Silica fume

Silica fume was used at percentages of 12, 15, and 20%, and this was produced by the Sika company. Adding silica fume fills in the spaces between cement grains because of its very small particles. The silica fume (SiO_2) also reacts with calcium hydroxide to form an additional binder material (calcium silicate hydrate (C-S-H)) which is very similar to the calcium silicate hydrate formed in Portland cement. The chemical composition of this silica fume conformed to ASTM C 1240-04 [12], as listed in Table 4.

Table 4. Composition of Silica Fume

Compound Composition	Chemical Composition	% Oxide Content
Lime	CaO	0.5
Iron oxide	Fe_2O_3	1.4
Alumina	Al_2O_3	0.5
Silica	SiO_2	92.1
Magnesia	MgO	0.3
Sulphate	SO_3	0.1
Potassium oxide	K_2O	0.7
Sodium oxide	Na_2O	0.3
Loss on ignition	L.O.I	2.8

2.5 Steel fibres
Short steel fibre was used with volume fractions of 1, 1.5, and 2%, as supplied by the Sika Company. The properties of the steel fibres are listed in Table 5.

Table 5. Properties of steel fibre

Property	Relative density (kg /m^3)	Yield strength (MPa)	Modulus of elasticity (MPa)	Strain at portion limit	Poisson's ratio	Average length (mm)	Nominal diameter (mm)	Aspect ratio (L_f/D_f)
Specifications	7860	1130	200000	0.00565	0.28	15.00	0.20	75

2.6 Superplasticizer
The physical properties of the superplasticizer, trade name Visco Crete –5930, are listed in Table 6. The ratio for superplasticizer was 6% by weight (cement plus silica fume).

Table 6. Physical properties of the superplasticizer

Specific Gravity	1.08 kg/l
Boiling	100˚C
pH Value	7-9

3. Concrete Specimen Tests

The specimens were cast as cylinders and prisms and tested to determine the mechanical properties of the reactive powder concrete in terms of compressive strength, splitting tensile strength, and modulus of rupture.

3.1 Mechanical Properties of Concrete

The investigation of compressive strength was made using cylindrical specimens with dimensions 150 mm diameter and 300 mm height according to ASTM C39-86 [13]. The machine used had a capacity of 2,000 KN for compression, as shown in Plate 1. Three specimens were tested for each type of mix and an average value was taken. Before the tests, each specimen was kept at room conditions for around three hours to release the remaining water and then placed in the machine's centre to prevent any eccentricity.

Plate 1. Specimen under machine and failure mode for compressive strength test

The splitting tensile strength tests were carried out based on the ASTM C496-04 [14]. Cylinders of 150 x 300 mm were used. Thin plywood strips were placed between the specimen and the upper and the lower bearing blocks of the testing machine, a hydraulic compression machine. The tests were done by applying a compressive force in the direction of the diameter along the length of the cylindrical specimen up to failure. The average value of three cylinders was taken; see Plate 2.

Plate 2. Specimen under machine and failure mode for splitting strength test

The flexural strength of concrete was measured by testing 400 x 100 x 100 mm prism specimens based on ASTM C293-10 [15]. The machine used in the tests has capacity of 2,000 kN, and Plate 3 shows the specimens before and after testing. Three specimens were tested for each type of mix.

Plate 3. Specimen before and after test for flexural strength

3.2 Results

The test results for compressive strength, splitting tensile strength, and flexural tensile strength are listed in Table 7. Figure 1 represents the variations adopted in the present study in terms of percentages of steel fibre, silica fume, and water cement ratio. An inverse relationship between silica fume and steel fibre and steel fibre with water cement ratio was adopted to maintain the compressive strength of the concrete. The mechanical properties increased as the percentage of steel fibre increased, as listed in Table 7. The deformation constant (*k*) behaviours for all cases are shown in Figures 2 to 5.

Table 7. Test results of mechanical properties for normal and reactive powder concrete

Mix mark	% steel fibre	Silica fume	w/c	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural tensile strength (MPa)
NC	__	__	0.35	67	5.18	5.44
G1	1.00	0.20	0.22	82	9.63	13.55
G2	1.50	0.15	0.22	94	11.74	16.95
G3	2.00	0.12	0.20	101	13.54	19.93

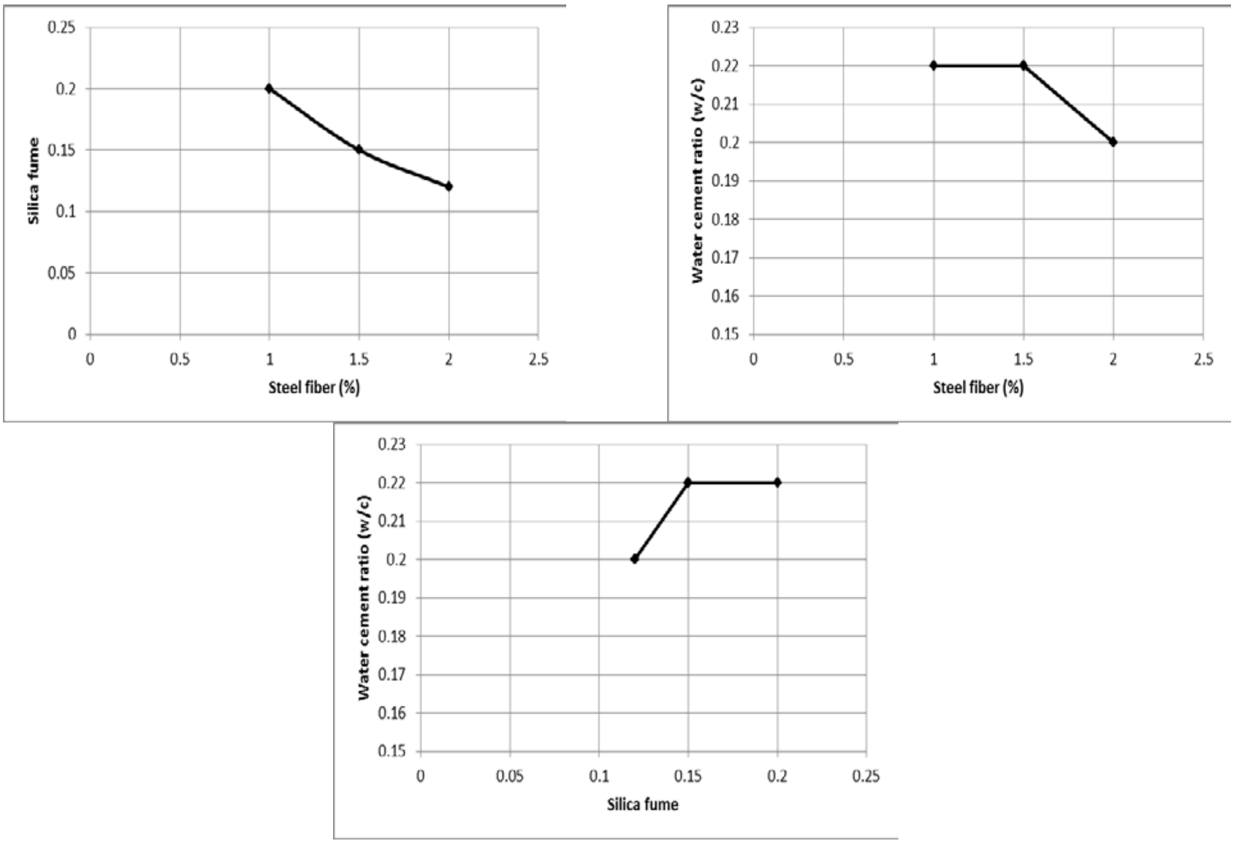


Figure 1. Steel fibre variations with silica fume and water cement ratio

3.3 Proposed equations

Proposed equations for compressive strength, splitting tensile strength, and modulus of rupture are derived from the test results in both the present study and other research [1, 16]. The compressive strength is suggested as a function of the percentage of steel fibre, as in equation (1). The splitting tensile strength is suggested as a function of tested compressive strength, fc', as seen in equation (2). The modulus of rupture is suggested as a function of compressive strength, fc', as in equation (3). The proposed equations are valid in case of steel fibre ratios of 1, 1.5, and 2%.

$$f_c' = 82.426 V_f^{(0.3)} \quad ...(1)$$

(Equation (1) is valid in presence of steel fibre)

$$f_{ct} = 0.007 f_c'^{(1.634)} \quad ...(2)$$

$$f_r = 0.003 f_c'^{(1.903)} \quad ...(3)$$

where f_c', V_f, f_{ct}, and f_r are the compressive strength of concrete (MPa), percentage of steel fibre, splitting tensile strength (MPa) and modulus of rupture (MPa), respectively. The proposed equations can be verified with test results from other researchers, as shown in Figures 2 and 3, showing very close agreement. Table 8 lists the results of experimental tests compared with results from the proposed equations and with the results from [1] and [16]. Figure 4 shows the comparisons between the experimental results and those suggested by equation (1), which represents the compressive strength. Figure (5) show the comparison between the test results and values from references [1 and 16], where the mean value represents the average ratio of compressive, splitting, and modulus of ruptures.

The proposed equations for reference [1] and reference [16] are:

$$f_{sp} = 22.744 - \frac{1303.047}{f_c^{'}} + 2.028 V_f \qquad ...(4)$$

Splitting tensile strength [1]

The modulus of rupture [1]:

$$f_r = \frac{332.848}{f_c^{'}} + 7.532 V_f \qquad ...(5)$$

The splitting tensile strength [16]

$$f_{ct} = 0.1 (f_c^{'})^{0.85} + 3.6 V_f \qquad ...(6)$$

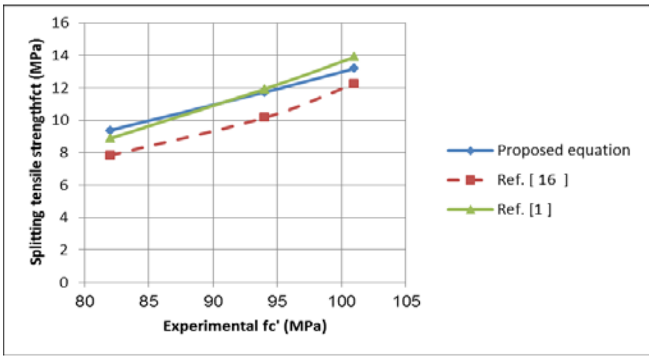


Figure 2. Comparisons between present study and other researchers for splitting tensile strength

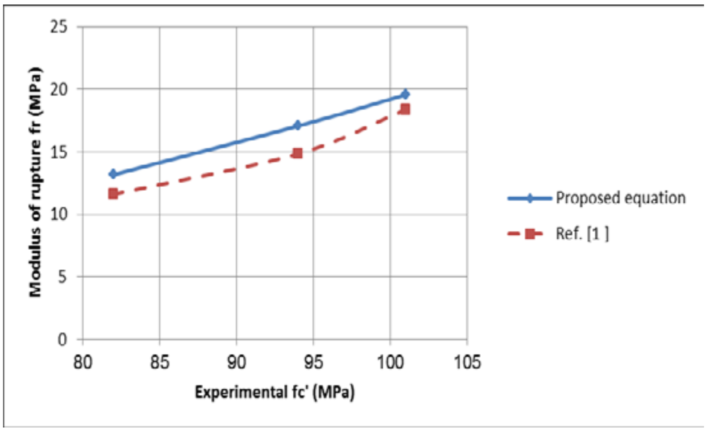


Figure 3. Comparisons between present study and other researchers for modulus of rupture

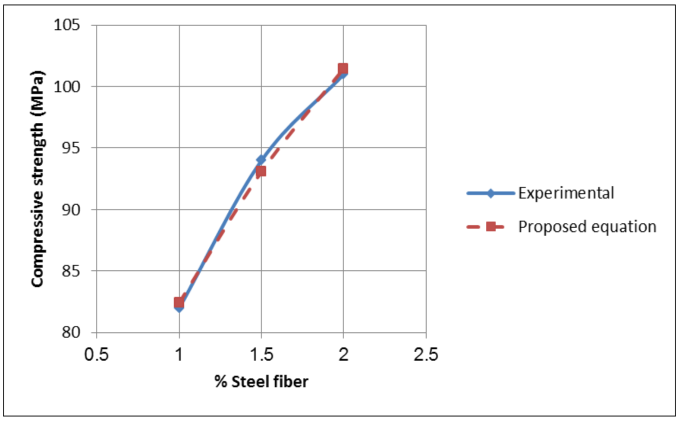
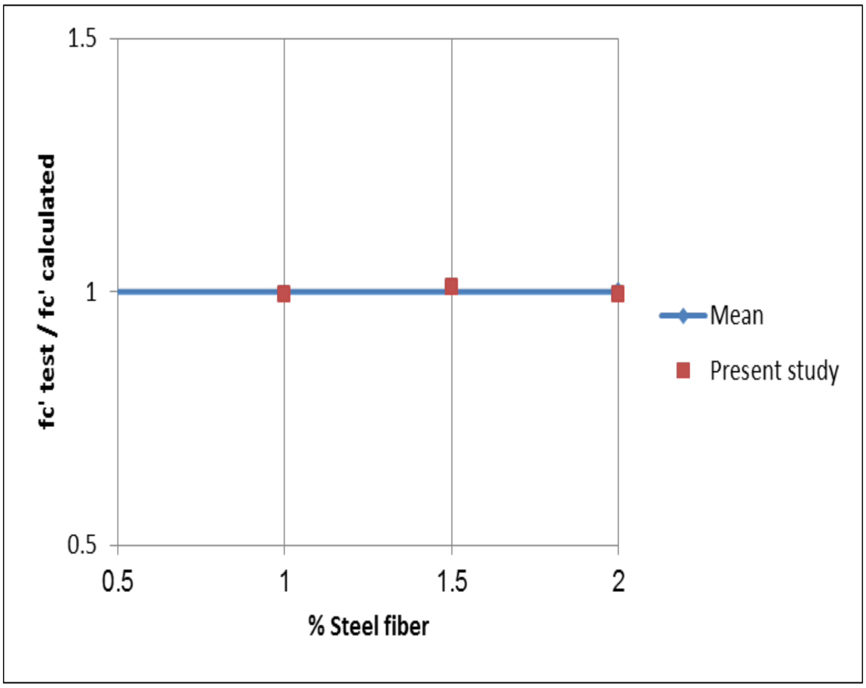
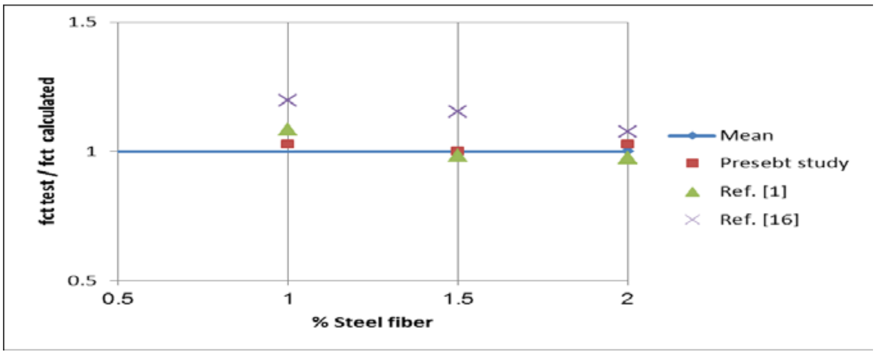


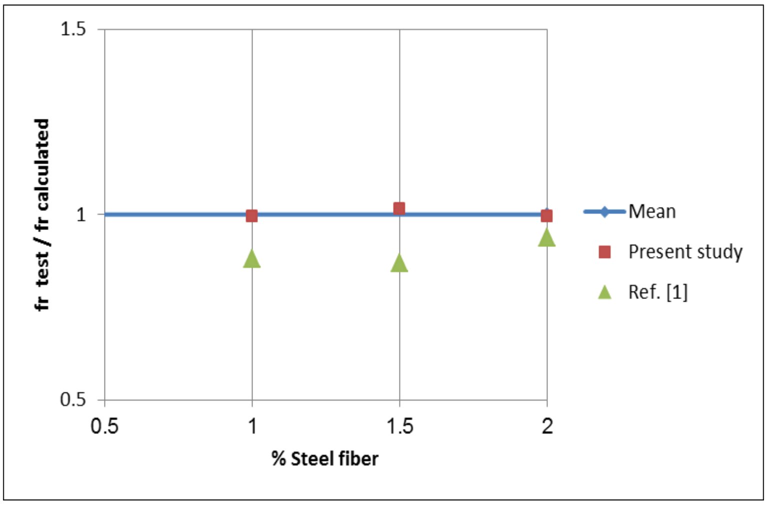
Figure 4. Comparisons between experimental test results and proposed equation for compressive strength.



(a)



(b)



(c)

Figure 5. Comparisons between ratio of test results and proposed equations for different ratios of steel fibre

Table 8. Test results, results of proposed equations, and results from references [1] and [16]

% Steel fibre	fc' experimental (MPa)	f_{ct} experimental (MPa)	f_r experimental (MPa)	fc' Eq. (1) (MPa)	f_{ct} Eq. (2) (MPa)	f_r Eq. (3) (MPa)	f_{ct} Ref [16]	f_{ct} Ref. [1]	f_r Ref. [1]
1	82	9.63	13.55	82.42	9.38	13.16	7.84	8.88	11.59
1.5	94	11.74	16.95	93.09	11.73	17.06	10.16	11.92	14.83
2	101	13.54	19.93	101.4	13.187	19.56	12.25	13.89	18.36

The proposed equations mentioned above are suitable for adoption in the design of RPC because of their alignment with the test results.

Static test for the deformation constant for contact surfaces

The deformation of two touching bodies at one or more points due to collision resulting from dynamic loading such as an impact is very important in dynamic analysis to uncover the force time history that develops during tests. The deformation constant for contact surfaces between steel mass and reactive powder reinforced concrete with and without steel plates were investigated. The deformation constant was found experimentally by testing the specimens under dynamic load and recording the deformation for each applied loading, then drawing the relationship between the applied load and the corresponding deformation. The Hertz law [17] was adopted to determine the deformation constant (*k*) to express the relationship between the applied force and the deformation due to the applied force as follows:

$$P = k\,\Delta^{(3/2)} \qquad \text{...(7)}$$

where *P* is the compressive force at the point of the contact, Δ is the difference displacement between the final and initial value of the strike mass, and *k* is the Hertz deformation constant. The deformation constant (*k*) relies on the elastic mechanical properties of the contact bodies. The test specimen in each case was a cube with dimensions 150 x 150 x 150 mm, and the deformation was measured by means of a dial gauge at each load increment. The behaviours of the applied loadings with deformations for all cases are shown in Figures 6 to 9.

The total number of specimens was 12, divided into three specimens for normal concrete (fc'=40 MPa), three specimens for RPC concrete (fc'=70 MPa), three specimens for RPC concrete covered with steel plate of 1 mm thickness, and three specimens for RPC concrete covered with steel plate of 1.4 mm thickness

Plot4. Cube specimens for reactive powder concrete without steel plate during and after test to determine the deformation constant *k*

Plate 5. Cube specimens for reactive powder concrete with steel plate of 1 and 1.4 mm thickness at the top face of cube during and after test to determine the deformation constant *k*

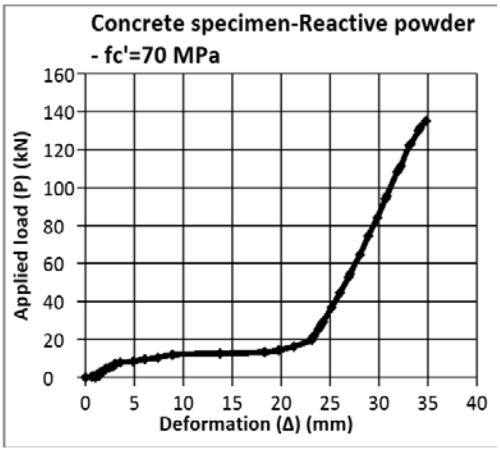


Figure 6. Deformation constant in case of normal concrete with fc' 40 MPa and k=40.1 E6 N/m$^{1.5}$

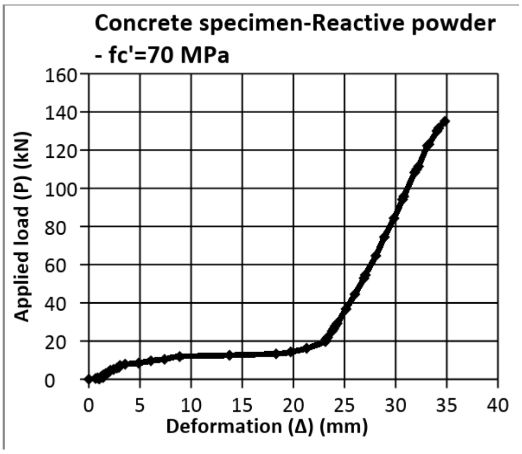


Figure 7. Deformation constant in case of RP concrete with fc' 70 MPa and k=49.3 E6 N/m$^{1.5}$

5. References

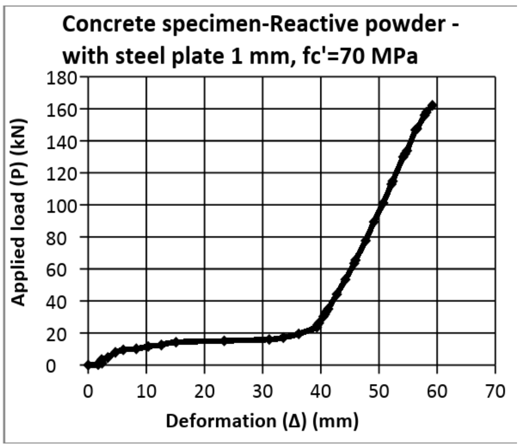


Figure 8. Deformation constant in case of RP concrete covered by steel plate 1 mm thickness with fc' 70 MPa and k=2.11 E9 N/m$^{1.5}$

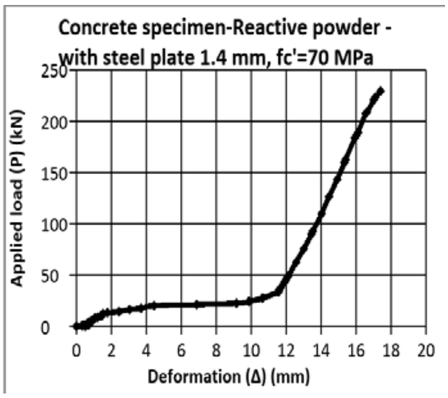


Figure 9. Deformation constant in case of RP concrete covered by steel plate 1.4 mm thickness with fc' 70 MPa and k=2.405 E9 N/m$^{1.5}$

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4. Discussion and Conclusions

Based on the experimental work results, the following points can be concluded:

1. The presence of steel fibre bridges micro cracks and delays specimen expansion. The transfer of the tensile forces to the SF effectively prevents the propagation of micro cracks.

2. The compressive strength increases when the steel fibre ratio increases because the concrete behaves as a reinforced concrete element; thus, the steel fibre creates strong bonds between the concrete particles that lead to increases in compressive strength.

3. The tensile strength of concrete as a function of splitting strength and modulus of rupture increases in presence of steel fibre because of its mechanical properties; the tensile strength of steel fibre is high, and thus the cracking load becomes greater.

4. The modulus of rupture increases in the presence of steel fibre because the steel fibre enhances the tensile strength of concrete.

5. The proposed equations were verified with other proposed equations and showed the best results in the range of steel fibre percentages 1 to 2% with the specific silica fume content.

6. The deformation constant, *k*, increased in the presence of steel fibre because of improvements in the mechanical properties.

7. In the presence of covering steel plates at the top face of concrete cubes, the *k* value increases because the steel absorbs the shock of applied masses and prevents punch damage occurring.

8. Increasing thickness of the covering steel plate leads to increases in stiffness, which increases the *k* value.

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