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Mechanical properties of reactive powder concrete: a comparison study

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ABSTRACT

Reactive Powder Concrete (RPC) is one of the new and most important concrete manufacturing advancements. A significant number of researchers have studied the mechanical properties of such type of concrete and the effect of different parameters on it. Some of these researchers presented questions to predict the properties of reactive powder concrete depends on its components and the method of curing. This research presents an experimental investigation on the mechanical properties of RPC such as compressive strength, splitting tensile strength and flexural strength. The findings were compared to the previous studies' experimental work and formulated equations.

1. Introduction

Reactive powder concrete (RPC) has gained tremendous attention in the world in recent years due to its superior mechanical properties such as high strength, high durability, high ductility, high abrasion and corrosion resistance and minimal shrinkage [1, 2]. The first output of RPC goes to [1, 2] when they published their first researches about RPC in 1994 and 1995 respectively. According to the superior structural performance, RPC is often known as UHPC (Ultra-High-Performance concrete). It consists of a large quantity of cement (800-1000 kg/m3), silica fume, sand finer than 600 μm particle size or crushed quartz, fibres, superplasticizers, w/c ratio is mostly less than 0.2, with the nonexistence of coarse aggregate Richard et al. [2]. After that, numerous numbers of researchers have followed their recommendations and attempt to explore and improve the mechanical properties of such concrete.

Roux et. al. [3] studied RPC′s durability. Biolzi et. al. [4] investigated the influence of micro steel fibres on compressive strength, direct tensile strength and the elastic modulus of RPC. Ograss et al. [5] studied the effect of short steel fibres and a combination of short and long fibres on the characteristics of UHPC especially that related to the ductility and the size impact. Chan et al. [6] investigated the influence of silica fume on the characteristics of steel fibres in RPC, involving pull-out energy, bond strength. Gao et al. [7] investigated the effect of dynamic loads on the characteristics of plain and fibres reinforced RPC. Fujikake et. al. [8] explored the influence of strain rate on the tensile behaviour of RPC samples when direct tension is applied. Tai et al. [9] investigated the response of RPC to uniaxial compression at different loading rates. Maroliya et al. [10] presented research to explore the effect of the type of superplasticizers on workability and compressive strength of RPC. Yu et. al. [11] studied the properties and mix design of ultra-high performance fibre reinforced concrete (UHPFRC). Tam et. al. [12] studied the fresh concrete properties of RPC to gain the optimal conditions for outputting reactive powder concrete utilizing local materials.

Many of these studies have formulated equations to predict the properties of RPC based on experimental results considering different

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Notations

Bf	The bond factor that accounts for bond characteristics of the fibers	mm	melemeter
Df	fibre diameter in mm	w/cm	
F	fiber factor	Mpa	Mega Pascal (N/mm^2)
fc	Cylinder compressive strength	***Abbreviations***	
fsp	splitting tensile strength	ACI	American Concrete Institute
fcu	Cube compressive strength	ASTM	American Society for Testing and Material
Lf	fibre length in mm	HSC	High strength concrete
fr	modulus of rupture	RPC	Reactive powder concrete
RIV	fibre reinforcing index	UHPC	Ultra-high performance concrete
Vf	fibre volume fraction	UHPFRC	Ultra-high performance fiber reinforced concrete

parameters, as mentioned before, such as the variability of its ingredients, and the curing regime. This research aims to determine the mechanical

characteristics of RPC, cured in water, involving compressive strength, flexural strength (Rupture modulus) and splitting tensile strength. The findings were compared to the previous studies' experimental work and formulated equations.

2. Experimental work

The experimental work consists of pouring and testing the control specimens (cylinder, cubes, prisms) and study the mechanical properties of kind of concrete such as compressive strength, splitting tensile strength and flexural tensile strength (modulus of rupture).

2.1 Material utilized

ASTM C150-Type I [13] Ordinary Portland cement was utilized in this study. The very fine sand, with a maximum size of (600μm), was provided and employed by sieving natural sand having fineness modulus of (2.63) and a specific gravity of 2.64. A grey densified silica fume follows the requirements of ASTM C1240-04 [14], was used. Superplasticizer, commercially known as Flocrete PC 200, was utilized following the requirements of ASTM C494 M-99 [15] type G. Straight micro steel fibres with a length of 13 mm and a diameter of 0.2 mm were utilized (aspect ratio of 65). The tensile strength of this type of fibre is 2500 Mpa and it conforms the requirements of ASTM A820-04 [16].

2.2 Patching and mixing procedure

The mix proportions are based on mixes from previous studies to achieve compressive strength greater than 100 MPa in water curing condition [17, 18]. The cement to sand ratio was 1:1 where the cement weight is (1000 kg/m^3). The superplasticizer dosage was chosen as 6% by the weight of cementitious materials (cm)) as recommended by the manufacturing company. The steel fibres ratio was 2% by total volume while the silica fume content was 25% By weight of cement. The w/cm ratio of the mix was (0.2).

The mixtures were produced through a horizontal rotary mixer. For three minutes, the dry materials were mixed first. Then 2/3 of the liquid (water and superplasticizer) was added, and the ingredients were combined for four minutes. The mixer was interrupted to shovel the mix, then resumed for another three minutes. The process was repeated until the homogeneous mix was achieved. As mixing was integrated, steel fibres were added by hand. The remaining liquid was added. The mixing process required 25-30 minutes approximate time.

2.3 Casting and curing

The samples of prisms, cylinders, and cubes were poured into the moulds and then covered with a polyethene sheet for 24 hours to prevent loss of moisture. After 24 hours, the specimens were extracted from the moulds, labelled and then placed in water until the age of 28.

3. Results and discussions

3.1 Compressive strength (f 'c):

This test was performed according to BS EN 122390 -03[19] using cube samples with dimensions of 150x150x150 mm and ASTM C39-05 [20] using cylinder samples with a diameter of 100 mm and a length of 200 mm.

Figure 1 - Compression failure of RPC cylinders and cubes.

The outputs of this test are shown in Error! Reference source not found. Error! Reference source not found. demonstrates the ductile failure of RPC cubes and cylinders. The ratio of cube compressive strength to cylinder compressive strength (fcu / f 'c) is (1.018). This ratio is lower than that stated by Neville [21] for conventional concrete which was 1.25. Graybeal et al. [22] addressed that the (fcu / f 'c) ratio is in the range of (1.0 - 1.075) for UHPFRC. The experimental results for Qasim [23] revealed that the relationship between f'c (cylinder 100x200)/fcu (cube 100x100) is equal to 0.95 which is very close to that of Ma et. al. [24] who found that f'c (cylinder 100x200)/ fcu (cube 100x100) for UHPC is equal to 0.98. Also, Ma'roof [25] found that this ratio is ranged from 0.9 to 0.979 for RPC.

Table 1 - Mechanical properties of concrete utilized in this study

f 'c (MPa)	fcu (MPa)	fsp (MPa)	fr (MPa)
111	113	13.33	15.29

Where: f 'c is cylinder compressive strength, fcu is cube compressive strength, fsp is splitting tensile strength, fr is the modulus of rupture

The higher powder content and the smaller maximum aggregate size of RPC can explain the closeness in the values of compressive strength for both specimen shapes Ma et al. [26]. The absence of the coarse aggregate and the existence of finer sand in the ingredients of RPC result in denser concrete and then higher strength compared to conventional concrete. The improvement in compressive strength for RPC can also be explained due to the influence of the high-performance superplasticizer (PC200) which reduces the (w/cm) ratio utilized in RPC mix. In addition to the chemical reaction of the silica fume with the calcium hydroxide Ca(OH)2, generated from cement hydration, which increases the compressive strength, decreases the microcracking and the voids and strengthen the microstructure. The existence of steel fibre results in a substantial increase in compressive strength. **Fig. 1** displays the steel fibre holds the specimen as one unit without separating its sections. These results were approved by a significant number of researchers [17, 18, 25].

The influence of steel fibres on compressive strength was also noticed by others like Ismail et al. [18] who found that when the steel fibre content is increased from 0% to 1% and 2% followed by an increase in compressive strength by about 22.71% and 35.05% respectively. In the case of silica fume, the results revealed that this type of materials is less effective than using fibre where increasing the ratio of silica fume from 15% to 20% and 25 % increases the compressive strength (fc) of RPC by 5.35% and 9.29% respectively. Hannawayya et al. [17] concluded that utilizing higher steel fibre ratio by 2% increases the compressive strength by about 38.06% while an insignificant change in the compressive strength (fc) was obtained for low values of Vf. Also, increasing silica fume up to 15% increases the compressive strength by about 16.136%.

Ma'roof [25] showed that increasing the steel fibre ratio from (0% - 2%) improves the strength in compression by about 26.42%. The silica fume content exhibits moderate influence on the compressive strength of RPC, where increasing the silica fume from (15% - 25%) of the weight of cement raises the compressive strength by about 16.47%.

3.2 Splitting tensile strength (fsp):

In this study, the test was performed on standard concrete cylinders with dimensions of (100 * 200 mm). The outcomes of this test are reported in **Table 1**. **Fig. 2** displays the splitting failure of RPC cylinders. It was revealed that the splitting tensile strength to the cylinder compressive strength ratio (fsp / f ′c) was about 12%. Danha [27] noticed that this ratio for the non-fibrous RPC mix is 4.65% and ranged from 7.26 to 14.24% for RPC mixes with (1-3%) volume fraction of steel fibres. Such performance is close to that achieved by other researchers such as Hannawayya [17] who found that the ratio of (fsp/f ′c) ranged from 6.92% to 14.18% for RPC mixes with (0%-2%) steel fibres' volume fraction. Graybeal [22] also established that this ratio is ranged from 13.1% to 15.7% for UHPC with 2% steel fibres volume fraction.

Many studies proposed a relation between (fc) and (fsp) strengths for normal and high strength concrete:

Figure 2 - Splitting failure of RPC

The ACI 318-11 [28] adopted the following relationship for estimating the splitting tensile strength (fsp) from compressive strength (f ′c) for normal and lightweight concrete:

$$fsp = 0.56\sqrt{fc} \quad (1)$$

Carino and Lew [29] revised the above relationship and proposed the following in place of the ACI code relationship:

$$fsp = 0.272 * fc^{0.71} \quad (2)$$

Arigolu et. al. [30] suggested the equation below after a large-scale regression analysis for concrete including silica fume or fly ash with compressive strengths ranging from 48 to 120 MPa.

$$fsp = 0.387\, fc^{0.64} \quad (3)$$

For HSC, Vogel et al [31] proposed utilizing the ACI 318 equation with the factor of 0.593 instead of 0.56, stated in Equation 1, as follows:

$$fsp = 0.593 * \sqrt{fc} \quad (4)$$

For fibre reinforced concrete, Thomas and Ramaswamy [32] proposed using the following relation to calculate the splitting tensile strength :

$$fsp = 0.63 * (fcu^{0.5}) + 0.288 * (fcu^{0.5}) * RIv + 0.052 * RIv \quad (5)$$

Where: RIv: is fibre reinforcing index determined from the equation below:

$$RI_v = V_f * L_f / D_f \tag{6}$$

where: Vf, Lf, Df are fibre length in mm, fibre diameter in mm and fibre volume fraction respectively.

Some local researchers attempted to find an empirical relation to predict the splitting tensile strength for RPC, the following equations are some examples:

Al-Ne'aime [33] performed a regression analysis to establish several empirical linear relations between the compressive and the splitting tensile strengths of RPC and modified reactive powder concrete MRPC with different cases as follows:

1-For original RPC at 20 C°, the relation may be given as below:

$$fsp = 0.0643 * fc + 6.428 \tag{7}$$

2- For modified RPC at 20 C°, the relation may be given as below:

$$fsp = 0.2104 * fc - 12.537 \tag{8}$$

3- For original RPC and MRPC at 20 C°, the relation may be given by the below linear equation:

$$fsp = 0.1372 * fc - 0.734 \tag{9}$$

Hannawayya [17] performed a regression analysis to establish an empirical equation. This relation can be utilized to calculate splitting tensile strength of RPC with cylindrical compressive strength varying from 79 MPa to 119 Mpa and has steel fibre ratios between 0% to 2%. The following simple form was introduced:

$$fsp = 22.744 - \frac{1303.74}{fc} + 2.028 * vf \tag{10}$$

Also, Mahdi [34] gave a 4th-order polynomial equation comparing compressive strength to splitting tensile strength for the situations of self-compacting plain RPC as well as with 2% volumetric ratio of steel fibre. The relationship's general form is reported as follows:

$$\boldsymbol{fsp = a(fc^3) + b(fc^2) + c(fc) + d} \tag{11}$$

where: a, b, c and d: are constants and their values are shown in **Table 2**.

Table 2 - Constants adopted by Mahdi [34]

Constant	Mix without fibres	Mix with fibres
a	-1.0651x10^{-4}	3.369469x10^{-4}
b	0.0234	-9.678x10^{-2}
c	-2.15565	12.22517
d	75.1165	-549.83067

Ridha [35] established a relationship for splitting tensile and compressive strengths of RPC for non-fibrous RPC (f'c) and for the steel fibres' volume fraction (Vf), according to the test results of their study and other investigators. The suggested expression may be written in the following form:

$$fsp = 0.37 * (fcf^{0.8}) * F^{0.2} \tag{12}$$

$$fsp = 0.94 * (fc^{0.5}) + 3.5 * vf \tag{13}$$

Ma'roof [25] proposed an expression for predicting splitting tensile strength of RPC with compressive strength ranged from 78 to 161 MPa which is:

$$fsp = 25.72 - \frac{1581.7}{fc} + 5.835 * F \tag{14}$$

$$F = (Lf/Df) * vf * Bf \tag{15}$$

A comparison between previous equations is listed in **Table 3** and **Fig. 3**. It can be spotted that in estimating splitting tensile strength of Figure 1 - Experimental and determined tensile splitting strength

RPC, Equation 7 has a better agreement with experimental results than other equations.

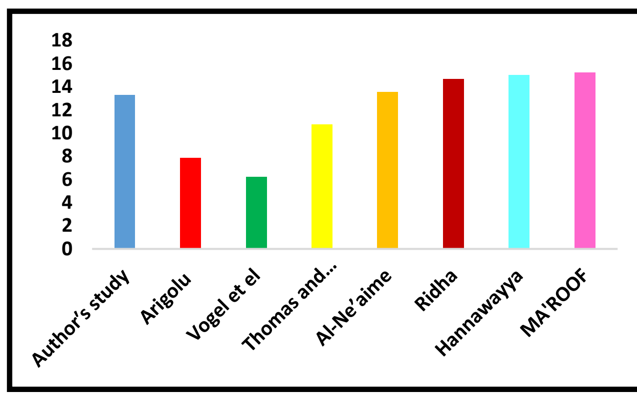

Figure 2 - Experimental and determined tensile splitting strength

Table 3 - Experimental and determined tensile splitting strength

Authors' results		Arigolu et. al. [30]	Vogel et. al. [31]	Thomas and Ramaswamy [32]	Al-Ne'aime [33]	Ridha 1 [35]	Hanna-wayya [17]	Ma'roof [25]
fc	fsp							
111	13.33	7.88	6.25	10.74	13.56	14.69	15.05	15.26

3.3 Flexural tensile strength (fr):

In this test, the flexural load was applied, by two-point loading, on prisms specimens, with dimensions of 100x100x500 mm, to obtain indirect tensile strength of concrete.

Table 1 records the results of the modulus of rupture for concrete utilized in this research. Each value reflecting the average of three prisms. The ratio of the flexural strength to cylinder compressive strength (fr /f 'c) for RPC in the present study is 13.77%. Danha [27] established that this ratio is 6.78% for the non-fibrous RPC mix and ranged from 10.42% to 19.28 for RPC mixes with (1%-3%) volumetric ratio of steel fibres. This ratio is so close to that obtained by other researchers such as Hannawayya [17] who found that it ranged from 6.3% to 17.33% for RPC mix with steel fibres volume fraction of (0%-2%). As well as, Graybeal [22] found that the ratio ranged between 14.02% to 25.04% for UHPC with 2% steel fibres volume fraction.

It is worthwhile to notice that the fibrous concrete mix is significantly higher in the modulus of rupture relative to the conventional concrete. This increase is due to the increment in the bonding strength between the fibres and the matrix and increasing the ductility of such material. Also, the increase in flexural strength can be attributed to the pozzolanic reaction with $Ca(OH)_2$ crystals located in the transition zone and as a result developing the bond between the cement particles and the aggregate surface.

Many studies were conducted to predict a correlation concerning the concrete's compressive strength and its modulus of rupture.

ACI 318M-11 [28] adopted the following equation for plain concrete to introduce the connection between flexural strength and compressive strength:

$$fr = 0.62\sqrt{fc} \qquad (16)$$

The above relationship excludes the influence of steel fibres ratio. Since the steel fibres have a substantial effect on compressive strength and modulus of rupture, an empirical linear relationship between the flexural strength of the RPC and its compressive strength for RPC mix cured at 20C° was proposed by Al-Wahili [36] who performed a regression analysis for this purpose. The measured correlation coefficient was 0.930. The relation can be described by the below linear expression:

$$fr = 0.184\,fc - 4.955 \qquad (17)$$

Ali et. al. [37] suggested a relation between compressive strength and modulus of rupture for RPC as follows:

$$fr = 0.03 * fc^{1.3} * (F^{0.004}) \qquad (18)$$

Kasser [38] performed a regression analysis to establish an empirical relation between compressive strength and modulus of rupture for all types of RP-SCC and FR-RPSCC (plain and steel fibre reinforced SC-RPC). These relationships can be implemented by the following linear equations:

$$fr = 0.0462 * fc + 4.2501 \quad \textit{for plain RPC} \qquad (19)$$

$$fr = 0.0901 * fc + 9.4383 \quad \textit{for RPC with steel fibre} \qquad (20)$$

To determine the flexural strength for fibre reinforced concrete, Thomas and Ramaswamy [32] proposed the below equation:

$$fr = 0.97 * (fcu)0.5 + 0.295 * (fcu)0.5RIv + 1.117 * RIv \qquad (21)$$

Where: $f$cu: cube compressive strength for non-fibrous concrete (MPa) and RIv: fibre reinforcing index calculated from Equation (6).

Hannawayya [17] suggested an empirical relationship for steel fibre reinforced RPC according to the results of his experimental study:

$$fr = \frac{332.848}{fc} + 7.532 * vf \qquad (22)$$

Mahdi [34] suggested two expressions for SC-RPC, one for plain and the other for steel fibre reinforced RPC which are respectively:

$$fr = 44.7537/(1 - 0.4979 * fc) \qquad (23)$$

$$fr = 44.7537 - 0.4949 * fc + 3.1808 * 10^{-2}(fc^{1.5}) \qquad (24)$$

Ridha [35] established the flexural tensile strength (frf) in terms of the compressive strength of non-fibrous RPC (fc) and with the volume fraction of steel fibre (Vf), according to the test results of her study and other studies. The suggested equation can be written in the form below:

$$frf = 2.8 * (fc * F)^{0.44} \qquad (25)$$

$$frf = 0.056 * fc + 6 * vf \qquad (26)$$

Ismail [18] proposed an expression to calculate the relation between compressive strength and modulus of rupture for RPC as shown below:

$$fr = \frac{668.475}{fc} + 6.486 * vf \qquad (27)$$

A comparison between previous equations is listed in **Table 4**, **Fig. 4**. It can be observed that Equation 21 has a promising result compared to the experimental findings than other equations in estimating RPC's modulus of rupture.

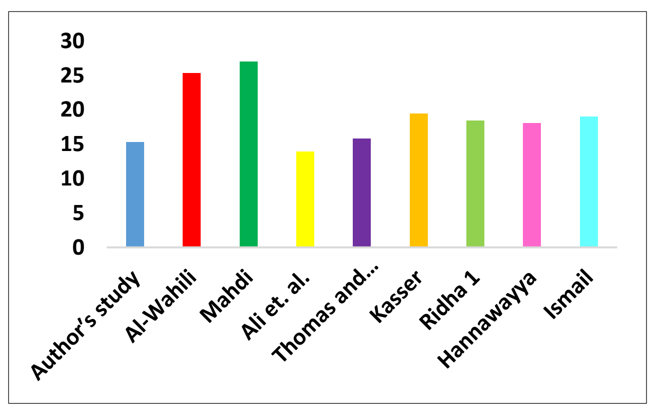

Figure 4 - Experimental and determining modulus of rapture for RPC

Table 4 - Experimental and determining modulus of rapture

Authors' results		Al- Wahili [36]	Mahdi [34]	Ali et. al. [37]	Thomas and Ramaswamy [32]	Kasser [38]	Ridha 1 [35]	Hannawayya [17]	Ismail [18]
fc	fr								
111	15.29	25.34	27.02	13.9	15.84	19.44	18.39	18.06	18.99

4. Conclusions

- It is possible to gain RPC with compressive strength of 111 MPa, modulus of rupture of 15.29 MPa and splitting tensile strength of 13.326

MPa at room temperature utilizing normal water curing instead of heat curing to save the cost with mix propotion of 1000 kg/m3 of cement, 1000 kg/m3 of sand, silica fume =25% by wt. of cement, steel fiber = 2% of mix volume, w/cm = 0.2 and superpasticeser = 6% by wt. of binder .

- In this study, a comparison between the compressive strength that resulted from cube and cylinder specimens showed that the shape of the specimens has limited influence on the RPC's compressive strength. The result revealed that the ratio of the cylinder to the cube compressive strength is 0.98.

- For splitting tensile strength, the results showed that the equation which proposed by Al-Ne'aime has a better agreement with the experimental results than other equations.

- For flexural tensile strength, the results showed that the equation which proposed by Thomas and Ramaswamy has a better agreement with the experimental results than other equations.

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