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
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/m³). 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.](image)

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 (cubc 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 UHPFRC is equal to 0.98. Also, Ma’roof [25] found that this ratio is ranged from 0.9 to 0.979 for RPC.

### Notations

| Symbol | Description |
|--------|-------------|
| Bf     | The bond factor that accounts for bond characteristics of the fibers |
| Df     | fibre diameter in mm |
| F      | fiber factor |
| fc     | Cylinder compressive strength |
| fsp    | splitting tensile strength |
| fcum   | Cube compressive strength |
| Lf     | fibre length in mm |
| fr     | modulus of rupture |
| RIV    | fibre reinforcing index |
| Vf     | fibre volume fraction |

### Abbreviations

- w/cm: melemeter
- Mpa: Mega Pascal (N/mm²)
- ACI: American Concrete Institute
- ASTM: American Society for Testing and Material
- HSC: High strength concrete
- RPC: Reactive powder concrete
- UHPC: Ultra-high performance concrete
- UHPPRC: Ultra-high performance fiber reinforced concrete
Many studies proposed a relation between (fc) and (fsp) strengths for normal and high strength concrete:

\[
fsp = 0.56 \sqrt{fc} 
\]  

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

\[
fsp = 0.272 \times f_c^{0.71} 
\]  

Arigol 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.

\[
fsp = 0.387 f_c^{0.64} 
\]  

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:

\[
fsp = 0.593 \sqrt{fc} 
\]  

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

\[
fsp = 0.63 \times f_{cu}^{0.5} + 0.288 \times (f_{cu}^{0.5} \times Rlv + 0.052 \times Rlv) 
\]
Where: $R_f$: is fibre reinforcing index determined from the equation below:

$$R_f = V_f \times L_f / D_f$$  \hspace{1cm} (6)$$

where: $V_f$, $L_f$, $D_f$ 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:

$$f_{sp} = 0.0643 \times f_c + 6.428$$  \hspace{1cm} (7)$$

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

$$f_{sp} = 0.2104 \times f_c - 12.537$$  \hspace{1cm} (8)$$

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

$$f_{sp} = 0.1372 \times f_c - 0.734$$  \hspace{1cm} (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:

$$f_{sp} = 22.744 - \frac{130.74}{f_c} + 2.028 \times vf$$  \hspace{1cm} (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:

$$f_{sp} = a(f_c^4) + b(f_c^2) + c(f_c) + d$$  \hspace{1cm} (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 |
|----------|--------------------|-----------------|
| $a$      | $-1.0651 \times 10^{-4}$ | $3.369469 \times 10^{-4}$ |
| $b$      | $0.0234$           | $-9.678 \times 10^{-2}$  |
| $c$      | $-2.15565$         | $12.22517$       |
| $d$      | $75.1165$          | $-549.83067$     |

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 ($V_f$), according to the test results of their study and other investigators. The suggested expression may be written in the following form:

$$f_{sp} = 0.37 \times (f_c f_v^{0.8}) \times F^{0.2}$$  \hspace{1cm} (12)$$

$$f_{sp} = 0.94 \times (f_c v_f^{0.5}) + 3.5 \times f_v$$  \hspace{1cm} (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:

$$f_{sp} = 25.72 - \frac{1581.7}{f_c} + 5.835 \times F$$  \hspace{1cm} (14)$$

$$F = (L_f / D_f) \times v_f \times B_f$$  \hspace{1cm} (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](image)

**Table 3 - Experimental and determined tensile splitting strength**

| Authors’ results | Authors’ results |
|------------------|------------------|
| $f_c$ | $f_{sp}$ |
| Angelo  | 113 | 13.33 |
| Vogel et al. [31] | 7.88 | 6.25 |
| Thomas and Ramy [32] | 10.74 | 13.56 |
| Al-Ne’aime [33] | 14.69 | 14.69 |
| Ridha [34] | 15.05 | 15.05 |
| Hannawayya [17] | 15.26 | 15.26 |
| Ma’roof [25] | 15.26 | 15.26 |

### 3.3 Flexural tensile strength ($f_{fr}$):

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 ($f_{fr} / f_c$) 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:

\[ fr = 0.62 \sqrt{fc} \]  (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 20°C 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:

\[ fr = 0.184 \cdot fc - 4.955 \]  (17)

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

\[ fr = 0.03 \cdot fc^{1.3} \cdot (F^{0.008}) \]  (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:

\[ fr = 0.0462 \cdot fc + 4.2501 \]  for plain RPC  (19)

\[ fr = 0.0901 \cdot fc + 9.4383 \]  for RPC with steel fibre  (20)

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

\[ fr = 0.97 \cdot (fcu)0.5 + 0.295 \cdot (fcu)0.5Rfv + 1.117 \cdot Rfv \]  (21)

Where: \( fcu \): cube compressive strength for non-fibrous concrete (MPa) and \( Rfv \): 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:

\[ fr = \frac{332.848}{fc} + 7.532 \cdot vf \]  (22)

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

\[ fr = 44.7537/(1 - 0.4979 \cdot fc) \]  (23)

\[ fr = 44.7537 - 0.4949 \cdot fc + 3.1808 \cdot 10^{-2}(fc^{1.5}) \]  (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:

\[ frf = 2.8 \cdot (fc \cdot F)^{0.44} \]  (25)

\[ frf = 0.056 \cdot fc + 6 \cdot vf \]  (26)

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

\[ fr = \frac{668.475}{fc} + 6.486 \cdot vf \]  (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 rupture for RPC](image)

| Author's name | Algebraic expression |
|---------------|---------------------|
| Al-Wahili     |                     |
| Mahdi         |                     |
| Ali et. al.   |                     |
| Thomas and Ramaswamy |   |
| Kasser   |                     |
| Ridha 1       |                     |
| Hannawayya    |                     |
| Ismail        |                     |

| Authors’ results | Al-Wahili | Mahdi | Ali et. al. | Thomas and Ramaswamy | Kasser | Ridha 1 | Hannawayya | Ismail |
|------------------|-----------|-------|-------------|-----------------------|--------|---------|------------|--------|
| fc               | 111       | 15.29 | 25.34       | 13.9                  | 15.84  | 19.44   | 18.39      | 18.06  |
| fr               | 25.34     | 27.02 | 10.9        | 13.9                  | 15.84  | 19.44   | 18.39      | 18.06  |

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 proportion 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 superplasticscer = 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.

REFERENCES

[1] Richard, P. and Cherezy, M., "Reactive Powder Concrete with High Ductility and
200-800 MPa Compressive Strength". ACI SP144-24, 1994: p. pp. 507-518.
[2] Richard, P. and M. Cherezy, "Composition of reactive powder concretes". Cement and concrete research, 1995. 25(7): p. 1501-1511.
[3] Roux, N., Andrade, C. and Sanjuan, M., "Experimental study of durability of reactive powder concretes". Journal of materials in civil engineering, 1996. 8(1): p. 1-6.
[4] Bisoli, L., Guerrini, G.L. and Rosati, G., "Overall structural behavior of high strength concrete specimens". Construction and Building Materials, 1997. 11(1): p. 57-63.
[5] Orgass, M. and Klug, Y., "Steel Fiber Reinforced Ultra High Strength Concretes", 2004: p. 12 pp.
[6] Chan, Y. and Chu, S., "Effect of silica fume on steel fiber bond characteristics in reactive powder concrete". Cement and concrete research, 2004. 34(7): p. 1167-1172.
[7] Gao, X., "Mix design and impact response of fibre reinforced and plain reactive powder concrete". 2007.
[8] Fujikake, K., Senga, T., Ueda, N., Ohno, T. and Katagiri, M., "Effects of strain rate on tensile behavior of reactive powder concrete". Journal of Advanced Concrete Technology, 2006. 4(1): p. 79-84.
[9] Tai, Y., "Uniaxial compression tests at various loading rates for reactive powder concrete". Theoretical and Applied Fracture Mechanics, 2009. 52(1): p. 14-21.
[10] Marolinya, M. and Modhera, C., "Influence of type of superplasticizers on workability and compressive strength of reactive powder concrete". International Journal of Advanced Engineering Technology, 2010. 1: p. 123-130.
[11] Yu, R., Spiesz, P. and Brouwers, H., "Mix design and properties assessment of ultra-high performance fibre reinforced concrete (UHPFRC)". Cement and concrete research, 2014. 56: p. 29-39.
[12] Ng, K.M., Tam, C.M. and Tam, V.W., "Studying the production process and mechanical properties of reactive powder concrete: a Hong Kong study". Magazine of concrete research, 2010. 62(9): p. 647-654.
[13] ASTM C150/C150M, "Standard specification for Portland cement", 2012: American Society for Testing and Materials, USA.
[14] ASTM C1240-04, "Standard Specification for the Use of Silica Fume as a
Mineral Admixture in Hydraulic Cement Concrete, Mortar and Grout", Vol. 4.2, 2004, 6p.
[15] ASTM C494/C494M-1999a, "Standard Specification for Chemical Admixtures for Concrete", Vol. 4.2, 1999, 9p.
[16] ASTM A 820/A 820M-04 “ Standard Specification for Steel Fiber for Fiber-
Reinforced Concrete “ , 2004 pp.1-4.
[17] Hannawayya, S. P.Y., "Behavior of Reactive Powder Concrete Beams in Bending", Ph.D. Thesis, Building and Construction Engineering Department. 2010, University of Technology: Baghdad. p. 239.
[18] Ismael, M.A., "Flexural Behavior of Reactive Powder Concrete Tee Beams", Ph.D. Thesis, civil Engineering Department,. 2013, University of Al-Mustansiriya: Baghdad. p. 122.
[19] BS EN 12390-3, "Testing hardened concrete. Method of determination of compressive strength of concrete cubes”. 2000.
[20] ASTM C39/C39M-05, "Standard Test Method for Compressive Strength of Cylindrical Test Specimens", Vol. 04.02, 2003.
[21] Neville, A.M., "Properties of concrete". Vol. 4. 1995: Longman London.
[22] Graybeal, B.A., "Material property characterization of ultra-high performance concrete". 2006, United States, Federal Highway Administration.
[23] Qasim, O.A., "Behavior of reinforced reactive powder concrete slabs with openings", Ph.D. Thesis, civil engineering department. 2013, Al-Nahrain University: Baghdad. p. 214.
[24] Tue, N.V., Ma, J. and Orgass, M., "Influence of addition method of superplasticizer on the properties of fresh UHPC", in Proceedings of the 2nd International Symposium on Ultra-High Performance Concrete, Kassel, Germany. 2008.
[25] Maddrif, A.S.A., "Behavior of reactive powder concrete deep beams", Ph.D. Thesis, Civil Engineering. 2013, College of Engineering of Alnahrain: Baghdad. p. 228.
[26] Ma, J., Dietz, J. and Dehn, F., "Ultra high performance self compacting concrete". Lacer, 2002. 7: p. 33-42.
[27] Danha, L. S., "Tensile Behavior of Reactive Powder Concrete", M.Sc. Thesis, Building and Construction Engineering Department. 2012, University of Technology: Baghdad. p. 115.
[28] ACI Committee 318M-318RM, "Building Code Requirements for Structural Concrete and Commentary", American Concrete Institute, Farmington Hills, Michigan, 2011, 503 pp.
[29] Carino, N.J. and Lew. H. H. "Re-examination of the relation between splitting tensile and compressive strength of normal weight concrete". in Journal Proceedings. 1982.
[30] Arioglu, N., Girgin, Z.C. and Arioglu, E., "Evaluation of Ratio between Splitting Tensile Strength and Compressive Strength for Concretes up to 120 MPa and its Application in Strength Criteria", . Vol., . pp. . ACI Materials Journal, 2006. 103(No. 1): p. 18-24.
[31] Vogel, H., Noel, M., Davoudi, S. and Svecova, D., "Evaluation of properties of high strength concrete for prestressed concrete prisms". in Proceedings of the Second International Symposium on Ultra High Performance Concrete. 2008.
[32] Thomas, J. and Ramaswamy, A., "Mechanical Properties of Steel Fiber-Reinforced Concrete", Journal of Materials in Civil Engineering, . pp. (2007). Vol. 19(No. 5): p. 385-392.
[33] Al-Ne’aime, S.S.H., "Static and Impact Properties of Reactive Powder Concrete", Ph.D. Thesis, Building and Construction Engineering Department. ( 2006 ), University of Technology: Baghdad p. 190p.
[34] Mahdi, B.S., "Properties of Self Compacted Reactive Powder Concrete Exposed to Saline Solution", Ph.D. Thesis, Building and Construction Engineering
[35] Ridha, M., "Shear behavior of reactive powder concrete beams", 2010, Ph. D. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, 2010, 204pp.

[36] Al-Wahili, A., "Mechanical Properties of Steel Fiber Reinforced Reactive Powder concrete", M.Sc. Thesis, Building and Construction Engineering Department. (2005), University of Technology: Baghdad. p. 123.

[37] Ali, H.M. and Hamad, N.T., “Shear Capacity and Mechanical Properties of Reactive Powder Concrete T-Beams”. Journal of Engineering and Sustainable Development, 2014. 18(4): p. 188-213.

[38] Kasser, F.M., “Mechanical Properties of Reactive Powder Self Compacting Concrete”. M.Sc. Thesis, Building and Construction Engineering Department. (2007), University of Technology: Baghdad. p. 132.