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# Optimal Strength Design of Reactive Powder Concrete

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*Abstract*— **Little, if any, researches deal with the optimization consideration of reactive powder concrete (RPC), that is normally tested under compression, indirect splitting tension and/or flexure. In this study, the mechanical properties of reactive powder concrete were investigated and optimized. All specimens were made at different water to cement ratios (0.15, 0.18, 0.21, 0.24), microsilica to cement ratios (0.05, 0.10, 0.15) and age of testing (7, 14, 28) days. The compressive strength, splitting tensile strength and flexural strength were determined and then optimized to maximize strength. In addition, two curing processes were examined: moist and autoclave curing.**

**Based on the present study, optimal composite materials and conditions for producing RPC were found by investigating the effect of several parameters, including curing method, water-to-cement (w/c) ratio, microsilica to cement (m/c) ratio, and testing age. Further, there is a definite proportion for various ingredients to achieve maximum strength properties. RPC with w/c of 0.20 by weight of cement, m/c of 0.09 by weight of cement, age of 28-day for moist curing and with w/c of 0.175 by weight of cement, m/c of 0.15 by weight of cement, age of 14-day for autoclave curing gave maximum RPC strength.**

*Keywords*— **Reactive Powder Concrete (RPC), optimization, mechanical properties, autoclaving, RSM.**

## I. Introduction

There is a growing use of reactive powder concrete (RPC) nowadays because of its superior mechanical properties and durability. Ultra high performance is the most valuable characteristic of RPC, the benefits of high performance properties are that to lower maintenance cost that gives a significant economic advantage and the wide variety of structural uses [1].

The high silica fume content and very low water to cement ratio are the most characteristic properties for reactive powder concrete mixes [2]. To avoid weaknesses of the microstructure, the elimination of coarse aggregate is needed, the addition of superplasticizer is used to achieve a low water/binder (cement and silica fume) ratio and heat-treatment (steam curing) is applied to achieve high early strength [3].

The basic principle in RPC is to achieve a desirable dense matrix by reducing the microcracks and capillary pores in cementitious matrix and to get a dense transition zone between cement matrix and aggregates [4]. All these requirements can be achieved by entirely eliminating the coarse aggregates and using sand of 0.6 mm maximum size. The properties further can also be improved by adding silica fume about 10 to 15 % by weight of the cement, which reacts with calcium hydrate to form calcium silicate hydrate which gives the additional strength to the cement matrix [5].

The pozzolanic reaction of silica fume greatly depends on the temperature of curing, heat curing has the ability to accelerate the pozzolanic reaction. Abdul-Hussain [6] claimed that the strength increases rapidly with curing temperature between 53 and 150°C due to the acceleration of the hydration process; and rises again between 200 and 300°C due to the pozzolanic reaction. So et al. [7] confirmed this finding and stated that at these temperatures, the formation of very dense calcium silicate hydrate (C-S-H) compounds with very low numbers of water molecules were happen. Thus, hydration reaction of RPC develops very quickly initially and drops down as all the mixed water is consumed.

The high brittleness is the most undesirable property of RPC, especially of ultra-high strength RP concrete [8]. It has been reported that the only really practical solution to the brittleness exhibited by all high strength cement-based materials is to incorporate fibers into the matrix [9]. Al-Hassani et al. [10] studied the effect of silica fume and steel fiber contents on the properties of RPC and found that concrete containing micro steel fibers had significantly higher strength and flexural toughness than that of ordinary concrete.

Khalil [11] performed a compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and impact strength tests on modified RPC incorporating crushed coarse aggregate. She found that the addition of crushed coarse aggregate increased the strength of MRPC as compared to plain RPC up to 150 MPa. On the contrast, Louis [12] stated that 28-day compressive strengths of MRPC were lower than that of plain RPC. He explained this was due to the low pozzolanic activity for using local powders with coarse aggregate in the mix. Similar findings were also reported in the study by Al-Jubory [13]. She explained the strength enhancement is due to the pore size refinement and matrix densification as well as the pozzolanic reaction which reduces the $Ca(OH)_2$ content.

An optimization experimental program was conducted by Sbia et al. [14] in order to identify the optimum dosages of carbon nano fiber CNF and polyvinyl alcohol PVA fiber in order to get balanced gains in flexural strength, energy absorption capacity, ductility, impact resistance, abrasion resistance, and compressive strength of UHPC without compromising the fresh mix workability. Experimental results indicated that significant and balanced gains in the UHPC performance characteristics could be realized when a relatively low volume fraction of CNF (0.047 vol.% of concrete) is used in combination with a moderate volume fraction of PVA fibers (0.37 vol.% of concrete).

### A. Objectives

The main objectives are:

Evaluating the effect of different parameters (w/c, m/c and age) on some mechanical properties of RPC.

Studying the effect of different curing processes (moist and autoclave) on mechanical properties of RPC.

Determining the optimum content of w/c, m/c and age for achieving balanced gains in mechanical properties of RPC by the analysis of experimental results.

## II. Materials and Mix Proportions

Mix proportions were selected based on mix design process for RPC and according to previous researches [1, 2, and 9]. Laboratory prepared samples with various silica fume contents, water to cement ratios, age and curing process were exposed to evaluate the effect of each of these mix variations on strength performance. The details of the mix proportions are given in Table 1.

Ordinary Portland cement from Tasluga factory was used for the preparation of all of the reactive powder concrete mixtures. It conforms to the Iraqi specification No.5/1984. 0.6 mm maximum aggregate size from local quarries in Kerbalaa were used as the fine aggregates for all mixtures in this study. It's grading and sulfate content conforms to Iraqi specification No.45/1984, and it lies in the second grading zone. In order to achieve the desired workability, a naphthalene based superplasticizer commercially known as SikaViscocrete-5930 was used. It complies with ASTM C494-99 type G and F. Microsilica supplied by BSAF Company was used throughout the experimental program. The microsilica conforms to the requirements of ASTM C1240-05 and ASTM C311-05 specifications and has a pozzolanic activity index (P.A.I.) of 156 %. Micro steel fibers with a diameter of 0.2 mm and length of 13 mm which provided by Sika Company with aspect ratio (l/d = 65) were used in all samples production.

## III. Experimental Work Set Up

The aim of this study was to optimize mix proportions in terms of mechanical features of RPC. Three different microsilica percentages, which were started from 5 to 15% with an increment of 5 %, were used. These mixtures were prepared using w/c of 0.15, 0.18, 0.21 and 0.24 at different testing ages (7, 14, 28 days) and curing process (moist and autoclaved).

The details of concrete which were made during the laboratory work are given in Table 1. The samples were kept underneath wet burlap and then covered with a plastic wrap and kept for 24 hours in the laboratory temperature. The samples were next removed from the mold, labelled, and completely covered with water in the moist curing process until the day of their testing, or autoclaved in an ELE apparatus for three hours following the ASTM C-151/05 as it shown in Plate 1, then they were left in the laboratory until their testing day.

## IV. Hardened Tests

### A. Compressive Strength

The compressive strength was determined by breaking the 150 mm concrete cubes in a MATEST compression-testing machine according to the requirements of BS 1881 part 116:1983 and taking the average result of three samples for each mix. For most of the mixes, testing was carried out at 7, 14 and 28 days after casting.

### B. Splitting Tensile Strength

Splitting tension test was conducted to study the material's ability to resist a diametric compressive force. Indirect tensile tests were conducted in accordance to ASTM C 496-04 of 100×200 mm cylinders. Three specimens were tested for each mixture at different ages after casting. The tests process started with aligning two hardboard bearing strips between the top and bottom platen of the cylinder when the cylinder was placed in the center of the testing jig.

### C. Flexural Strength

Three point bending test is considered the most important test in studying and analyzing the behavior fibers reinforced concrete composite. The flexural strength of RP concrete specimens was determined with regard to ASTM C 78-02. Beams were made 400 mm in length and 100 × 100 mm cross-section, steam cured on the day after casting for 3 hours or moist cured, then transferred to the curing room, demolded and left there until the day of testing. The testing apparatus was a frame containing two supporting rollers and two loading rollers. The sample was placed on its side with respect to its position as molded and then was centered on the supporting rollers.

### D. Optimization Process

The main objective of the optimization process in this study was to find suitable mix proportions that maximize the mechanical strength performance (compressive, splitting, and flexural strengths). In order to find the optimum manufacturing parameters of RPC, an optimization software (SigmaXL v. 6.11/2011) was used depending on the analysis of response surface method (RSM), using the Design of Experiments (DOE) principles.

## V. Results and Discussion

In this research, the influence of key mix design parameters is examined and then optimized. The micro silica dosage (m/c) and water/cement ratio (w/c) are the two most important factors in the mix design process. They can significantly affect the pozzolanic reaction in reactive powder concrete. The curing procedure and age are also investigated because they have an impact on the strength development of RPC. Three different doses of micro silica and four water/cement ratios have been used to explore their influence on the mechanical properties of RPC at different ages.

Figures 1-6 show the compressive strength of the RPC samples at different curing ages, micro silica dosages and water/cement ratios. For both curing processes, these figures indicated that the compressive strength tends to increase as the micro silica dosage increases. This observation is in good agreement with the findings of Man [3] and AL-Hassani et al [8] studies. Although, the mixture of 0.15 water/cement ratio at 28-day did not match this trend. This could be explained by the mixture not mixing well and not casting well or it could be attributed to the low pozzolanic activity due to the insufficient water that is needed for pozzolana to react. Furthermore, moist cured specimens have lower compressive strength values when compared to autoclaved cured specimens at the same testing age. In fact the 7 days compressive strength results of autoclaved cured concrete specimens, are higher than the 14 days compressive strength of moist cured specimens. It is also noted that the rate of strength development of the moist cured RPC at 7 days is higher than that of 14 and 28 days by 8 % and 27 % respectively. On the contrast, the rate of strength development of the autoclaved cured RPC at 7 days is higher than that of 14 and 28 days by 12 % and 19 % respectively. Hot water curing is understood to result in higher early compressive strength due to the effect of increasing both pozzolanic activity and cement hydration reaction of the RPC. The ultimate strengths are lower with a water/cement ratio of 0.15 than for a ratio of 0.18 by 41, 32 and 13 % for moist curing and 36, 25 and 18 % for autoclave curing regardless of the micro silica dosage at 7, 14 and 28 days respectively. More water addition results in higher workability and improved compactness of the fresh concrete and pozzolanic activity. Consequently, beyond 0.18 (w/c) there is a maximum decrease in the compressive strength results by 17 % and 30 % at (w/c) of 0.21 and 0.24 respectively.

From Figures 7-12 it can be observed that moist cured samples have less splitting tensile strength compared to rest of the mixes. The Cylinders did not break completely because, the fibers were holding the concrete together. Results also showed that increasing micro silica dosage would increase composite splitting tensile strength. Figures 7-9, show that increasing the m/c by 5 % and 10 % there is a maximum increase in splitting strength by (12, 17), (10, 14) and (3, 4) % for w/c of 0.18, 0.21 and 0.24 at 7, 14 and 28 days respectively. However, from Figures 10-12 these values became (6, 7), (3, 5) and (2, 4) % for w/c of 0.18, 0.21 and 0.24 at 7, 14 and 28 days respectively. The effect of curing process and age in splitting is similar to that pronounced in compressive. Since RPC contains no coarse aggregates, void content in the bulk of particles of the paste is reduced, small amount of water will be needed to fill up the voids among the particles and thus the strength of RPC is always high.

Furthermore, there is a general trend for the flexural strength to increase with an increase in micro silica content and decreasing the water/cement ratio down to 0.18. The results presented in Figures 13-15, point out that the increase is slight at 7 days, while it is more pronounced at 14 and 28 days respectively. From these figures, it can be seen that the produced RPC mostly have a flexural strength ranging from 7.8 to 16.62 MPa. However, the flexural strengths of the mixes containing w/c of 0.15 were the least among all mixes. For moist cured specimens, the results show that as the percentage of microsilica replacing the cement increases in the mix, the greater the increment in the magnitudes of the flexural strength. Additionally, the same trend was observed for the autoclave curing process and higher strengths were gained at early ages (7-days).

Using more extensive experimental works, applying mathematical modelling and computational tools, a more precise mix optimization have been studied to produce high quality and cost-effective RPC, and to increase the range of formulations so as to meet the specific requirements of individual applications. The results in Figures 19-24 show that the maximum strength of moist cured specimens will be obtained at a water-to-cement ratio of 0.20, microsilica-to cement ratio of 0.09 and age of 28 days. The model estimated a maximum compressive strength of 91 MPa, with an R2 and adjusted R2 of 0.96 and 0.89 respectively, which corresponds to an average error of 3.26%. On the other hand, results in Figures 25-30 show that the maximum strength of autoclave cured specimens will be obtained at a water-to-cement ratio of 0.175, microsilica-to cement ratio of 0.15 and age of 14 days. The model estimated a maximum compressive strength of 102 MPa, with an R2 and adjusted R2 of 0.97 and 0.94 respectively, which corresponds to an average error of 1.83%. The high R2 and adjusted R2 values are very desirable for a Designed Experiment in addition to the low average error percent.

## CONCLUSIONS

Investigating and optimizing the mechanical properties of RPC had the following outlines:-

1. A long mixing time is required for the RPC mixes for ensuring that dry-balled particles have become plastic-flowable.
2. The compressive strength, splitting tensile strength and flexural strength of the autoclaved RPC are higher than those of the moist cured RPC over the entire curing period under the same water-to-cement ratio.
3. Too low w/c ratio (0.15) mixes are difficult to achieve full compaction whereas too high w/c ratio (0.24) mixes are more susceptible to entraining air bubbles, which then leads to formation of large capillary voids and thus considerable reduction in strength.
4. The compressive strength of RPC increases as the micro silica dosage increases in the range of 10 % to 15 %. The effects of curing process and age in splitting and flexure are similar to that pronounced in compressive.
5. A w/c ratio of 0.18 provided a higher compressive strength than other ratios. The highest compressive strength 93 MPa was gained at a 15 % micro silica dosage with 0.18 w/c ratio for moist curing. However, this value become 102 MPa at same conditions for autoclave curing.
6. The optimal conditions to produce RPC were

investigated and estimated to be: w/c = 0.20, m/c = 0.09 and age = 28 days for moist curing process, while they would be: w/c = 0.175, m/c = 0.15 and age = 14 days for autoclaving curing process. The verification test demonstrated that the optimized processing parameters indeed made the composites superior in strength, which was predicted well by the mathematical model.

7. It is very recommended to investigate other parameters rather than that used throughout this study like steel fiber content, sand content and gradation, late ages (56 and 90).

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Table (1): Mix proportions and parameters of all RPC mixes

| Curing method | Cement ($kg/m^3$) | w/c (%) | Sand ($kg/m^3$) | SP by w.t. of cement (%) | Microsilica by w.t. (%) | Microsilica ($kg/m^3$) | Steel fiber by vol. (%) | Age (days) |
|---|---|---|---|---|---|---|---|---|
| Moist | 1100 | 15 | 1100 | 7 | control | control | 2 | 7 |
| | 1045 | 18 | | | 5 | 55 | | 14 |
| | 990 | 21 | | | 10 | 110 | | 28 |
| | 935 | 24 | | | 15 | 165 | | |
| Autoclave | 1100 | 15 | 1100 | 7 | control | control | 2 | 7 |
| | 1045 | 18 | | | 5 | 55 | | 14 |
| | 990 | 21 | | | 10 | 110 | | 28 |
| | 935 | 24 | | | 15 | 165 | | |

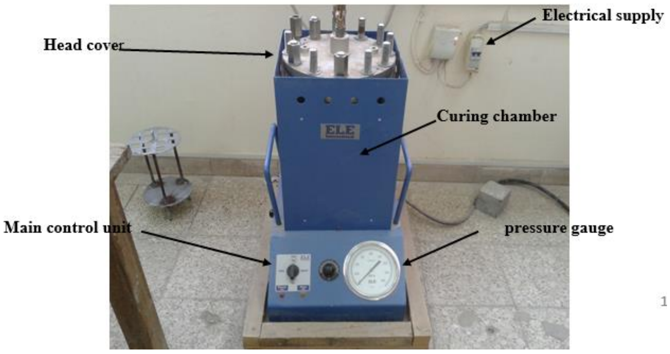


Plate 1: Autoclave curing apparatus in the University of Technology/Baghdad

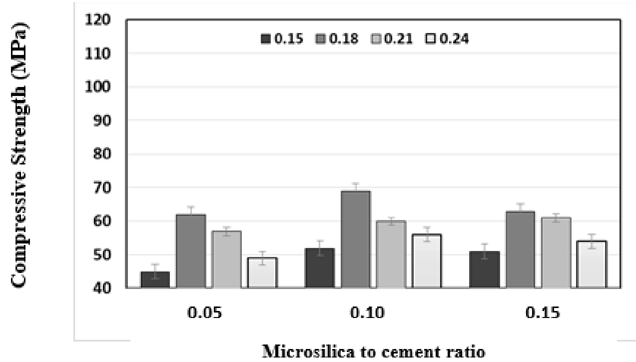


Figure (1): Compressive strength results at 7-day for moist cured specimens

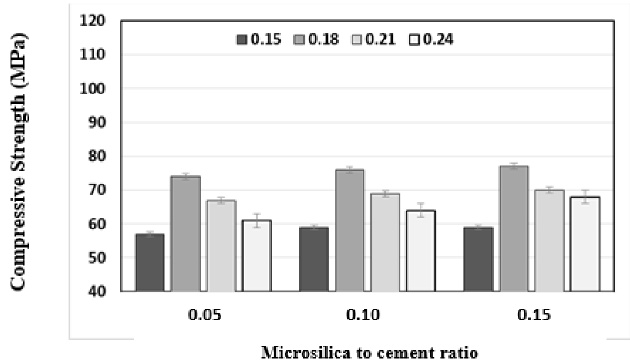


Figure (2): Compressive strength results at 14-day for moist cured specimens

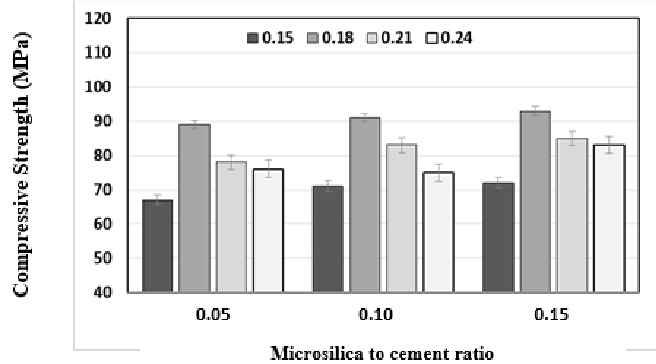


Figure (3): Compressive strength results at 28-day for moist cured specimens.

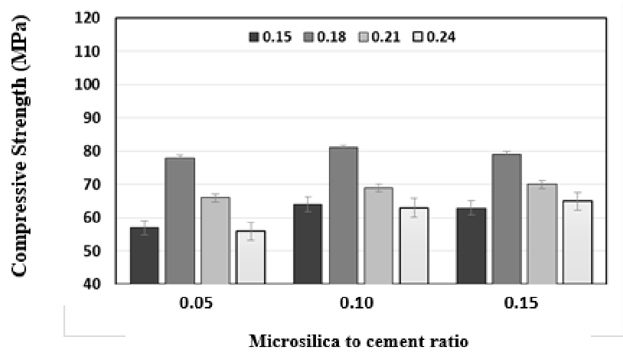


Figure (4): Compressive strength results at 7-day for autoclave cured specimens.

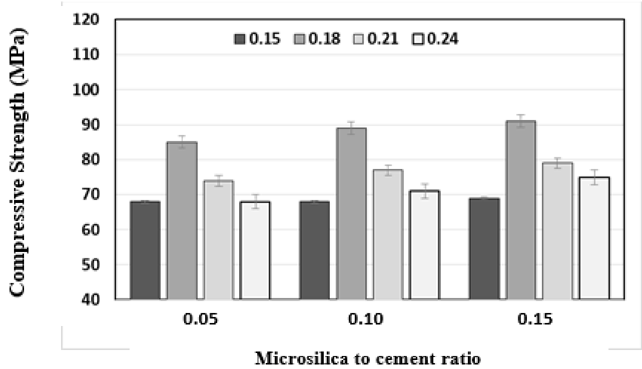


Figure (5): Compressive strength results at 14-day for autoclave cured specimens.

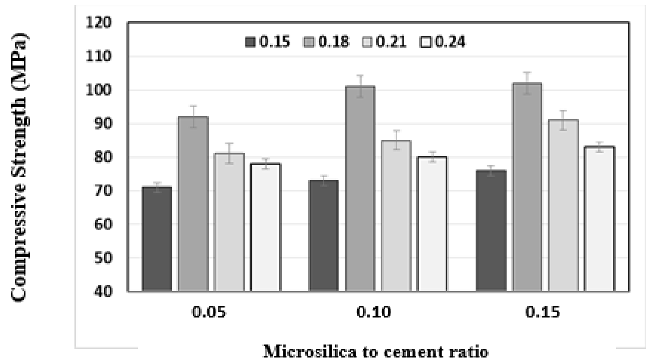


Figure (6): Compressive strength results at 28-day for autoclave cured specimens

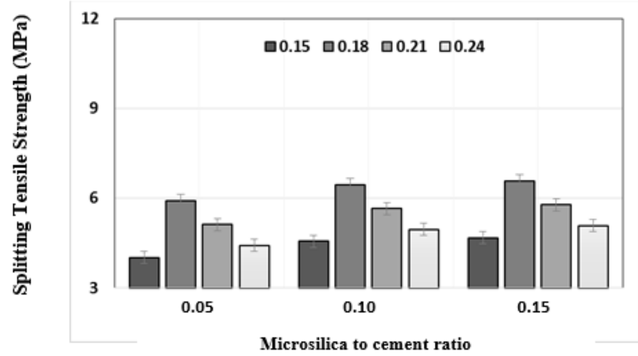


Figure (7): Splitting tensile strength results at 7-day for moist cured specimens.

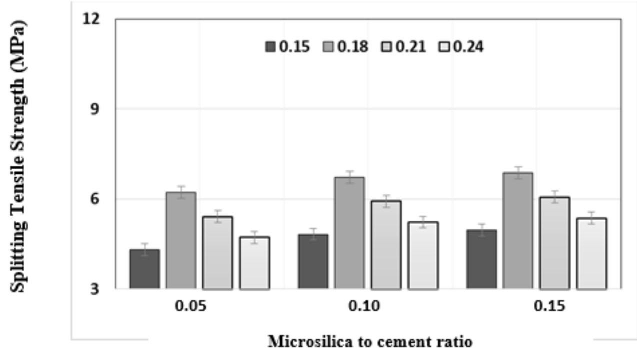


Figure (8): Splitting tensile strength results at 14-day for moist cured specimens

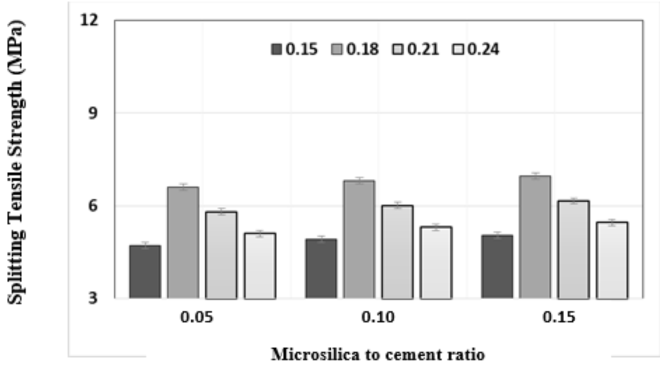


Figure (9): Splitting tensile strength results at 28-day for moist cured specimens.

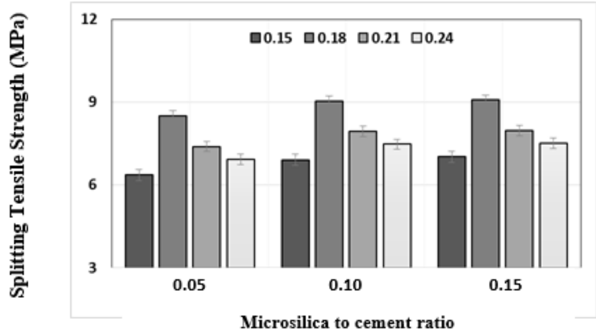


Figure (10): Splitting tensile strength results at 7-day for autoclave cured specimens

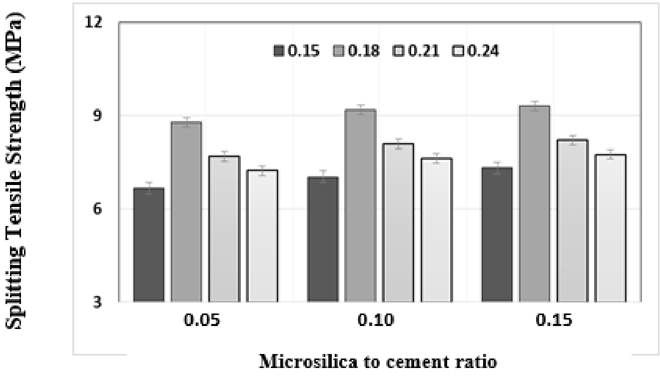


Figure (11): Splitting tensile strength results at 14-day for autoclave cured specimens.

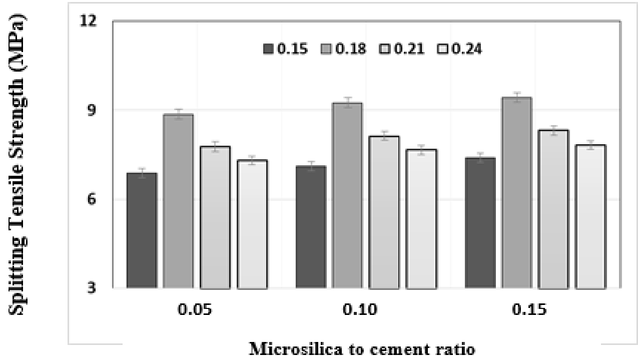


Figure (12): Splitting tensile strength results at 28-day for autoclave cured specimens

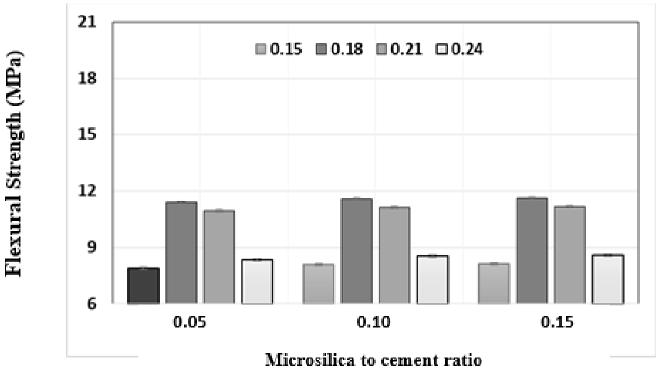


Figure (13): Flexural strength results at 7-day for moist cured specimens

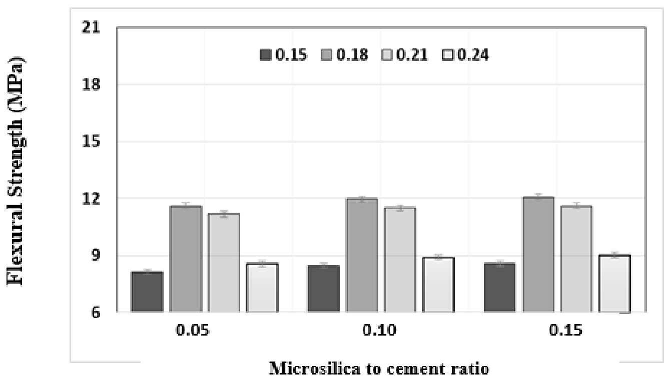


Figure (14): Flexural strength results at 14-day for moist cured specimens.

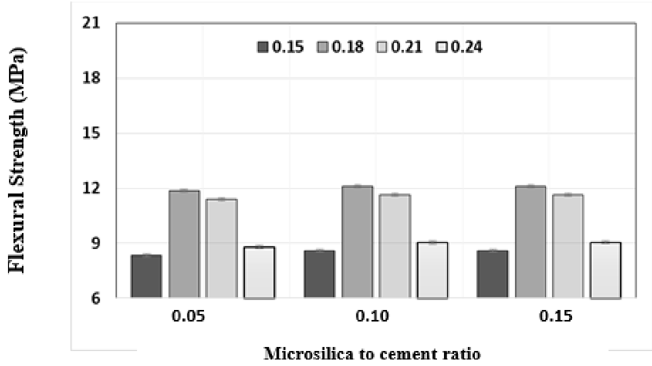


Figure (15): Flexural strength results at 28-day for moist cured specimens.

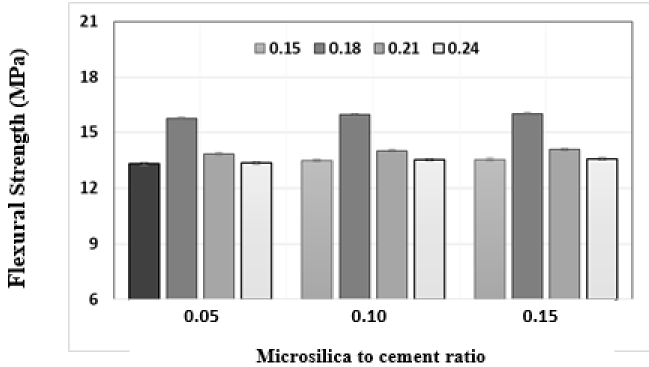


Figure (16): Flexural strength results at 7-day for autoclave cured specimens.

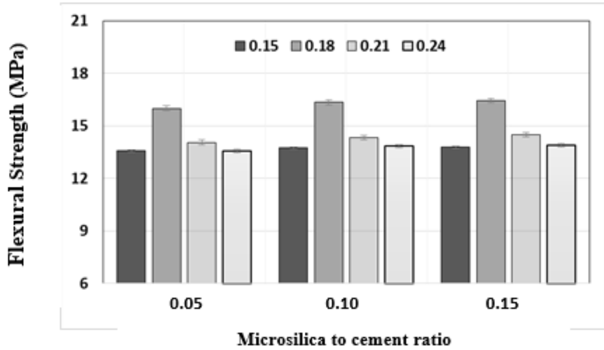


Figure (17): Flexural strength results at 14-day for autoclave cured specimens.

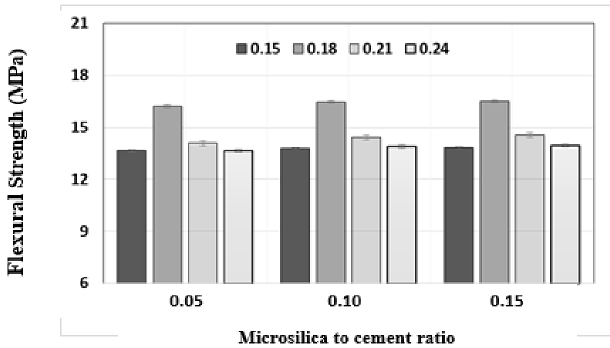


Figure (18): Flexural strength results at 28-day for autoclave cured specimens

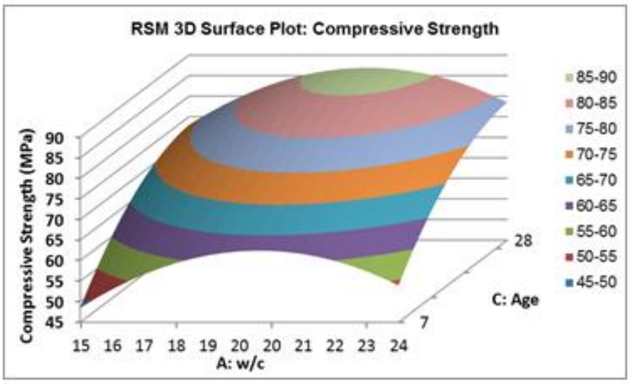


Figure (19): Three dimension RSM maximum compressive response surfaces for moist cured RPC between w/c and age.

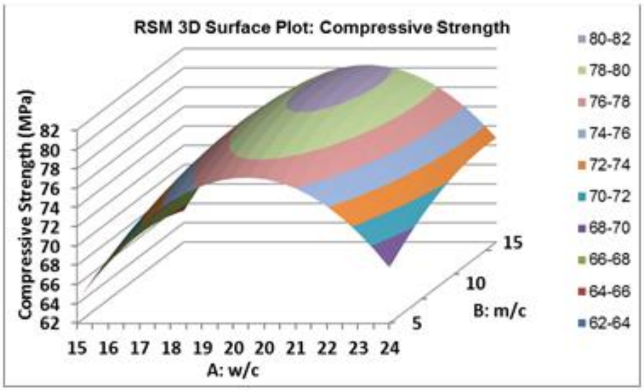


Figure (20): Three dimension RSM maximum compressive response surfaces for moist cured RPC between w/c and m/c.

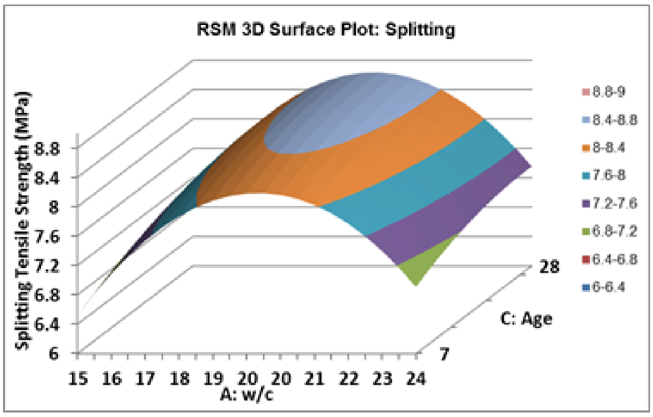


Figure (21): Three dimension RSM maximum splitting response surfaces for moist cured RPC between w/c and age

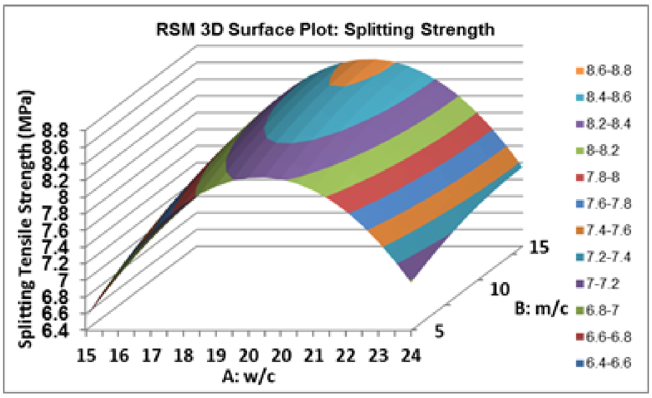


Figure (22): Three dimension RSM maximum splitting response surfaces for moist cured RPC between w/c and m/c.

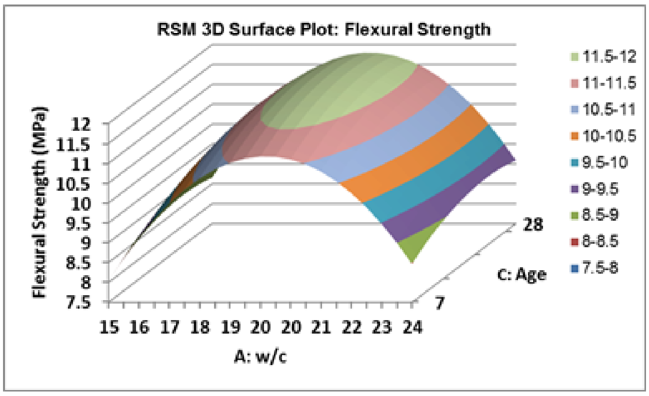


Figure (23): Three dimension RSM maximum flexural response surfaces for moist cured RPC between w/c and age.

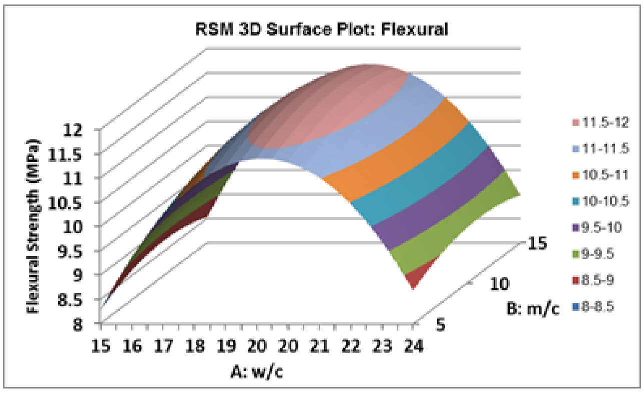


Figure (24): Three dimension RSM maximum flexural response surfaces for moist cured RPC between w/c and m/c.

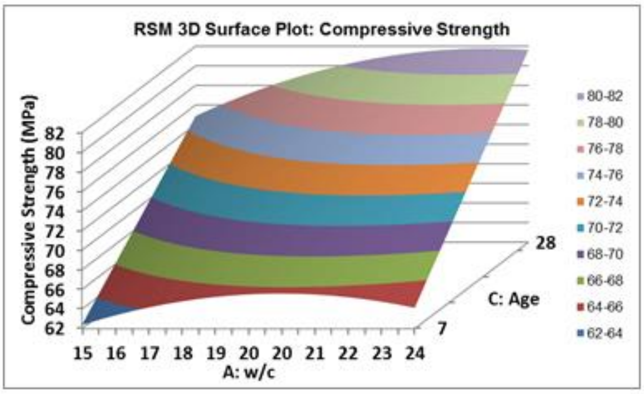


Figure (25): Three dimension RSM maximum compressive response surfaces for autoclaved cured RPC between w/c and age.

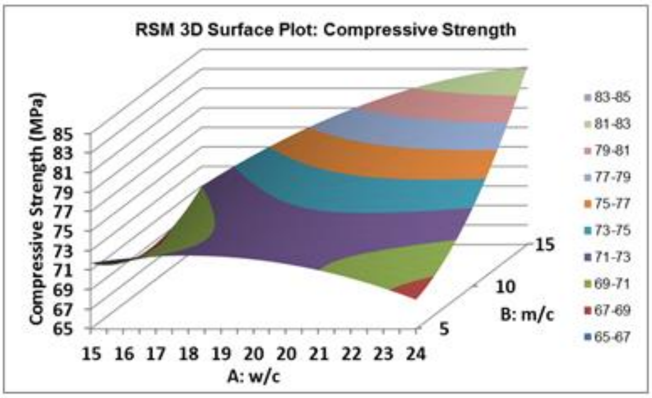

Figure (26): Three dimension RSM maximum compressive response surfaces for autoclaved cured RPC between w/c and m/c.

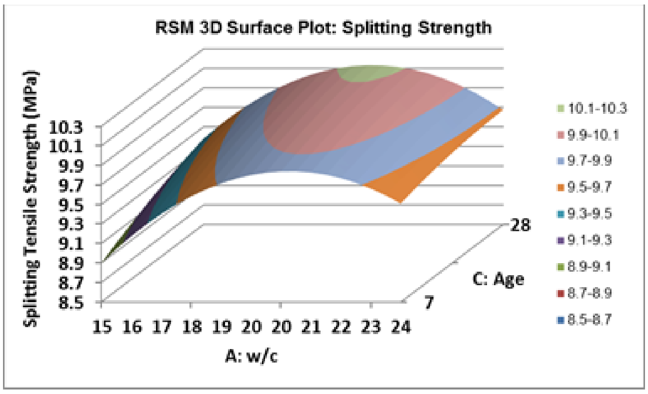


Figure (27): Three dimension RSM maximum splitting response surfaces for autoclaved cured RPC between w/c and age

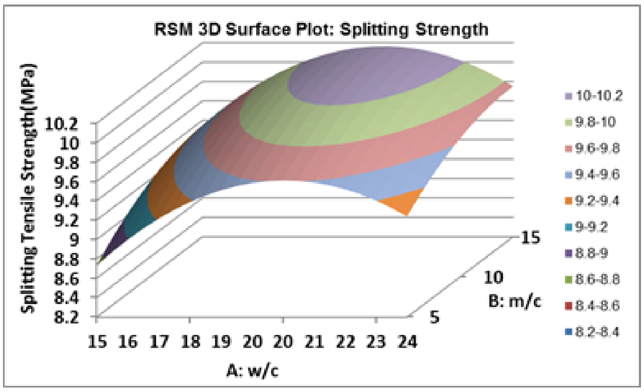


Figure (28): Three dimension RSM maximum splitting response surfaces for autoclaved cured RPC between w/c and m/c.

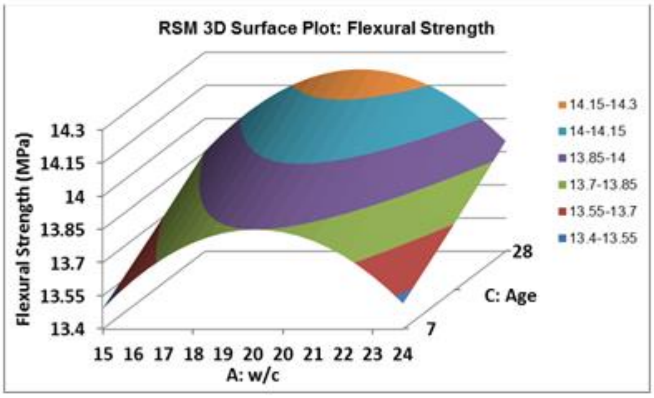


Figure (29): Three dimension RSM maximum flexural response surfaces for autoclaved cured RPC between w/c and age.

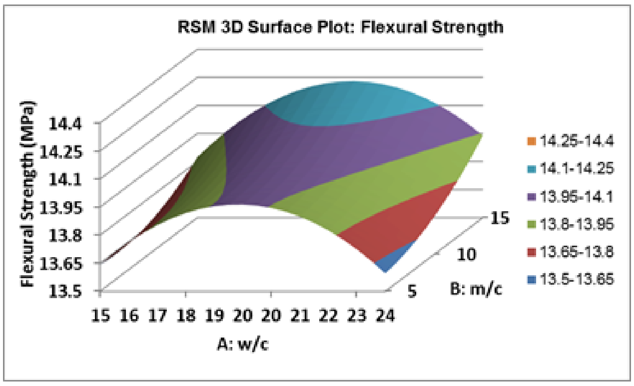


Figure (30): Three dimension RSM maximum flexural response surfaces for autoclaved cured RPC between w/c and m/c.