Mechanical Characteristics of Reactive Powder Concrete

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Abstract. Reactive Powder concrete has become one of the most important types of concrete due to its perfect features in terms of strength and durability, in addition to its small sections compared to regular concrete, which provides enormous possibilities for multiple applications. The mechanical properties of different mixtures of this concrete were tested in this study. They included many variables, namely three types of pozzolanic materials and two types of reinforcing fibers, in addition to three percentages of fiber content. The effects of variables, such as the type of fibers and the type of pozzolanic materials, had a greater impact on the mechanical properties of these mixtures. All mixes at the early ages, showed high compressive strength values, because of the specimens' curing process using steam. Mixtures that contain micro-silica with steel fibers have a high compressive strength at early ages, reaching 118 MPa, while those containing propylene fibers reach 115 MPa. The mixtures containing silica showed higher results at 28 days of age than those containing micro-silica. Compressive strength values with steel fibers reach 195 MPa and 187 with polypropylene fibers. Mixes containing meta-kaolin gave lower results. For the second variable, the type of fiber, the mixtures containing steel fibers gave higher compressive strength results than those containing polypropylene fibers, at a rate of up to 5%. Changing the percentage of fiber content in the mixtures also led to a change in the compressive strength results in all mixtures, with varying percentages of up to 6%. The effect of the three variables on the density obtained for the mixtures was low. The highest density obtained was 2510 kg/m3 for Mix S9, while the highest density was 2398 kg/m3 for Mix P3. The highest absorption reached 0.56% at 3 days of age for mixture P3, and the lowest absorption at the same age was 0.18% for mixture S7, where the difference reached 60%.

Keywords: Reactive powder concrete; Mechanical properties; steel Fiber; polypropylene fiber; Meta-kaolin; Silica Fume**.**

1. INTRODUCTION

RPC is the latest generation of UHPC "Ultra High-Performance Concrete" is characterized by superior ductility and high durability [1]. This type of concrete requires good knowledge of its mechanical properties to be used appropriately in construction work [2]. It has become a new material with good construction progress. It is distinguished by the fact that it consists of a high percentage of cement versus a low percentage of water, which leads to high strength and durability, which qualifies it as ideal in construction applications [3]. It is used in applications that require strong structures and better use of building materials due to its superior strength and high performance [4]. The mineral admixture used as an essential component of RPC has great importance as it binds other materials to form a highly-strength solid concrete [5]. The use of mineral additives, especially silica fume, due to its pozzolanic properties and superior ability to fill leads to strong bonds between the components, which gives RPC outstanding durability [6].

Based on its superior structural performance RPC is often known as "Ultra High Performance Concrete), as it contains high percentages of cement "800-1000 kg/m^3", mineral additives such as silica fumes, and small-sized aggregates of up to 600 micrometers. In addition to plasticizers and reinforcing fibers, it is characterized by the absence of rough materials [7]. The physical properties of RBC concrete are greatly affected by the materials used in its production. Therefore, researchers conducted many studies to demonstrate the effect of changing these components on the properties of the produced concrete. This type of concrete is greatly affected by its contents, including the percentage of fibers. This fiber is usually added as a percentage by volume. Increasing the proportions of these fibers leads to improvements in RPC properties, especially elasticity, modulus of rupture, and split tensile strength [8, 9]. In her research, Hanafiah [10] used silica fumes as a pozzolanic material in addition to steel reinforcement fibers with a ratio of “w/c = 0.23”. She focused on the curing method for concrete models, where different temperatures were used in curing the specimens. The results indicated that using high temperatures in curing concrete models, which reaches 90º degrees leads to high specifications, especially in compressive and tensile strength. Selvi [11] used fly ash as a pozzolanic material in the production of RPC at rates of up to 15%. The results showed that adding fly ash also leads to an improvement in the properties of fresh and dry concrete, in addition to improving compressive strength in general. Sultan [12] used in his study the dolomite material to produce high-performance concrete and achieved compressive strength values of up to 134 MPa. He also confirmed the effect of the fine aggregate and silica fumes on the tensile, compression, and dry shrinkage strength of RPC.

This study conducted an experimental investigation to study the mechanical properties of RPC by using different variables in producing such concrete. The study used three different types of pozzolanic materials, (micro-silica, silica-fume, and meta-kaolin). Another variable adopted in this study was the type of fiber used. Two types of fibers (steel and polypropylene) with three percentages of each type of fiber were used as a third variable. Accordingly, 18 different mixes were adopted in this study in addition to a reference mix and a special mix to find the right dosage of superplasticizer. The main specimens taken from each mix were 3 cubes of 50 mm for each test. The main tests adopted were Compressive strength, absorption, and density. The study adopted a unique process for curing the specimens. The specimens were cured by steam for 48 hours. This process led to high features, especially for compressive strength, which exceeded 190 MPa for some mixes.

2. Experimental Work

As mentioned before many variables were adopted to produce different mixes of RPC. The first one is three different kinds of pozzolanic admixtures. The second was two kinds of reinforced fibers and the third one was the content percentage of the fibers, which was (0.75%, 1.0%, or 1.25%). The overall mixes were 18 mixes.

The properties of the materials used in the RPC mixes are described in the following sections together with specifying their mix proportions.

2.1 Materials

2.1.1 Cement

The cement used was sulfate resisting with chemical contents comply with ASTM specifications [14], as in Table 1.

Table 1: Chemical Components of Cement.

Composition	Content	ASTM Specification
MgO	2.09	≤ 6.0 %
Al2O3	3.50	-
CaO	62.54	-
Fe2O3	4.88	-
I.R.	0.59	≤ 0.75 %
SO3	2.02	≤ 2.3 %
SiO2	22.25	-
L.O.I.	1.41	≤ 3.0 %

2.1.2 Sand

The sand was from Al-Ekhaider, its maximum size was 4.75mm. It was separated to achieve super fine sand of 600µm using special sieves. The sieved sand complies with B.S. specification [15], as in Table 2.Table 2: Sand Grading According to B.S. Specifications

Sieve No.	Passing% as Cumulative	B.S. Specification
4.75	100	89-100
2.36	89	60-100
1.18	78	30-100
0.600	61	15-100
0.300	18	5-70
0.150	7	0-15

2.1.3 Fibers

Steel and polypropylene fibers were used in producing RPC in this study. Tables 3 and 4 show the properties of steel and polypropylene fiber respectively.

Table 3: Steel Fiber Properties.

S.G (kg/m^3)	Length (mm)	Diameter (mm)	T strength (MPa)	E (GPa)
7850	12	0.18	1700	220

Table 4: Polypropylene Fiber Properties.

Length (mm)	Diameter (µm)	Tensile strength (MPa)	E (MPa)
12	19	330-400	3500-3900

2.1.4 Pozzolanic admixtures

Micro-silica, silica-fume, and meta-kaolin were the pozzolanic admixtures. Tables (5, 6, and 7) show the properties of Meta-kaolin, Micro Silica, and Silica fume respectively.

Table 5: Physical Properties of Meta-kaolin (MK).

Physical Properties	MK	Pozzolan Class N
Specific Gravity	2.62	5% Max.
Surface Area (Blaine Method) cm^2/gm	19000	–
Pozzolanic Activity Index	152.7	75

Table 6: Physical Properties of Micro-Silica

Physical Properties	Micro silica	Specification Requirement ASTM C 1240
Retained on sieve No. 325	8	10 % Max.
Activity Index	198	105 % Max.
Specific Surface (m^2/g)	18	15 Min.

Table 7: Chemical Compositions of Silica Fume (SF)

Composition (%)	Silica fume
SiO_2	98.87 %
Al_2O_3	0.01%
Fe_2O_3	0.01 %
CaO	0.23 %
MgO	0.01 %
K_2O	0.08 %
Na_2O	0.00 %

2.1.5 Chemical Admixture

RPC mixes. From so many trials it was found that the most compatible type is a combination of Structuro 335 with Structuro 480, as 6.7% and 2.3% of the weight of cement respectively for mixes with steel, and 7% and 2.5% for mixes with polypropylene. The dosage of superplasticizer was increased gradually until reaching the optimum percentage by weight of cement. Table 8 shows the properties of Structuro 335, whereas Table 9 shows the properties of Structuro 480.

2.2 Concrete Mixes

A reference mix in addition to 18 different RPC mixes was tested. Figure 1 shows those mixes.

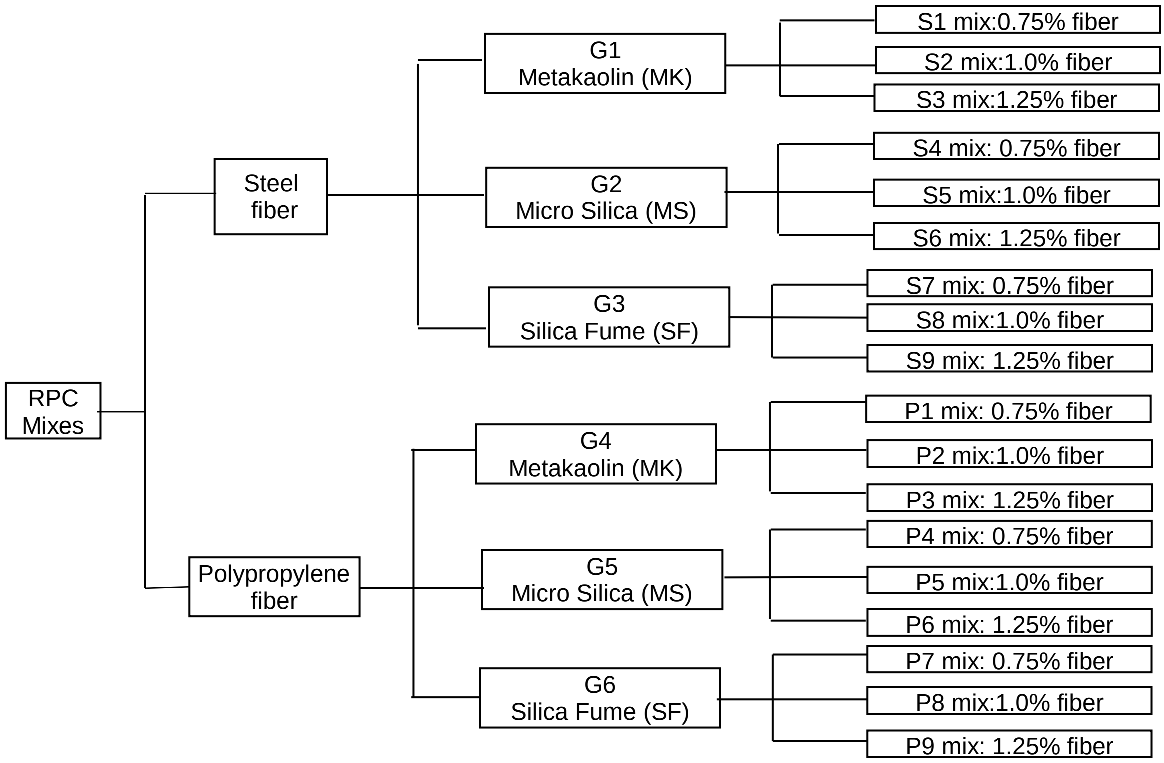

Figure 1: Reference and 18 RPC mixes

Table 8: Typical Properties of Structuro 335.

Appearance	Light yellow colored liquid	Appearance
Volumetric mass	1.06 kg/ltr @ 20C°	Volumetric mass
Chloride content	< 0.1%	Chloride content

Alkali content	Typically less than 1.5 gm	Alkali content

Table 9: Typical Properties of Structuro 480.

Appearance	Opaque liquid	Appearance
Specific gravity	1.01 @ 20C°	Specific gravity
Chloride content	< 0.1%	Chloride content

2.3 Mixing of Concrete

For trial mixes of concrete, a rotary mixer with a small capacity of about 0.01 m3 was used, whereas a bigger rotary mixer with a capacity of about 0.1 m3. The needed quantity of the mineral powder i.e. MK (Meta-kaolin), MS (Micro-Silica), or SF (Silica Fume) was mixed with the needed cement quantity at the dry phase. Then they were mixed with the sand. The superplasticizer was mixed with water before adding it to the dry ingredients. The "flow table test" was used to obtain the required workability, as to comply with the ASTM specification [16]. Figure 2 shows some of the devices used in the laboratory.

Figure 2: devices used in different steps to produce the RPC

2.4 Casting and Curing

All molds were cleaned and their internal surfaces were oiled to prevent adhesion to concrete after hardening. Different curing regimes can be adopted to study the RPC characteristics. Among these curing regimes, the steam was used for 48 hours at 90°C, and a humidity rate of up to 95%. After preliminary curing at 20˚C for 24 hours all specimens were placed in tanks specially made for this purpose, to be strong enough to withstand continuous heating for 48 hours. These tanks were filled with water to a specific level without touching the specimens, the latter of which were placed on steel tables higher than the water level. The tanks were then tightly covered and allowed to be heated until water began to evaporate then they were quickly opened and the specimens were placed inside them, then tightly covered. This operation continued for 48 hours for each group of specimens. After that the specimens were taken out of the tanks and left at room temperature, then put in water to be tested at the required age.

2.5. Concrete Tests

- Compressive Strength Test: Laboratory models were tested at the ages of (3, 7, and 28) days after treatment by steam for 48 hours and then immersion in water until examination. The device used was an Averey-Dension with a capacity of 2000 Newton according to ASTM C109 [17].
- Absorption Test: The cubes (aged 28 days) were dried in the oven at 105 ± 0.5. After 72±2 hours, they were covered with nylon paper, and placed in water. They were then dried and weighed after immersion to calculate absorption as follows B.S.1881 [18]:

$$\text{Total absorption (\%)} = \left[\frac{w_2 - w_1}{w_1}\right] \times 100 \qquad \text{……………………. (1)}$$

where: w_1: the dry specimen's average weight (g).
w_2: the wet specimen's average weight (g).

- Density: Density was determined by dividing the dry weight of the air-dried specimen by its volume (50 mm).

3. Results and Discussion

3.1 Calibration of Superplasticizer Dosages

Different dosages of superplasticizers were used to obtain the optimum dosage. The results show that the optimum quantity of HRWRA was 6% by weight of cement. On the other hand, the dosages of HRWRA for Reactive Powder Concrete mixes that contain different mineral admixtures (Mk, MS, or SF) and one type of fiber (polypropylene or steel), should be increased to achieve the same workability at the same water cement ratio (i.e. same flow). The maximum optimum quantity of superplasticizer used for RPC mixes that contain steel fibers, was for the S1 mix (56.5%). The minimum quantity was (52.5%) for mix S9 whereas for mixes with Polypropylene, it was (56%) for P1, and (52.5%) for P9.

The results indicated that the reference mix needed just 6% by cement weight, whereas the RPC mixes that contained steel fiber needed about 9%, and those with polypropylene fiber needed about 9.5%

3.2 Compressive Strength

Tables 10 and 11 show the results of the compressive strength tests for all RPC mixes. Figure 3 and Figure 4 show the compressive strength of steel and polypropylene Fiber Mixes.

Table 10: Compressive Strength at 3, 7, and 28 Days Age of RPC with Steel Fibers.

Mix	Steel Fiber	w/c	Compressive Strength - MPa		
			Age 3days	7 days	28 days
Ref.	-----	0.4	38	60	75
HRWRA mix	-----	0.17	59	75	105
S1	0.75%	0.174	86	100	146
S2	1%	0.178	88	103	151
S3	1.25%	0.179	89	106	155
S4	0.75%	0.174	112.5	119	164
S5	1%	0.176	115	123	168
S6	1.25%	0.180	118	129	173
S7	0.75%	0.186	97	120	188
S8	1%	0.189	98	122	191
S9	1.25%	0.19	101	125	195

Table 11: Compressive Strength at 3, 7, and 28 Days Age of RPC with Polypropylene Fibers.

Mix	Polypropylene Fiber	w/c	Compressive Strength - MPa		
			Age 3days	Age 7days	Age 28 days
Ref.	-----	0.4	38	60	75
HRWRA	-----	0.17	59	75	105
P1	0.75%	0.175	84.5	99.5	144
P2	1%	0.18	84	99.5	143
P3	1.25%	0.183	84	99	144
P4	0.75%	0.175	111.5	117.5	162
P5	1%	0.178	111	117.5	162
P6	1.25%	0.183	111.5	117	161.5
P7	0.75%	0.187	94	118	186.5
P8	1%	0.189	93.5	118	186
P9	1.25%	0.19	94	118	187

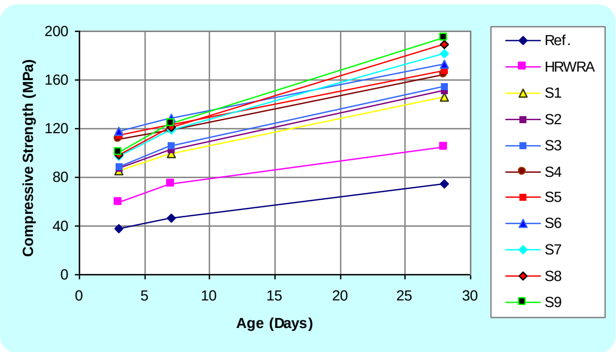

Figure 3: Compressive Strength for Steel Fiber Mixes

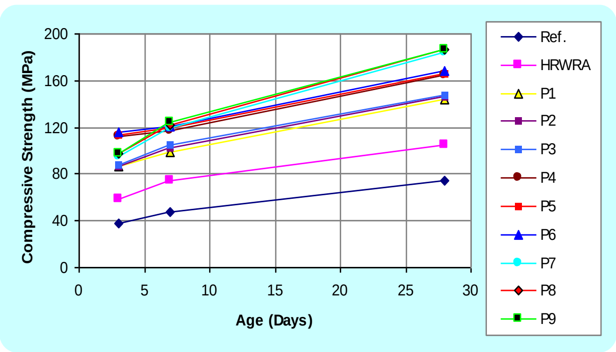

Figure 4: Compressive Strength for Polypropylene Fiber Mixes

Results indicated that compressive strength at 28 days for the S9 mix was 195 MPa, and 187 MPa at the same age for the P9 mix.

As reviewing the results, it can be seen that all mixtures show a rapid increment in compressive strength at an early age. The reason is the high cement content and low water percentage, in addition to the presence of plasticizers, which consequently leads to a significant development of compressive strength. After that, the compressive stress tends to increase regularly. Steam curing also has an important effect on concrete strength. It produces a stabilized RPC, which has gained its final mechanical properties through curing. The improvement is related to the densified microstructure of the cement [19].

- Effects of the type of pozzolanic admixture

The results indicate that mixes of silica-fume had the maximum compressive strength values compared with that contained meta-kaolin or micro-silica. Figures 5 and 6 show the effect of the type of mineral admixtures for mixes with steel and poly-propylene fibers respectively. The compressive strength results for P1, P4, and P7 which contained polypropylene fibers of 0.75%, showed that P7 had the maximum value, which was 186.5 MPa at the age of 28 days. Where P1 and P4 reached values of 105 and 144 MPa respectively. The same comparison can be made for other mixes. The results indicate that meta-kaolin always gives minimum values for compressive strength at different ages, where micro silica gives high values in the early days, then at the age of 28 days, its value was less than the value gained with silica fume. It can be seen that all Groups of mixes exhibited the same behavior. The type of pozzolanic material had the same effect on RPC mixes which contain polypropylene fibers, as shown in Figure 6

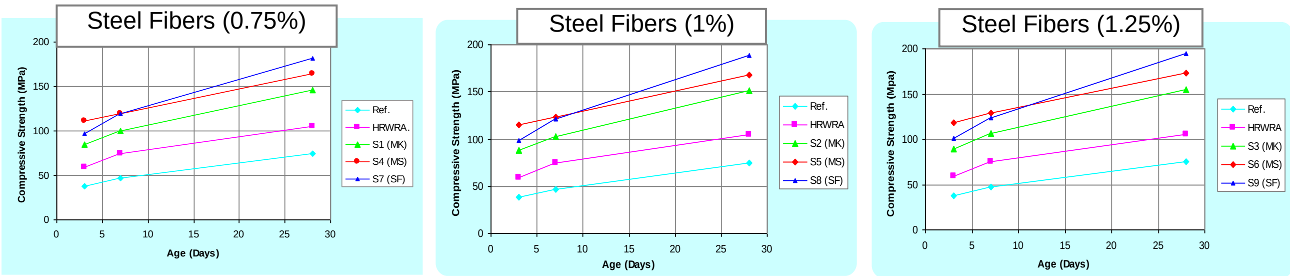

Figure 5: Effects of Mineral Admixture on Compressive Strength of RPC of Steel Fibers

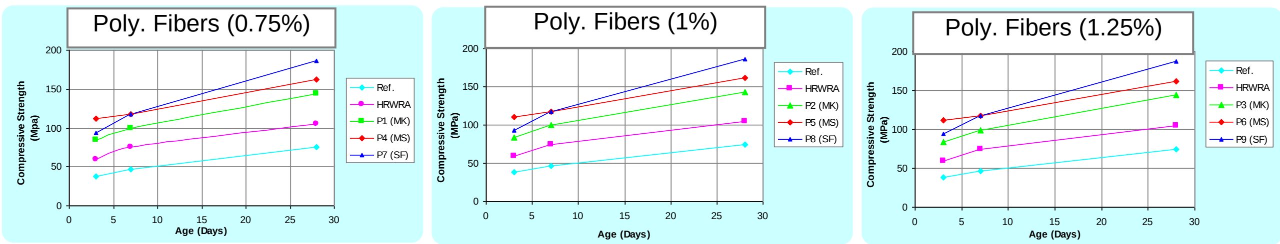

Figure 6: Effects of Mineral Admixture on Compressive Strength of RPC of Polypropylene Fibers.

- Effects of Fiber Content:

The results of the compressive strength tests for the different RPC mixtures, mentioned in Tables 10 and 11, clearly indicate that the compressive strength is not significantly affected by changing the percentage of reinforcement fibers used. This is what we see in all mixtures. For example, changing the percentage of fibers in the mixtures (P1, P, and P3) from 0.75 to 1%, then 1.5%, respectively, led to obtaining values of 144, 143, and 144, respectively, for compressive resistance at 28 days age.

The same thing is evident in the rest of the mixtures. Figures 7 and 8 show this effect. The results also show that the difference is relatively clearer when using steel fibers than polypropylene fibers.

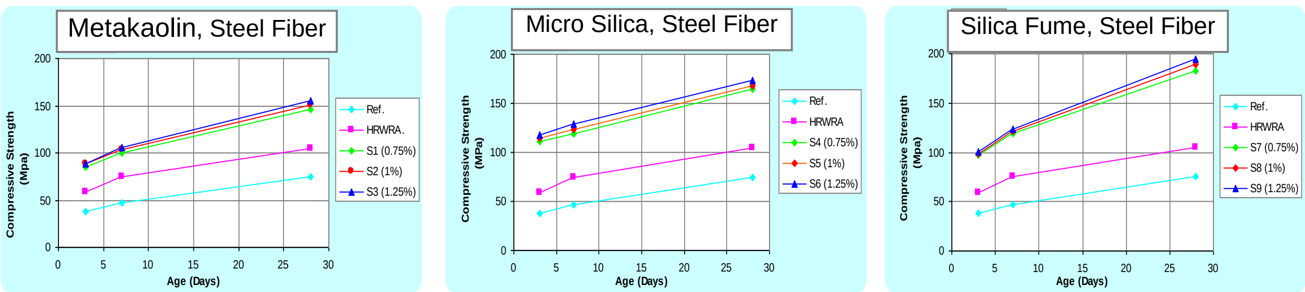

Figure 7: Effect of Volume Fraction of steel fibers on Compressive Strength of RPC Mixes

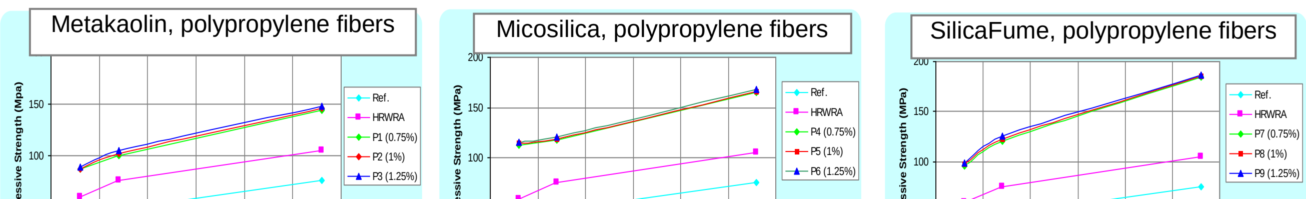

Figure 8: Effect of Volume Fraction of Polypropylene Fibers on Compressive Strength of RPC Mixes.

- Effects of Fiber Type

The effect of the type of fiber also does not lead to significant differences in the results, this is clear from the results of laboratory tests. The compressive strength, in general, is not affected by changing the proportions of fibers and does not change by changing the type of fibers except in small proportions. The important note here is that steel fibers have a greater effect than polypropylene fibers, and this is because they are an inherently weak material, in addition to the fact that their addition causes a decrease in workability and also an increase in the air trapped inside the concrete, in addition to segregation and bleeding. Accordingly, higher content of it produces a concrete with lower unit weight and may lead to a decrease in compressive strength. Figures 9, 10, and 11 illustrate the effect of fiber type on the RPC mixes compressive strength.

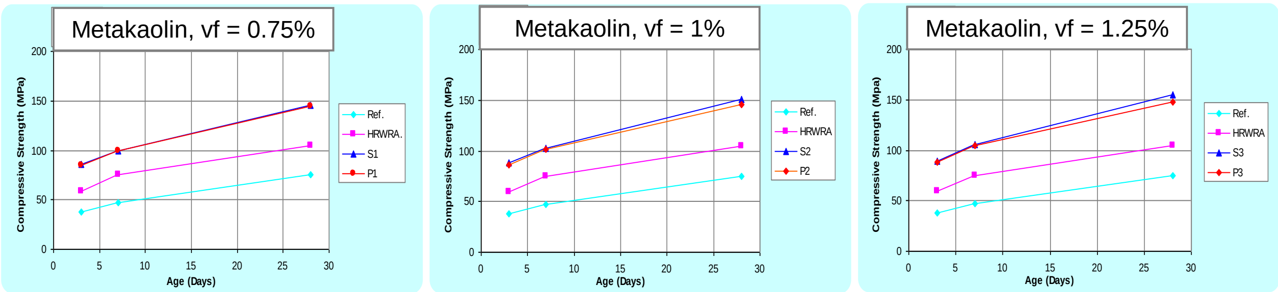

Figure 9: Effects of kind of Fibers on the Compressive Stress of RPC with Meta-kaolin.

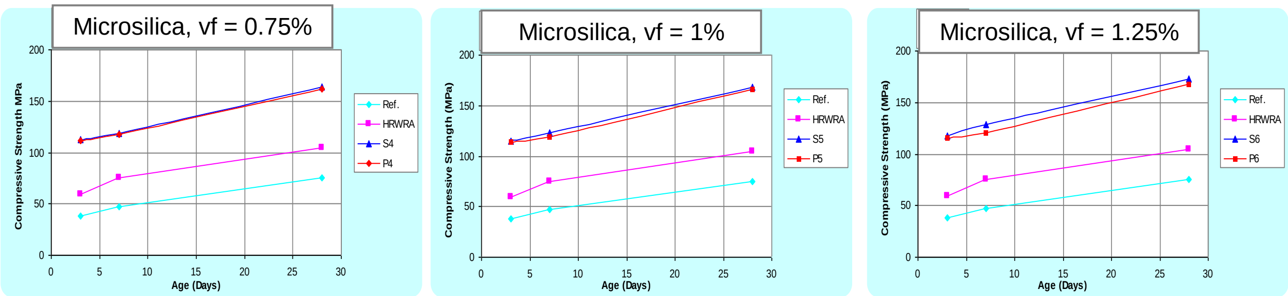

Figure 10: Effects of kind of Fibers on the Compressive Stress of RPC with Micro-silica.

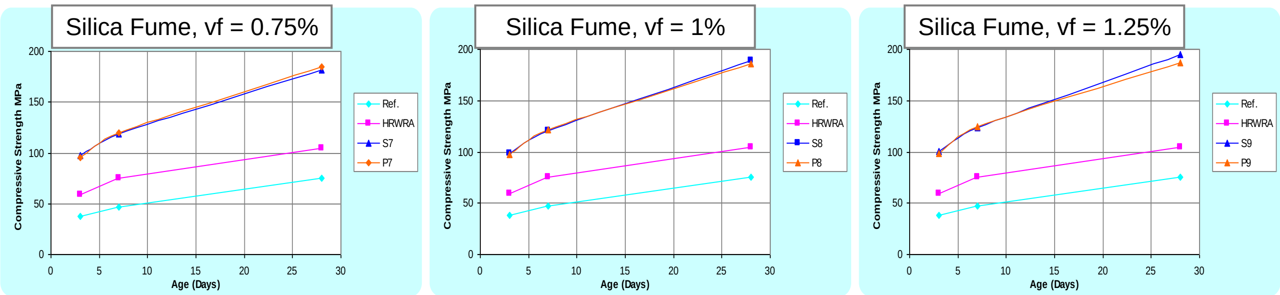

Figure 11: Effects of kind of Fibers on the Compressive Stress of RPC with Silica Fume.

3.3 Absorption

Tables 12 and 13 show the laboratory results of the absorption test for RPC mixtures at 7 and 28 days of age. The results indicate that the absorption of all mixtures is significantly less than the absorption of the reference mixture. The reason is that the size of the pores in these mixtures is too small, due to the reaction occurring in the presence of superplasticizers and highly effective pozzolanic materials.

- Effects of the type of pozzolanic admixture

The results showed that RPC mixtures with silica fume showed the lowest absorption rate compared to RPC mixtures that contain either meta-kaolin or micro-silica (with the same fiber and volumetric ratio). Mixtures with micro-silica were more absorbed, moreover, mixtures with meta-kaolin had the greatest absorption compared to other mixes. This is because the silica particles are so fine compared to other pozzolanic materials.

- **Effects of Fiber Content**

It can be noticed from the laboratory results that the mixes with a high content of fibers showed higher values of absorption. That is because the mixes with more fibers need more water for workability.

- **Effects of Fiber Type**

One of the properties of propylene fibers is porous which makes it absorb water. Because of this property, the results indicate that polypropylene mixtures have greater absorption than those containing steel fibers.

Table 12: Percentage Absorption at 7&28 Days Age, and Density for Mixes with Steel Fiber.

Mix	**Steel Fiber**	**w/c or W/Cementous**	**Absorption %**		**Density (kg/m^3)**
			7 days	**28 days**	
Ref.	-----	0.4	1.4	1.1	2365
HRWRA mix	-----	0.17	0.9	0.7	2378
S1	0.75%	0.174	0.3	0.23	2440
S2	1%	0.178	0.44	0.27	2458
S3	1.25%	0.179	0.49	0.33	2475
S4	0.75%	0.174	0.29	0.17	2455
S5	1%	0.176	0.32	0.2	2469
S6	1.25%	0.180	0.37	0.31	2481
S7	0.75%	0.186	0.18	0.11	2470
S8	1%	0.189	0.22	0.14	2485
S9	1.25%	0.19	0.25	0.2	2510

Table 13: Percentage Absorption at 7&28 Days Age, and Density for Mixes with polypropylene Fiber

Mix	**polypropylene Fiber**	**w/c or W/Cementous**	**Absorption %**		**Density kg/m^3)**
			7 days	**28 days**	
Ref.	-----	0.4	1.4	1.1	2365
HRWRA mix	-----	0.17	0.9	0.7	2378
P1	0.75%	0.175	0.45	0.27	2399
P2	1%	0.18	0.5	0.3	2400
P3	1.25%	0.183	0.57	0.39	2398
P4	0.75%	0.175	0.39	0.23	2440
P5	1%	0.178	0.46	0.29	2441
P6	1.25%	0.183	0.52	0.37	2440
P7	0.75%	0.187	0.3	0.19	2449
P8	1%	0.189	0.39	0.25	2448
P9	1.25%	0.19	0.45	0.33	2450

3.4 Density Results

Tables 12 and 13 show the density results. The results indicated a clear difference in the density value of the different mixtures, ranging from 2380 to 2520 kg/m3. This is normal due to the different components of the mixtures. In general, the densities of all mixes are greater than those of the Ref. mix and HRWRA mix. The high density of any RPC mix is due to the reduction in w/cement ratio caused by adding superplasticizer, which means lower porosity and higher density.

- Effects of the type of pozzolanic admixture

Results illustrate that the density of mixes containing silica fume is higher than those containing other pozzolanic materials, because of its fine particles.

- Effects of Fiber Content

The results indicate that increasing the fiber content in general leads to increasing the density, and this is due to the fiber density. However, the fibers differ from each other in density, as the propylene fibers are low, which leads to a decrease in the density of the mixture as the propylene fibers increase, and this is the opposite of mixtures containing steel fibers.

- Effects of Fiber Type

Looking at the results, it can be inferred that mixtures containing iron fibers gave high-density results, in contrast to polypropylene fibers, in which the density of the mixture decreases due to the lower density of those fibers. Figure 12 shows the relationship between compressive strength and density of different RPC mixes. It is also clear from the results that the denser mixtures, especially those containing steel fibers, also have a high compressive strength.

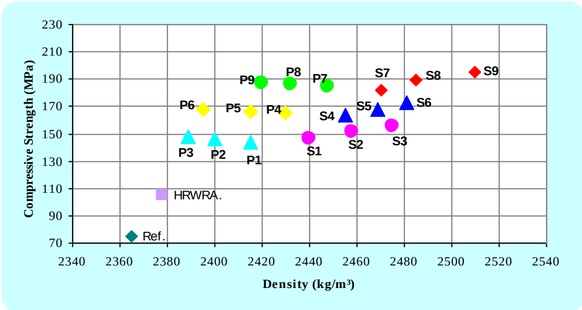

Figure 12: Correlation between Compressive Strength and Density for Different RPC Mixes.

4. Conclusions

- It was found that the best type of HRWRA was a combination of 6.7% Structuro with 2.3% Structuro 480 for RPC mixes containing steel fibers. RPC mixes with polypropylene fibers the same combination was used but at 7% for Structuro 335 and 2.5% for Structuro 480.
- For mixes containing steel fiber adding HRWRA at optimum dosages led to water reduction of high values ranging between 52.5% for S9 mix (RPC mix with SF and steel fibers of 1.25%) to 56.5% for S1 mix (RPC mix with MK and steel fibers of 0.75%) relating to reference mix.
- For mixes containing polypropylene fiber adding HRWRA at optimum dosages led to water reduction of high values ranging between 51.8% for P9 (RPC mix with SF and polypropylene fibers of 1.25%) to 55% for P1 mix (RPC mix with MK and steel fibers of 0.75%) relating to reference mix.
- All mixtures with various variables gave high values of compressive strength at the early ages, as a result of the curing process for the specimens using steam.
- All mixtures showed high compressive strength values, with differences in these values in the different mixtures due to variables in their components. Mixtures that contain micro-silica with steel fibers have a high compressive strength at early ages, reaching 118 MPa, while those containing propylene fibers reach 115 MPa. The mixtures containing silica showed higher results at 28 days of age than those containing micro-silica. Compressive strength values with steel fibers reach 195 MPa and 187 with polypropylene fibers. The mixtures that contained meta-kaolin gave lower results.
- Regarding the second variable the type of fiber, the mixtures containing steel fibers gave higher compressive strength results than those shown by the mixtures containing polypropylene fibers, at a rate of up to 5%.
- Changing the percentage of fiber content in the mixtures also led to a change in the compressive strength results in all mixtures, with varying percentages of up to 6%.
- The effect of the three variables on the density obtained for the mixtures was low. The highest density obtained was 2510 kg/m3 for Mix S9, while the highest density was 2398 kg/m3 for Mix P3.
- The effect of variables used in the various mixtures was clear in the absorption results. The highest absorption reached 0.56% at 3 days of age for mixture P3, and the lowest absorption at the same age was 0.18% for mixture S7, where the difference reached 60%.

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