Misan Journal of Engineering Sciences ISSN-E: 2957-4250
Vol. 2, No. 1, October 2023 ISSN: 2957-4242

Experimental Study on The Effect of Size, Type, and Replacement Ratio of Recycled Aggregate on The Mechanical Properties of Reactive Powder Concrete

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(Received 14 Aug, Revised 22 Aug, Accepted 22 Aug)

Abstract: This paper presents an experimental investigation of the mechanical characteristics of Reactive Powder Concrete (RPC) and Recycled Aggregate Reactive Powder Concrete (RPC-RA), utilizing two types of recycled aggregate (RA), recycled concrete aggregate (RCA), and recycled concrete brick aggregate (RCBA) as alternative aggregates. A series of sixteen RPC and RPC-RA mixes were prepared and tested. A reference RPC mix without RA was tested to determine the maximum compressive strength of 128.17 MPa, the tensile strength of 15.56 MPa, and the flexural strength of 25.90 MPa. Then, the study examines twelve different mixes of RPC-RA, each with RCA with maximum particle sizes of 0.6, 1.18, 2.36, and 4.75 mm and replacement ratios of 20%, 40%, and 60%, to study the effects of varying replacement ratios of the RCA and various maximum particle sizes. Additionally, three mixes of RPC-RA are investigated using RCBA with a maximum particle size of 0.6 mm and replacement ratios of 20%, 40%, and 60%. The use of RA resulted in various percentages of reduction in compressive, splitting, and flexural strength, as shown in the results of the study.

Keywords: Reactive Powder Concrete, Recycled Aggregate, Crushed Concrete Aggregate, Crushed Concrete with Brick Aggregate, Sustainable RPC.

1. Introduction

As concrete is one of the most important materials used in construction work around the world [1], researchers have tried for many years to produce a new type of concrete characterized by unusual specifications with very high resistance and durability and can be operated and used on work sites at a low cost. Reactive powder concrete (RPC) is one of the most significant types of concrete. It is also referred to as ultra-high-performance concrete (UHPC) due to its superior characteristics and high resistance [2]. RPC has excellent mechanical properties. It contains a silica fume-cement mixture with superplasticizer, steel of fiber, and ratio of water to cement (w/c) that is low, it is distinguished by the existence of very small particles of sand (600 μm) instead of typical aggregate [3]. The first researcher who produced this type of concrete was Pierre Richard with Marcel Cheyrezy in 1994 [4]. The construction industry is one of the most responsible economic sectors for working with natural resources and producing waste. Construction and demolition processes involving the use of concrete contribute significantly to recycling accumulation. Each year, thousands of tons of concrete are produced worldwide [5]. Masood et al. (2012) [6] estimated that every year, the amount of concrete demolition waste in the United States and the European Union reaches 100 million tons. Given the high costs of transportation and disposal and a lack of suitable sites for receiving these materials. These huge quantities of waste are presently one of the greatest challenges and concerns in the construction industry. The recycling of concrete waste by pulverizing and grinding it to a classification similar to that of regular sand and producing an alternative aggregate for RPC is an option for responding to these problems. Recycled reactive powder concrete (RRPC) containing this recycled concrete aggregate is accepted internationally. Chkheiwer and Kadim (2019) [7] The availability of the proposed materials in the local market helps to conclude a better cost and higher economic concrete. To assess their effects on concrete compressive strength, the study examined curing processes, sand particle size distribution, binder type and ratio, and steel fiber content. The curing technique, which required 5 days

and consisted of 2 days at 60 °C and 3 days at 80 °C, had the maximum strength compared to other approaches. Smaller sand particles, silica fumes, and steel fibers increase compressive strength significantly. The analyzed factors' effects on concrete compressive strength were shown by many correlations. Mirjana et al. (2010) [8] Using different percentages of recycled and natural coarse aggregate replacements, experimental results were compared for newly mixed and cured concrete. Three concrete combinations were tested. The primary characteristics of hardened concrete were investigated using 99 different samples. In this experimental work, recycled aggregate concrete performed similarly to reference concrete regardless of the replacement ratio. Recycled aggregate quality determines concrete compressive strength. When fresh concrete is made from crushed high-strength concrete aggregate. Compressive strength was unaffected by recycled coarse aggregate. Concrete's flexural and splitting tensile strengths are similar. Togay Ozbakkaloglu et al. (2018) [9] Compression characteristics, elastic modulus, flexural resistance, splitting tensile strength, work, shrinkage, and water absorption for concrete compositions using recycled aggregates of various sizes and concentrations were examined. Fourteen RAC samples were made. Recycled aggregate replacement, coarse aggregate size, and mixing technique are examined. Results show that RAC mechanical and durability qualities were affected more than compressive strength. The coarse aggregate size and content influence RAC mixtures of the same compressive strength.
The aggregate occupies about three-quarters of the volume of concrete and thus can be expected to have an important influence on its properties [10]. Therefore, the main purpose of this study is to preserve the natural resources of aggregate and to make the work easier and more economical by using RA to produce modified RPC but, crushing RCA and RCBA to get a maximum particle size of 0.6 mm is very difficult to implement and expensive. So, to obtain a more economical, practical, and easy to apply mix, several mixes will be produced by replacing (20, 40, and 60%) proportions of RCA with different sizes (1.18, 2.36, and 4.75 mm) and types (RCA and RCBA) to produce RPC-RA concrete with high resistance and durability at a lower cost while preserving the environment and its resources.

2. Experimental program:

The objectives of the experimental work were to investigate the mechanical properties of sixteen RPC and RPC-RA specimens that were prepared and tested. The parameters that affect the mechanical properties of specimens are the replacement percentage of RCA with various maximum particle sizes and two types of RA. The experimental work was carried out in the Structure Lab of the Department of Civil Engineering, University of Basrah.

2.1 Materials

The following parts describe the characteristics of cement, aggregate, steel fiber, silica fume, and high-range reduction of water admixture. The concrete specimens were mixed and cured using potable water. All the tests of the used materials were conducted according to ASTM and Iraqi specifications.

2.1.1 Cement

Iraqi Portland cement was used, and all physical and chemical tests of the cement were carried out according to Iraqi standard specifications (IQ.S. No. 5/1984) [11]. The chemical analysis and physical test results of the used cement are shown in Tables 1 and 2, respectively.

Table 1 Chemical Analysis of Cement Compounds

Oxide Composition	Abbreviation	Content%	Limit of IQ.S. No.5/1984
Lime	CaO	61.39	
Silica	SiO_2	17.36	
Alumina	Al_2O_3	3.28	
Iron oxide %	Fe_2O_3	3.09	0.5-6
Lime Saturation Factor	L.S. F	0.94	0.66-1.02
Magnesia %	MgO	3.1	5% Max
Sulfate %	SO_3	1.8	2.85% Max
Loss on ignition	L.O.I.	2.25	4% Max

Insoluble Residue%		I.R.	1.2	1.5% Max
Main Compounds	(Tricalcium Silicate)	(C_3S)	47.62	
(Bogue's Equation)	(Dicalcium Silicate)	(C_2S)	22.91	
	(Tricalcium Aluminate) %	(C_3A)	2.5	3.5 % Max
	(Tetracalcium aluminoferrite)	(C_4AF)	12.52	

Table 2 Cement's Physical Characteristics

Properties		Test result	limits of IQ.S. NO. 5/1984
specific surface area (Blaine method) (cm^2/g)		330	≥ 230
(Setting time)	(Initial min.)	120	≥ 45
	(Final min.)	240	≤ 600
(Compressive strength) MPa	3 days	22.86	>15
	7 days	27.45	> 23

2.1.2 Aggregate

Two types of aggregates were used, as follows:

2.1.2.1 Fine Natural Aggregate (FNA)

Natural fine aggregate was used in the production of mixes. Very fine sand with a maximum size of 600 µm was used. The sand classification shown in Tables 3 and 4 was found to be following Iraqi specification requirements (IQ.S. No. 45/1984) [12].

2.1.2.2 Recycled Aggregate (RA)

Two types of Recycled Aggregate with different replacement ratios (20, 40, and 60 %) were prepared by manually crushing:

1. RCA, old concrete cubes were sieved by four sieves with sizes of (0.6, 1.18, 2.36, and 4.75 mm).
2. RCBA (old concrete cubes 50 % and brick 50 %) was sieved with a sieve size of 0.6 mm only.

2.1.3 Silica Fume

Densified silica fume, known commercially as MegaAdd MS (D) from CONMIX Company, was used as a partial replacement for cement in this research. Table 5 lists the properties of the silica fume that conforms to both the physical and chemical requirements stated in ASTM C1240-20 [13].

Table 3 Grading of FNA

Sieve Size (mm)	Passing% FNA	Limits of IQ.S.No.45/1984, Zone 4
4.75	-	95-100
2.36	-	95-100
1.18	-	90-100
0.6	100	80-100
0.3	45	15-50
0.15	11	0-15

Table 4 Properties for FNA

Properties	FNA	Limits of IQ.S. No.45/1984
Physical Properties		
Fineness Modulus	2.39	
Bulk Density kg/m^3	1662	
Specific gravity	2.62	
Absorption %	1.5	
Chemical Properties		
Sulfate content %	0.25	≤ 0.5%

Table 5 Properties of Silica Fume*

Properties	
The state	sub-micron powder
The color	(Grey - medium Grey)
Specific Gravity	(2.10 - 2.40)
Bulk Density Kg/m^3	(500 to 700)
Chemical Requirements	
(Sio_2)	The minimum is 85%
Moisture Content (H_2O)	The maximum is 3%
Loss on Ignition (LOl)	The maximum is 6%
physical requirements	
specific surface area m^2/g	The minimum is 15 m^2/g
pozzolanic activity index, 7 days	The maximum is 105%
over size particles retained on (45) μm sieve	The maximum is 10%

* Supplied by the manufacturer

2.1.4 Superplasticizer

MasterGlenium54 in this work from BASF Company was used as a water reduction. Its characteristics are listed in Table 6, following ASTM C494/C494M-19 standards [14].

Table 6 The Characteristics of MasterGlenium54*	
chemical base	modified carboxylic ether polymer
appearance The colors	Liquid (White - Yellow)
Density (at +20°C) g/cm^3	1.07
PH value	5-8
Dosage: liters for every 100 kilograms of cement	(0.5-1.75)
storage condition	The storage temperature should be maintained at a minimum of 5°C. To mitigate the effects of evaporation and extreme temperatures, closed containers or storage tanks a re employed.

* Supplied by the manufacturer

2.1.5 Micro Steel Fibers

A significant factor in raising the tensile strength of the concrete is the presence of steel fiber in the RPC. The function of these fibers is to reduce and delay the development of microcracks. Straight short brass-coated gold colored steel fibers that are shown in Fig. 1 were used and the properties shown in Table 7 conform to ASTM A820/A820M-16 [15].

Table 7 Properties of Steel Fiber*.

Description	Length (mm)	Diameter (mm)	Aspect Ratio	Ultimate Tensile Strength (f_t) MPa	Appearance	Cross Section	Density kg/m^3
Straight	13	0.2	65	> 2600	Gold-colored	Round	7800

* Supplied by the manufacturer.

Fig. 1 Micro steel fibers.

2.2 Mix Design

Six groups of mixes have been designed and casted in this investigation to get high compressive strength, tensile splitting strength, and modulus of rupture. The mixed proportions are tabulated in Table 8.
The first group is the reference RPC mix, which is designed using FNA with a maximum particle size of 0.6 mm without replacement (0% replacement). In the specimens of the second to fifth groups, only RCA was used as recycled material with a replacement ratio of 20, 40, and 60%, and the maximum particle size of RCA was 0.6, 1.18, 2.36, and 4.75 mm for these groups, respectively, and FNA had a maximum particle size of 0.6 mm. The sixth group specimens, crushed bricks and crushed concrete RCBA, were used equally, together as RA, all the particles with a maximum size of 0.6 mm and the replacement ratios (20, 40, and 60%). Only the maximum particle size of RCA was increased to 1.18, 2.36, and 4.75 for economic reasons; it was considered the most significant variable in this study. However, the maximum particle size of natural aggregate remains 0.6 mm.

Table 8 Proportions of reference RPC and RPC-RA Mixes.

Materials	Cement kg/m^3	Sand kg/m^3	Recycled Concrete Aggregate RCA kg/m^3	Recycled Brick Aggregate RBA kg/m^3	Silica Fume S.F kg/m^3	Water kg/m^3	Superplasticizer S.P kg/m^3	Steel fibers SF kg/m^3
N-0.6-0	925	925	0	0	231	177	55.5	196
C-0.6-20	925	739	168	0	231	185	55.5	196
C-0.6-40	925	554	336	0	231	194	55.5	196
C-0.6-60	925	370	504	0	231	202	55.5	196
C-1.18-20	925	739	168	0	231	185	55.5	196
C-1.18-40	925	554	336	0	231	194	55.5	196
C-1.18-60	925	370	504	0	231	202	55.5	196

C-2.36-20	925	739	142	0	231	184	55.5	196
C-2.36-40	925	554	284	0	231	191	55.5	196
C-2.36-60	925	370	426	0	231	198	55.5	196
C-4.75-20	925	739	154	0	231	185	55.5	196
C-4.75-40	925	554	308	0	231	192	55.5	196
C-4.75-60	925	370	462	0	231	200	55.5	196
CB-0.6-20	925	739	84	84	231	193	55.5	196
CB-0.6-40	925	554	168	168	231	209	55.5	196
CB-0.6-60	925	370	252	252	231	2۲۳	55.5	196

The symbols designation [(N, C, CB) - (0.6, 1.18, 2.36, 4.75) - (0, 20, 40, 60)] mean:
N, C, CB: Type of the used replacement, N: no recycled material, C: crushed concrete only, CB: crushed concrete and crushed brick, 0.6, 1.18, 2.36, 4.75: Maximum particle size of recycled materials, 0, 20, 40, 60: Replacement ratio of natural aggregate with recycled aggregate.

2.2.1 Mixing Procedure

The mixing process was conducted using a horizontal rotary mixer. The estimated duration of the sequencing procedure is about 15 minutes. Fine sand and silica fume mixed in a dry state. This process was extended for 3 minutes in order to ensure an even distribution of the silica fume powder with the sand particles. Then cement was added to the other dry components and the mix continues for an additional 2 minutes. The superplasticizer was added to the water, the resulting mixture was combined with the dry mix while the mixer rotated. This process is sustained for 5 minutes. During the mixing process, steel fibers were carefully added to the mixture for 5 minutes.

2.2.2 Curing of Specimens

The curing regime, which includes 5 days (2 days at 60° and 3 days at 80°) was applied after 24 hours. After the curing time was completed, the samples were removed from the boiling water and carried for testing.

2.2.3 Testing procedure

Three cubes of (100×100×100) mm were used for each mix. To determine the compressive strength (f_{cu}) of the concrete, a digital compression testing machine with a capacity of 2000 kN, as shown in Fig. 2 is used. The compressive strength test was conducted according to BS EN 12390-3:2019[16]. All the cubes were taken out of curing, and the average value of three cubes for every mix was taken.

Fig. 2 Compressive testing of cubes

An average of three cylinders (100×200) mm was taken to obtain the splitting tensile strength (f_t). This test was conducted according to ASTM C496/C496M-17 [17]. The specimens were subjected to testing using a hydraulic universal testing machine with a maximum capacity of 2000 kN, as shown in Fig. 3. Splitting tensile strength was calculated using the following formula Eq. (1):

$$f_t = \frac{2P}{\pi D_c l} \tag{1}$$

where:
f_t: Splitting strength of tensile (MPa).
P : The applied load (N).
D_c: Cylinder diameter (mm).
l: Length of the cylinder (mm).

Fig. 3 Hydraulic Universal testing machine for splitting tensile strength test

The flexural strength (f_r) of concrete was measured using a (50×50×250) mm prism specimen in accordance with ASTM C293/C293M-16 [18]. Each prism was simply supported using a simple beam with center-point loading using a hydraulic testing device with a (0-95) kN capacity, as shown in Fig. 4. The equation used for the estimation of flexural strength was as follows Eq. (2):

$$f_r = \frac{3PL}{2bd^2} \quad (2)$$

where:
f_r: The flexural strength (MPa)
P: The maximum applied load by the testing machine (N)
L: length of span (mm)
b: average prism width (mm)
d: average prism depth (mm)

Fig. 4 Hydraulic testing machine for the modulus of rupture test

3. Results and discussion

3.1 Mechanical Properties of Concrete

The mechanical properties resulting from compressive strength f_{cu}, modulus of rupture f_r, and splitting tensile strength f_t for all the studied mixes are listed and shown in Table 9. In the reference RPC mix, the first group, the compressive strength is 128.17 MPa, the modulus of rupture is 25.90 MPa and the tensile strength is 15.56 MPa. For all the mixes studied, the compression strength of concrete ranges between 128.17 and 89.33 MPa, the modulus of rupture of concrete ranges between 25.90 and 15.54 MPa, and the tensile strength of concrete ranges between 15.56 and 9.19 MPa.
The value for the relation between the modulus of rupture and compressive strength f_r/ f_{cu} is calculated, the percentage is 20.2 % for the first group. For other groups, when using recycled materials as a fine aggregate, the modulus of rupture ranges from 17.4 % to 22.3 % of the compressive strength.
The value for the relation between the splitting tensile strength and modulus of rupture f_t/ f_r is also calculated, the percentage is 60.1% for the first group. For other groups, when using recycled materials as a fine aggregate, the tensile strength of concrete ranges from 57.8 % to 61.3 % of the modulus of rupture.

Table 9 Mechanical properties of RPC and RPC-RA mixes.

No.	Mix designation	Compressive strength f_{cu} (MPa)	Flexural strength f_r (MPa)	Tensile strength f_t (MPa)	f_r/f_{cu} %	f_t/f_r %	Decrease in f_{cu} %	Decrease in f_r %	Decrease in f_t %
1	N-0.6-0	128.17	25.90	15.56	20.2	60.1	-	-	-
2	C-0.6-20	118.38	24.66	14.46	20.8	58.6	7.6	4.8	7.1
3	C-0.6-40	111.45	23.37	13.52	21.0	57.9	13.0	9.8	13.1
4	C-0.6-60	102.91	21.30	12.57	20.7	59.0	19.7	17.8	19.2
5	C-1.18-20	114.24	23.89	14.17	20.9	59.3	10.9	7.8	8.9
6	C-1.18-40	103.19	22.01	12.97	21.3	58.9	19.5	15.0	16.6
7	C-1.18-60	97.99	20.93	12.19	21.4	58.2	23.5	19.2	21.7
8	C-2.36-20	104.90	23.07	13.46	22.0	58.3	18.2	10.9	13.5
9	C-2.36-40	95.98	20.85	12.45	21.7	59.7	25.1	19.5	20.0
10	C-2.36-60	89.53	19.56	11.53	21.8	58.9	30.1	24.5	25.9
11	C-4.75-20	101.32	22.06	13.19	21.8	59.8	20.9	14.8	15.2
12	C-4.75-40	86.42	19.31	11.83	22.3	61.3	32.6	25.4	24.0
13	C-4.75-60	83.33	18.36	11.07	22.0	60.3	35.0	29.1	28.9
14	CB-0.6-20	108.67	22.44	13.42	20.6	59.8	15.2	13.4	13.8
15	CB-0.6-40	93.33	18.69	10.81	20.0	57.8	27.2	27.8	30.5
16	CB-0.6-60	89.33	15.54	9.19	17.4	59.1	30.3	40.0	40.9

3.1.1 Compressive Strength

Compressive strength is the most important property of hardened concrete, and it expresses the degree of its quality, validity, and other strengths such as tension, bending, and shear improve and increase by increasing the compressive strength and the opposite is true.
The high compressive strength for reference RPC and RPC-RA mixes can be attributed to the effect of superplasticizer (Glenium 54) as a water reduction agent because their low water cementitious ratio gain strength more rapidly than mixes with higher water cement ratio.
The second factor could be attributed to the phenomenon of chemical reactions occurring in pozzolanic materials. The observed phenomenon can be attributed to the significant pozzolanic reaction occurring between silica fume particles and calcium hydroxide, which is released during cement hydration. This reaction leads to an improvement in pore size and grain size, thereby enhancing the microstructure and reducing micro-cracking. Particularly, the application of heat curing to the samples results in a substantial increase in strength. In addition, the effect of steel fiber delays the development of micro cracks.

Fig. 5 shows the compressive strength values for various mixes with different replacement ratios and maximum particle size. The following observations are noted:

3.1.1.1 Effect of Replacement Ratio on Compressive Strength

The compressive strength decreased when replacing fine natural aggregates with RCA at replacement ratios of 20%, 40%, and 60%, respectively. With the maximum particle sizes of 0.6 mm and 1.18 mm for RCA, the compressive strength decreased by (7.6, 13.0, and 19.7%), and (10.9, 19.5, and 23.5 %), respectively. When using RCA with maximum particle sizes of 2.36 mm and 4.75 mm, the compressive strength decreased by (18.2, 25.1, and 30.1%), and (20.9, 32.6, and 35.0%), respectively.

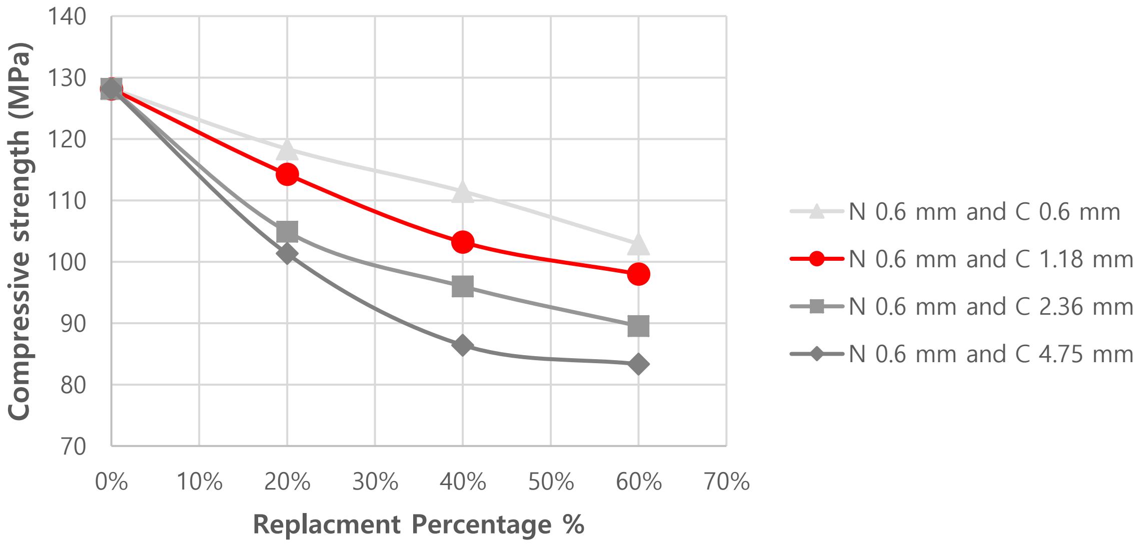

Fig. 5 Compressive strength of RPC-RA with RCA of different replacement ratios and various maximum particle sizes

3.1.1.2 Effect of Maximum Particle Size of Recycled Aggregate on Compressive Strength

It was noticed that the compressive strength decreases with increasing the maximum particle sizes (0.6, 1.18, 2.36, and 4.75 mm). For the replacement ratio of RCA 20%, the compressive strength decreased by (7.6, 10.9, 18.2, and 20.9%), respectively. Also, for the replacement ratios of RCA 40% and 60%, the compressive strength decreased by (13.0, 19.5, 25.1, and 32.6%) and (19.7, 23.5, 30.1, and 35.0%), respectively.
Fine aggregate has a significantly greater surface area than coarse aggregate. Surface area is the main factor affecting the resistance of concrete because strength depends on the cohesion between the cement paste and the aggregate used, cement paste coated the surfaces of the aggregates. So compressive strength increases if the surface area increases which is clear when using RCA has maximum particle sizes of (1.18, 2.36, and 4.75mm).

3.1.1.3 Effect of Recycled Materials' Type on Compressive Strength

Fig. 6 shows the compressive strength of the RCA and the RCBA. When using RCA and RCBA that has a maximum particle size of 0.6 mm, the compressive strength decreased by (7.6, 15.2%), (13.0, 27.2%), and (19.7, 30.3%) for the replacement ratio of 20%, 40%, and 60%, respectively.
It was observed that the use of RCBA resulted in decreased compression strength compared to the use of RCA. The rate of replacement of RCBA is (50 % concrete and 50 % bricks) so, in the case of 20%, for

Misan Journal of Engineering Sciences ISSN-E: 2957-4250
Vol. 2, No. 1, October 2023 ISSN: 2957-4242

instance, the percentage of bricks is 10%, which has a small effect on the strength.

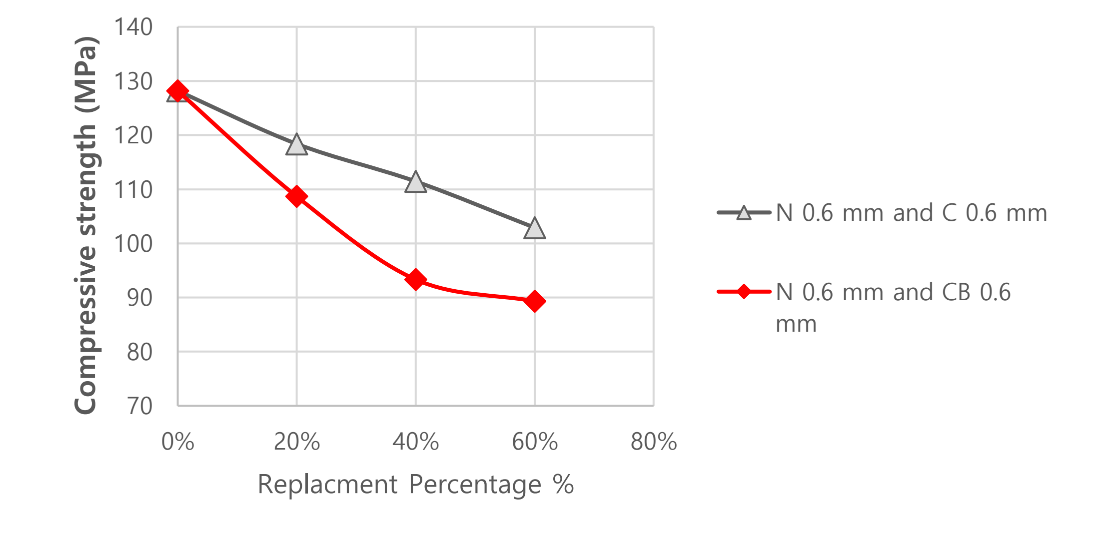

Fig. 6 Compressive strength of RPC-RA for RCA and RCBA with maximum particle sizes of 0.6 mm

3.1.2 Modulus of Rupture

The results were studied to determine the modulus of rupture values of the prism (50×50×250 mm), for various mixes as shown in Fig. 7. The following observations are noted:

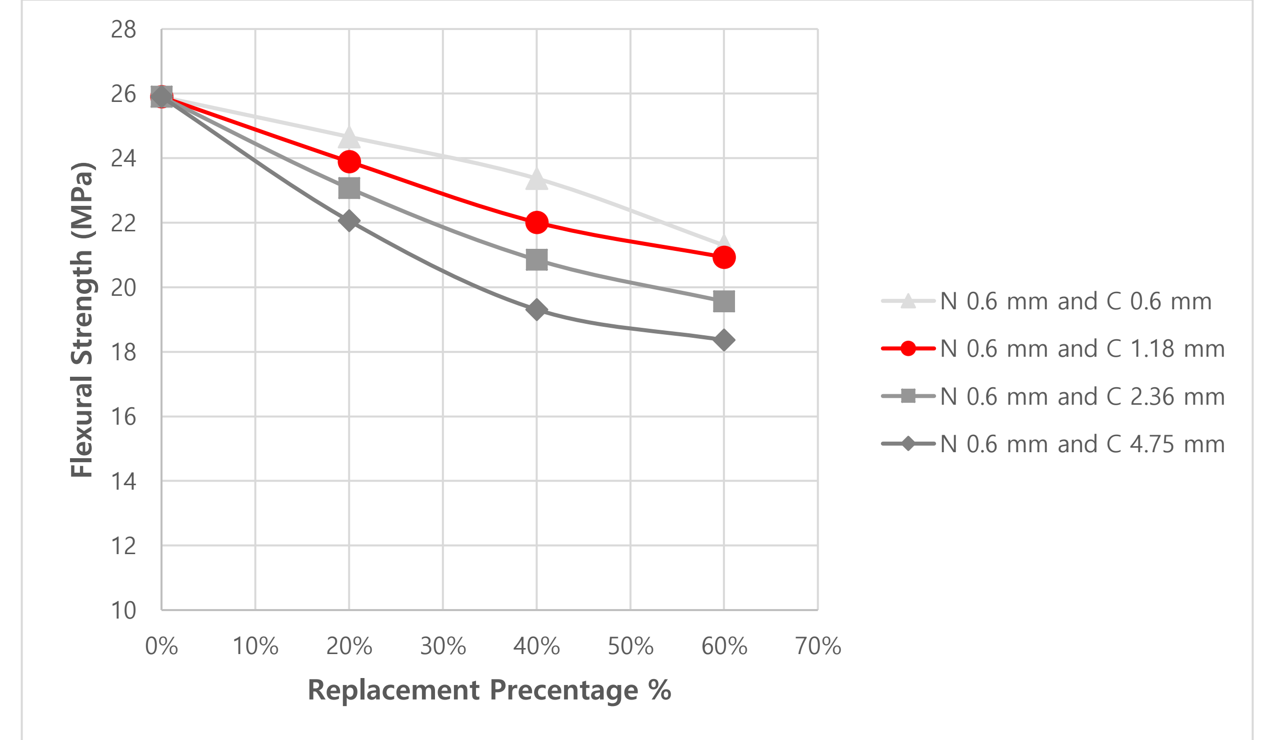

Fig. 7 Flexural strength of RPC-RA with RCA of different replacement ratios and various maximum particle sizes

3.1.2.1 Effect of Replacement Ratio on Modulus of Rupture

The modulus of rupture decreased when replacing fine natural aggregates with RCA at replacement ratios of 20%, 40%, and 60%, respectively. With the maximum particle sizes of 0.6 mm and 1.18 mm for RCA, the modulus of rupture decreased by (4.8, 9.8, and 17.8%), and (7.8, 15, and 19.2%), respectively. When using RCA with maximum particle sizes of 2.36 mm and 4.75 mm, the modulus of rupture decreased by (10.9, 19.5, and 24.5%), and (14.8, 25.4, and 29.1%), respectively.

3.1.2.2 Effect of Maximum Particle Size of Recycled Aggregate on Modulus of Rupture

The modulus of rupture decreased as the maximum particle sizes increased (0.6, 1.18, 2.36, and 4.75 mm). For the replacement ratio of 20% the modulus of rupture decreased by (4.8, 7.8, 10.9, and 14.8%), respectively. When the replacement ratio of RCA was 40% and 60% the modulus of rupture decreased by (9.8, 15, 19.5, and 25.4%) and (17.8, 19.2, 24.5, and 29.1%), respectively.

3.1.2.3 Effect of Recycled Materials' Type on Modulus of Rupture

When using RCA and RCBA with a maximum particle size of 0.6 mm, the modulus of rupture decreased by (4.8, 13.4%), (9.8, 27.8%) and (17.8, 40%), for replacement ratios of (20, 40, and 60%), respectively. Fig. 8 shows the modulus of rupture of the RCA and the RCBA.

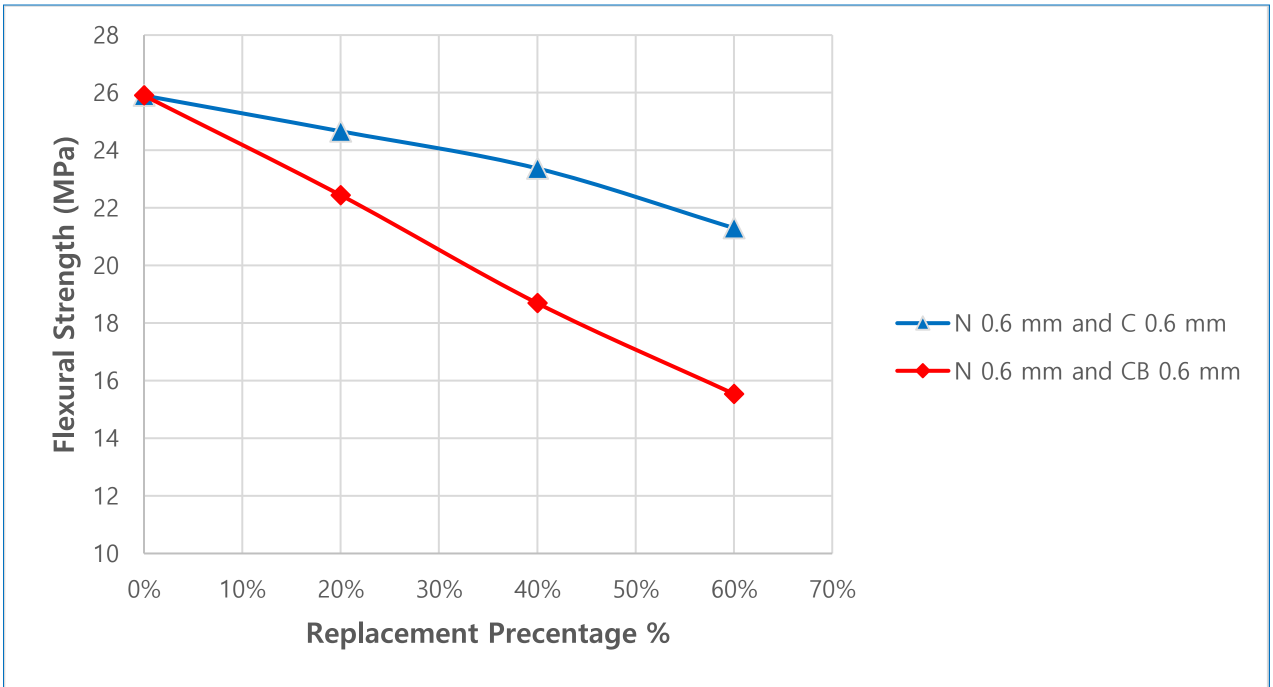

Fig. 8 Flexural strength of RPC-RA for RCA and RCBA with maximum particle sizes of 0.6 mm

3.1.3 Splitting Tensile Strength

The results were studied to determine the splitting tensile strength values of the cylinder (200×100 mm), for various mixes as shown in Fig. 9. The following observations are noted:

ISSN-E: 2957-4250
ISSN: 2957-4242

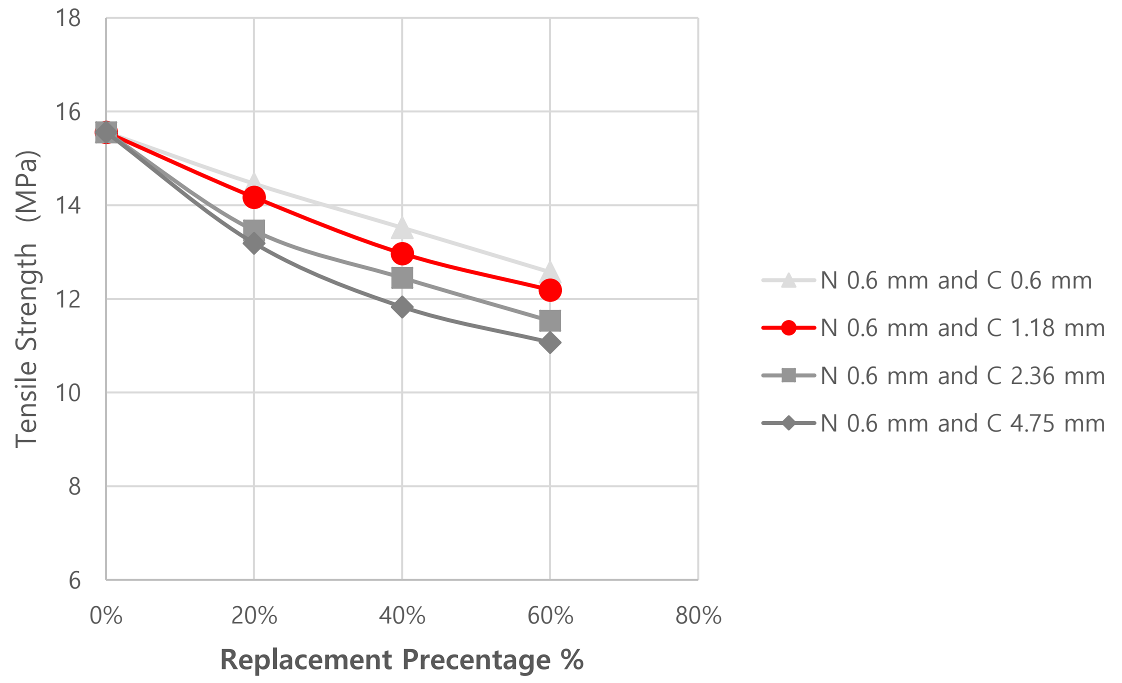

Fig. 9 Splitting tensile strength of RPC-RA with RCA of different replacement ratios and various maximum particle sizes

3.1.3.1 Effect of Replacement Ratio on Splitting Tensile Strength

The tensile strength decreases when replacing fine natural aggregates with RCA at replacement ratios of 20%, 40%, and 60%, respectively. With the maximum particle sizes of 0.6 mm and 1.18 mm for RCA, the tensile strength decreased by (7.1, 13.1, and 19.2%), and (8.9, 16.6, and 21.7%), respectively. When using RCA with maximum particle sizes of 2.36 mm and 4.75 mm, the tensile strength decreased by (13.5, 20, and 25.9%), and (15.2, 24, and 28.9%), respectively.

3.1.3.2 Effect of Max. Particle Size of Recycled Aggregate on Splitting Tensile Strength

As the maximum particle sizes of RCA increase (0.6, 1.18, 2.36, and 4.75 mm), the splitting tensile strength decreases. For the replacement ratio of RCA 20%, splitting tensile strength decreased by (7.1, 8.9, 13.5, and 15.2%), respectively. While it was decreased by (13.1, 16.6, 20, and 24%) and by (19.2, 21.7, 25.9, and 28.9%) for the replacement ratio of 40% and 60%, respectively.

3.1.3.3 Effect of Recycled Materials' Type on Splitting Tensile Strength

When using RCA and RCBA with a maximum particle size of 0.6 mm, the splitting tensile strength decreased by (7.1 and 13.8%), (13.1 and 30.5%), and (19.2 and 40.9%), for replacement ratios of (20, 40, and 60%), respectively. Fig. 10 shows the splitting tensile strength of RCA and RCBA.

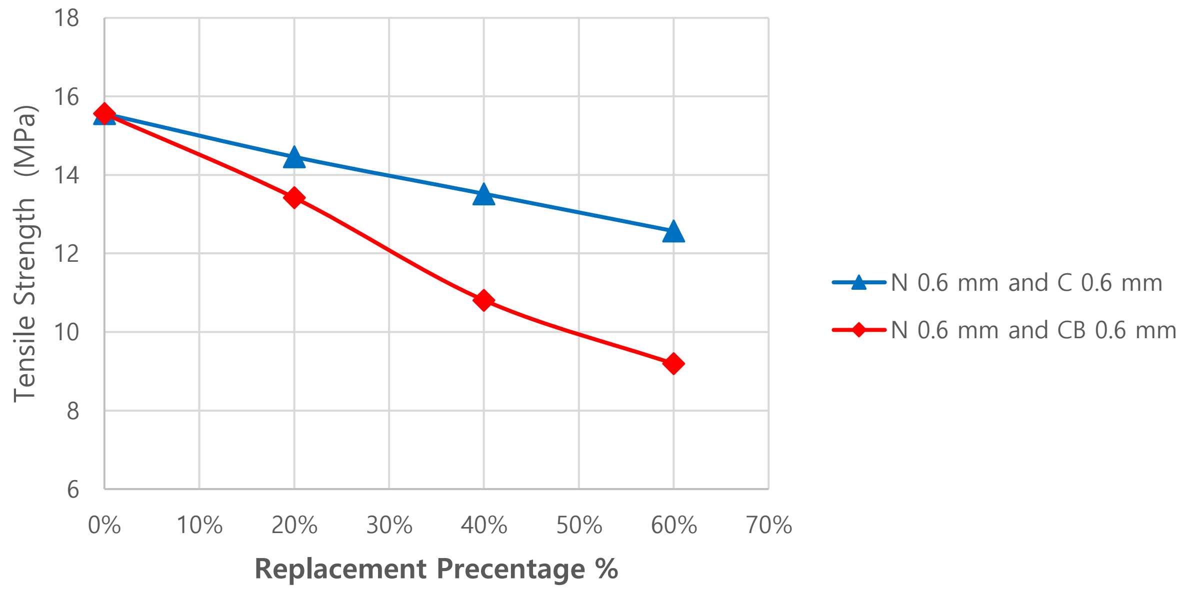

Fig. 10 Splitting tensile strength of RPC-RA for RCA and RCBA with maximum particle sizes of 0.6 mm

4. Conclusion

The experimental results showed that the flexure strength ranges from 17.4% to 22.3% of the compressive strength, and the tensile strength ranges from 57.8% to 61.3% of the flexural strength. It was observed that as the percentage of the RCA replacement ratio increased, there was a decrease in compressive strength, tensile strength, and flexural strength. The decrease in compressive and splitting strength for RCA with a maximum particle size of 0.6 mm and a replacement ratio of 20% to 60% is higher compared to the flexural strength. Results also showed a significant decrease in compressive strength, flexural strength, and tensile strength as the maximum particle sizes increased. It was observed that the effect of increasing maximum particle sizes is more significant in reducing compressive strength when compared to flexural and tensile strength for the same particle size and replacement ratio. Based on the results, it was observed that the use of RCBA resulted in decreased compression, flexure, and splitting strength compared to the use of RCA. When the percentage of RCBA replacement increased by more than 20%, the effect was to reduce tension and flexural strength more than compression strength.

Acknowledgments: The researcher would like to express their gratitude to all those who have assisted in the course of this study.

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