Misan Journal of Engineering Sciences ISSN-E: 2957-4250
Vol. 4, No. 1, June 2025 ISSN: 2957-4242

Torsional Strength of Beams Made of Reactive Powder Concrete Containing Recycled Aggregate

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(Received 12 Nov 2024, Revised 22 Dec 2024, Accepted 14 Jan 2025)

Abstract: This study investigates the torsional strength of beams made of a reactive powder concrete mix containing fine recycled aggregate. It also studies the mechanical properties of reactive powder concrete (RPC) in its fresh and hard state and the impacts of replacing it with recycled aggregate in different grading sizes. Seven RPC beams were examined and divided into two groups: the first group (control 0%, 20%, 40%, and 60%) of replacement with natural fine aggregate (600µm) and the second group at constant replacement 40% with different grading maximum sizes (1.18 mm, 2.36 mm, and 4.75 mm). The results indicate that reactive powder concrete at 40% replacement and particle size 2.36 mm of recycled aggregate gives the highest result regarding torsion behavior strength.

Keywords: reactive powder concrete, recycled aggregate size, torsion strength, workability, ultra-high strength concrete, curing type.

1. Introduction

Reactive powder concrete (RPC) is an emerging unique composite Cementous material that will enable the mix with high-quality microstructures. It possesses lesser porosity and extremely high flexural and compressive strengths. Many researchers have studied, investigated, and developed reactive powder mixes. In 2013, Yazıcı et al. [1] studied reactive powder concrete under autoclave treatment and compared it to standard concrete curing and the effect of autoclave temperature, pressure levels, and duration of treatment. Moreover, study the effects of components of RPC mix (silica fume dosage and steel fiber percentage) and its incorporation on performance influence. Optimizing autoclave parameters and incorporating silica fume and steel fibers improves mechanical properties in reactive powder concrete. Higher autoclave temperatures improve RPC's mechanical properties; increased pressure enhances RPC strength. In 2013, Sana [2] studied the reactive powder concrete mixes at different steel fiber percentages. The effect of high temperatures reached 600° c as a type of treatment on the strength of the RPC mixes. The results showed that you could get RPC with compressive strength over 120 Mpa treated under normal standard curing, but at 200° c, the RPC mix showed higher values. However, the compressive and tensile strengths dropped with treatment at temperatures up to 400° C and 600 c. In the year 2016, Sugathan [3] studied reactive powder concrete mixes with high workability as the RPC mixes achieved flowability comparable to self-compacted concrete mixes, examined the effect of micro steel fibers and the impact at various water-to-cement ratios and different cement content, and examined the properties of these mixes and their strengths. In 2020, Grzeszczyk et al. [4] studied the effect of basalt fibers on the overall mechanical properties and strength of reactive powder concrete. They found that the flow reduced when the basalt fibers were added and decreased when the basalt fibers increased. Compressive strength and tensile strength decreased except for the flexural, where there was an enhancement at 6 Kg/m3 of basalt fibers in the RPC mix. In 2020, Salahuddin et al. [5] investigated and evaluated the influence of high temperatures on varied properties of reactive powder concrete mix having different replacement percentages of fine recycled aggregates.

DOI: https://doi.org/10.61263/mjes.v4i1.121

Moreover, showed enhancement in overall hard mechanical properties at all temperature exposures.
In 2020, Salahuddin et al. [6] examined RPC mixes and the influence of adding recycled aggregates as a partial replacement for silica sand under different curing conditions on the overall performance. The tests showed improvements when adding recycled aggregates as a partial replacement, up to 50% partial replacement as optimum, but the strength dropped when adding higher replacement, like at 75% replacement, but better than the reference mix at 0% replacement. In 2021, Borg et al. [7] studied the effect of a recycled aggregate made from ultra-high durability concrete at different mixes with 50% and 100% replacement percentages. The result presents probable improvements over the control mix because of the addition of recycled aggregate made of ultra-high strength mix. In 2024, Mizaal et al. [8] Studied the behavior of reactive powder concrete with different types of recycled aggregates made from ceramic glass and bricks at various replacement percentages. The results showed that there was a decrease in the flowability after the replacements and an enhancement in the overall strengths (mechanical properties) caused by enhanced practical packing, and these mixes containing nanoparticles with a large amount of calcium silicate hydrate (C-S-H) and micro-steel fibers and dense cementitious materials with good bonding between them. In 2024, Nasser et al. [9] Studied the reactive powder concrete mixes at different curing regimes and various percentages of steel fiber at different types and lengths. They found that the curing regimes that involve heat curing give better results than the ones with only standard curing at the same mix proportions and same steel fibres ratio, and type results also showed that increasing the percentage of steel fibre increases the total strength of the RPC mix.

The other research studied the behavior of torsion of beams made of reactive powder concrete and ultra-high-strength concrete**.** In 2010, Wameedh [10] examined the performance of reactive powder concrete beams under pure torsion conditions. The study took 15 square beams at different volume fractions of steel fiber (0%,0.5%,1%,1.5%,2%), and different transverse and longitudinal steel bars ratios were used too, the result shows adding 1% of steel fibers to the reactive powder concrete mix, seriously increase the torsional strength. In 2015, Waryosh et al. [11] examined the torsional behavior of reinforced concrete beams with hollow and solid sections. The study also investigated the shape, location, and size of hollow beams done under pure torsion conditions. Results from the experimental investigation show that the magnitude of the torsion stiffness of the solid beam is higher than that of other hollow beams. Also, the twist angle increases in a hollow shape compared to a solid beam. The hollow-shaped beams behaved weaker than solid ones. The hollow core decreases significantly at the first crack and the ultimate torsional load capacity. Also, the failure mode has changed. More cracks have appeared in the hollow sections rather than solid sections. Furthermore, it has been cracking under pure torsion at an angle of around 45°. , the circular-shaped hollow core has better crack resistance and ultimate failure torsion loads than that with a rectangular hollow-shaped beam core. In 2016, Ahmed and Saad [12] investigated seven beams made of composite-modified RPC mix under pure torsion conditions. Two reference beams the first one was without a steel plate, and the second one was a solid with a steel plate, the other five were cast as composite-modified RPC beams with openings. The results show that using steel plates increases the ultimate torque of composite beams. The torsion behavior of the solid beam is better than the ones with an opening, and the circler opening shape is better than the square opening. In 2017, Alamli and Abdulameer [13] evaluated the strength of I-section beams made with reactive powder concrete mixes with an opening under pure torsion and studied nine RPC I beam shapes with different opening circles and squares. The crack torques decreased when the opening increased. Cracks density increased as the opening increased and became non-uniform. Increasing the hollow beam size reduces cracking torque and ultimate torque. In 2018, Ashour et al. [14] studied a hollow-reinforced reactive powder concrete T-beam shape that was investigated for torsion behavior. The T-beam was supported and had constant dimensions. The parameters are steel fiber volume friction percentage and silica fume with different dosages. The result they found was using silica fume in a percentage of 25% cement, which gives the best result from the compressive test, with 12% and split tensile by 32% modulus of rupture by 26% modulus of elasticity. 9% overall enhancement, the best steel fibres contain 2% per cubic meter; more than this, there will be some problems with workability. RPC beams with no fibres contain brittle material and fail suddenly and violently by adding steel fibres change, respectively, into ductile ones and improving the overall strength. In 2020, Mohammed et al. [15] studied the beams constructed as hybrid reinforced concrete beams consisting of two types of concrete mix (RPC) and (regular concrete mix). The conventional concrete (CC) mix is cast at the core cover around reactive powder concrete. Four types of reinforced concrete beams were cast and examined. Moreover, they found a significant influence on the thickness of the RPC cover. How much did they increase the RPC cover thickness and get more torsional strength, and, of course, did this apply to cracking torsional capacity and ultimate torsion. The hybrid beThe hybridarger torsional capacities than (CC) beams but less than RPC beams. Compared to regular concrete beams (CC), the twist angle in hybrid beams decreased during cracking torsion. In 2020, Alamli et al. [16] studied the torsional behavior of a T beam made of reactive powder concrete mixture with an open web in shapes like rectangular and circles. The ultimate torques decrease when the opening increases. In 2022, Abdullah and Aqeel [17] investigated the torsional strength of reinforced reactive powder concrete beams. The parameters are hollow (shape-location-dimension), stirrup spacing, and longitudinal reinforcement. The reinforced solid RPC beam's torsional cracking and pre-cracking torsional toughness values were enhanced with tremendous values compared to beams without reinforcement (plain). Increasing the hollow area reduces the first crack torsion moment and torsion moment at the ultimate state. The hollow beam with a circular shape is better than the square shape and rectangular hollow shape in the beam's cross-sections, and the hollow section is best located within the center of the cross-section. Extensive studies were conducted on the overall mechanical properties of the reactive powder concrete mix at different proportions and curing regimes and the addition of recycled aggregate, but limited studies are available about the torsional behavior of beams made of RPC with recycled aggregate at various replacements and particle sizes. The study also focuses on both cracking and ultimate torsional moments, which remain underexplored offering an opportunity to enhance structural performance and environmental sustainability. This study also addresses these gaps by evaluating the torsional strengths of reactive powder concrete beams containing recycled aggregates at acceptable workability.

2. Experimental program and materials

The experimental work in the Structure Lab at the University of Basrah tested the torsional behavior of seven beams made from reactive powder concrete containing recycled aggregate. The reference RPC mix is made of 900 kg/m^3 of Iraqi Portland cement, 1100 kg/m^3 of fine natural aggregate from Basrah, 225 kg/m^3 of micro silica fume, which is the most important ingredient, followed by 55 liter/m^3 of super-plasticizer known as high range water reducer which is no less important than silica fume in RPC mix and water content is 242 liter/m^3, with golden color steel fiber 1.5% or near 117 kg/m^3 this balanced mix design to achieve good workability and strengths for structure and fit to use it in tiltling drum mixer. All RPC mixtures and the replacements listed in Table (1)

Table (1) Reactive powder concrete mixes design

NO	Mix RPC	Cement Content kg/m^3	Fine aggregate Kg/m^3 (600μm)	Recycled aggregate Kg/m^3	Silica fume kg/m^3	HRWR liter/m^3	Water liter/m^3	Steel fiber kg/m^3
1	R0SS	900	1100	---------	225	55	242	117
2	R20/0.6SS	900	880	220	225	55	247.5	117
3	R40/0.6SS	900	660	440	225	55	252	117
4	R60/0.6SS	900	440	660	225	55	256.5	117
5	R40/1.18SS	900	660	440	225	55	256.5	117
6	R40/2.36SS	900	660	440	225	55	256.5	117
7	R40/4.75SS	900	600	440	225	55	256.5	117

Misan Journal of Engineering Sciences ISSN: 2957-4250
Vol. 4, No. 1, June 2025 ISSN-E: 2957-4242

2.1 Cement

Iraqi Portland cement was used in this experiment. It was stored in a dry place to preserve it from various weather conditions. Cement was examined with all physical and chemical cement tests based on IQ.S. No. 5/1984 [18], as shown in Tables (2) and (3).

Table (2) Chemical analysis of cement

Properties	Content (%)	Limit of IQ.S. No.5/1984[18]
Lime (CaO)	59.58	60
Silica (SiO_2)	19.66	17-25
Iron oxide (Fe_2O_3)	4.79	0.5-6
Magnesia (MgO)	2.75	5% Maximum
Sulfate (SO_3)	1.89	2.85% Maximum

Table (3) Physical analysis of cement

Properties	Results	Limit of IQ.S. No.5/1984[18]
specific surface area (Blaine method) (cm^2/g)	340	≥ 230
Setting time at Initial min.	120	≥ 45
Setting time at Final min.	240	≤ 600
Compressive strength MPa at 3 days	20.15	> 15
Compressive strength MPa at 7 days	27.5	> 23

2.2 Aggregates

Two types of aggregates (Natural fine aggregate) used in this research were evaluated by sieve analysis test as well as chemical and physical property testes, according to the Limits of IQ.S. No.45/1984, Zone 4 [19] as shown in Tables (4), and (5).

The first type of aggregate is a natural fine aggregate, which is used in all mixes with a maximum particle aggregate size of 0.6 mm. The second type is fine recycled aggregate, prepared by a recycled crushing machine. The recycled aggregate came from old concrete cubes and cylinder test specimens. Available at the University of Basrah laboratory from different projects, the crushed concrete was passed into four sieves with sizes of (0.6 mm, 1.18 mm, 2.36 mm, and 4.75 mm). The range of compressive of these crushed concrete is between (25MPa-40MPa).

Table (4) Grading of natural and recycled fine aggregates

Sieve Size (mm)	NA^{*1} (0.6 mm)	RA^{*2} (0.6 mm)	RA^{*2} (1.18 mm)	RA^{2} (2.36 mm)	RA^{*2} (4.75 mm)	Limits of IQ.S. No.45/1984, Zone 4 [19]
4.75	100	100	100	100	100	95-100
2.36	100	100	100	100	76	95-100
1.18	100	100	100	85	55	90-100
0.6	100	100	76	30	22	80-100
0.3	46	47	52	24	5	15-50

0.15	11	14	11	1	-	0-15

NA*1: natural aggrgate; RA*2; recycled aggregate

Table (5) Chemical and physical properties of aggregates

Properties	Natural fine aggregate	Recycled fine aggregate	IQ.S No.45/1984
Fineness Modulus	2.39	2.74	Min 2.30
Bulk Density Kg/m^3	1573	1434	
Moisture Content %	1.2	0.31	
Specific gravity	2.55	2.78	
Sulfate content	0.25	0.35	> 0.5
Absorption %	1.55	5.7	

2.3 Silica Fume

Densified micro-silica was used by a chemical construction Company named (CONMIX), with code material name (MegaAdd MS (D)) all the data sheets where mentioned in Tables (6) which complies with (ASTM C1240-20) [20]

Table (6) properties of silica fume

Properties	
grain size	Sub-micron powder
Color	Mid-grey powder
Specific Gravity	From 2.10 to 2.40
Bulk Density	From 500 to 700 kg/m^3
Chemical properties	
Silicon Dioxide (SiO_2)	Min (85%)
Moisture Content (H_2O)	Max (3%)
Loss on Ignition (LOI)	Max (6%)
Physical Requirements	
Specific Surface Area	Min (15 m^2/g)
Pozzolanic reaction Activity Index, 7 days	Max (105%)
Silica fume particles retained on the (45-micron sieve)	Max (10%)

* Supplied by the manufacturer

2.4 Super-Plasticizer (HRWR)

MasterGlenium 200 is an innovative third–generation super-plasticizer based on polycarboxylic ether (P.C) polymers. It is specially engineered for ready-mix concrete in hot weather conditions.all the data sheet where mentioned in Tables (7) which comply with ASTM C494/C494M-20 [21].

Table (7) Properties of super-plasticizer

colure	Light brown
Specific gravity at 20° c	1.08±0.02
pH range value	6.0± 1.0
Chloride content	0%

* Supplied by the manufacturer

2.5 Micro Steel Fibers

Microfibers with straight, short brass-coated gold-colored steel fibers with a length of 12-13 mm and diameter of 0.2 mm. manufactured by (Tianjin Hengfeng Xuxiang New Metal Material) complying with (ASTM A820/A820M standards, Type 1) [22]. All steel fiber properties mention in Table (8)

Table (8) Properties of steel fiber

Description	Length (mm)	Diameter (mm)	Aspect Ratio	Ultimate Tensile Strength MPa.	Color	Cross Section	Density kg/m^3
Straight	12-13	0.2	60-65	> 2600	Golden	Circular	7800

* Supplied by the manufacturer

2.6 Steel Reinforcement Bars

All beams in this research had two types of reinforcement (transverse and longitudinal), which is very important for the torsional behavior of RPC beams. Two local steel bars of different sizes were used: the Ø16mm bars for longitudinal reinforcement and the Ø10mm bars for closed stirrups. The properties of steel bars complied with ASTM A615 [23]. All steel bar testes are mentioned in Table (9). All the RPC-beam were cast using plywood plates with a thickness of 18mm. All plywood plates were screwed to secure the mixture from leaking.

Table (9) properties of steel bars reinforcement test

Steel Bar Size (mm)	Steel Bar Area (mm^2)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Limits based on ASTM A615 [23]		
					Yield strength (MPa)	Tensile Strength (MPa)	Elongation (%)
Ø10 mm	78.5	462	625	14	420	620	9
Ø16 mm	201	504	635	16	420	620	9

2.7 Curing

The reactive powder concrete test specimens cubes for compressive strength were kept in a water reservoir for 28 and 56 days, and the cubes others were stored in hot water in a water reservoir for 7 days at 65°c. But for cylinders and prisms cured on standard treatment for 56 days to check the tensile and flexural strengths. However, reinforced reactive powder concrete beams for the torsion test were covered with damp canvas and nylon sheets, and normal water-curing continued for 56 days.

2.8 Beam identifications

The solid square cross-section beam shape was included for all beams (R0SS, R20/0.6SS, R40/0.6, R60/0.6SS, R40/1.18SS, R40/2.36SS, R40/4.75SS) a 200 mm by 200 mm cross-section and a length of 1200 mm, four main steel bars one at each beam cross-section corner which represent for longitudinal reinforcement with diameter size of these main bars (Ø16mm) and the Ø10mm bars for closed stirrups with spacing (80mm). RPC beams details that are used are shown in Fig.1.

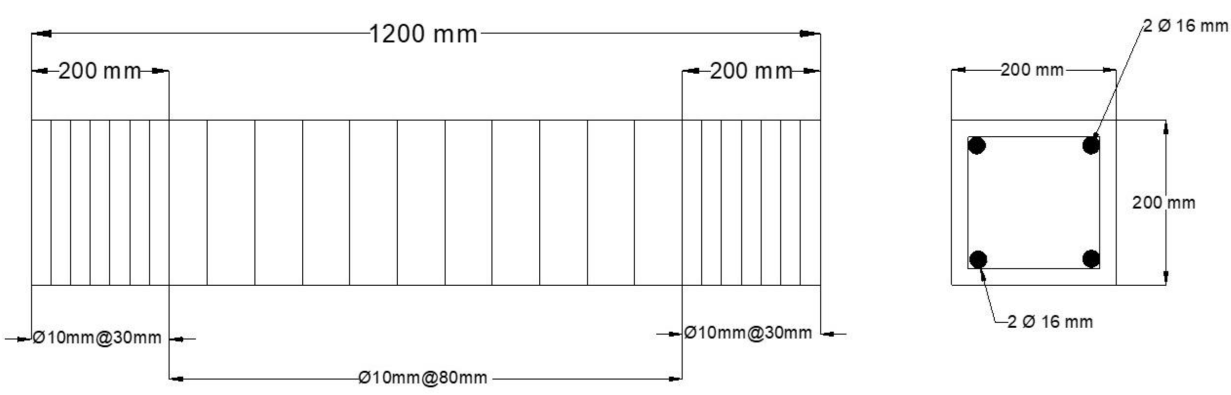

Fig. 1 beam reinforcements deteals

2.9 Test procedure for mechanical properties

The compressive strength test was conducted according to BS EN 12390-3:2019 [24]. The cube's size was (100×100×100) mm, and it was cured under hot water baths for seven days at 65°c by a large basin. Moreover, the Splitting tensile strength test was performed based on (ASTM C496/C496M) [25].To determine Splitting tensile strength at cylinder test size (100×200) mm. at the same curing condition and for the flexural strength, 100x100x400 mm concrete prisms were prepared and tested under two-point loading according to the ASTM C78-84 specification [26] to determine the flexural strength of all concrete mixes in this work. The flexural strength of RPC mixes was measured with a Universal Testing Machine at the University of Basrah. Prisms were tested using two loading points with a clear span of 300 mm according to the ASTM specification [26], and all the prisms were cured in the same condition as testing cylinders and cubes. For workability assessment, the flow table test was done to measure the flowability of all the mixtures according to ASTM C1437 [27]. Where the reactive powder concrete mixes at fresh state but in small cones mold and then lifted to measure the diameter of spreading of the fresh mix which is the same principle as the slump flow test in self-compacted concrete [28] but in the flow table test done in smaller cones.

2.10 Mixing procedure

All The RPC beam mixes were mixed in a 350-litre capacity rotary tilting drum mixer. The mixer drum was cleaned and damped before every batch. The mixing steps first by adding all the dry ingredients (materials) in a drum mixer and mixing for more than 3 to 5 minutes by ensuring the drum mixer is at an angle of 15-25° for optimum performance, then adding (¾) of water gradually followed by all superplasticizer liquid and keep mixing for more than 5 minutes then add the remaining water while mixing to get a homogenous mixture. After that test the workability of the RPC mix then add the steel fiber and continue mixing for 3-5 min to ensure fiber disruption in the mix.

2.11 Test procedure for torsion behavior test

The beams were tested using a Universal Testing Machine at the University of Basrah with a maximum capacity of over 200 tons. Beams were placed on the testing machine with free-supported rollers at both ends and a clear span of 800 mm to ensure proper torsion load application. The test setup of pure torsion reactive powder concrete beam was attached to the two steel I-sections reinforced by a tapered plate acting as lever arms, which provide an eccentricity load of 450 mm relative to the longitudinal axis of the beam, crucial to induce the desired torsional load. a steel box girder was diagonally positioned across the lever arms, secured with threaded rods, and loaded centrally using the load machine.

Misan Journal of Engineering Sciences ISSN: 2957-4250
Vol. 4, No. 1, June 2025 ISSN-E: 2957-4242

The reaction arms were fixed with threaded rods to the frame of the testing machine. A steel box girder, fabricated from two-channel sections, was laid diagonally across the top of the lever arms and supported by hinged end supports. The mid-span of this box section girder was then loaded and this load applied the torsional force to the beam. Spherical seats were used at the end supports of the beam specimens to avoid any axial constraint. Such seats allow longitudinal movement and free rotation of the beams so tha the applied torque can be the major force acting on the specimens. The first crack torsion was calculated by eyesight during the test as the load increased gradually, with the displacement gauge placed strategically to calculate the twist angle at both states (first crack, ultimate failure). This method ensures measuring both the torsion moment and angle of twist at the same time during the test and understanding torsion behavior.The Construction Laboratories and Research Center, Basrah University, College of Engineering, provided all the equipment and accessories for manufacturing and testing the beams under pure torsion as shown in Fig.2 and Fig.3.

Fig.2 Reactive powder beam under pure torsion

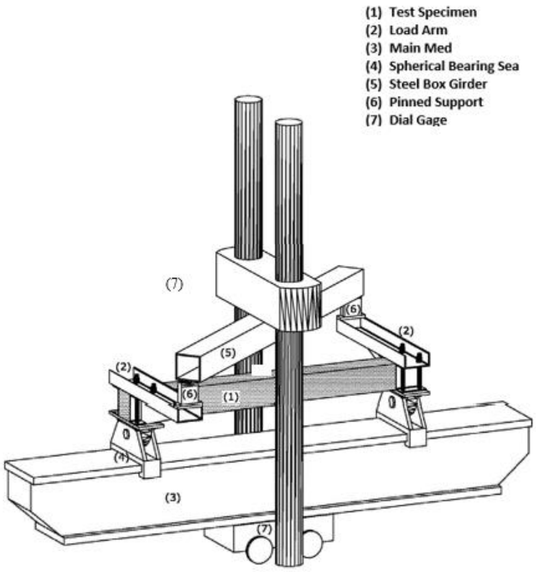

Fig.3 Torsion beam test diagram

3 Experimental Results and Discussion

3.1 Effect of recycled Aggregate on density and Workability of (RPC)

The workability (flow ability) of mix with and without recycled aggregate was assessed using a flow table test at the university lab. The recycled aggregate was used at different replacement levels in the mix (0%, 20%, 40%, 60 %). The rough texture and irregular, angular particle shape of the recycled aggregate, resulting from crushed concrete, reduced the flow of the reactive powder concrete mix [29]. As shown in Table (5), At the constant 40% replacement level with fine recycled aggregate, using different maximum particle sizes at (1.18 mm, 2.36 mm, and 4.75 mm) of fine recycled aggregate, the Reactive powder concrete mix exhibited similar workability and flow characteristics, indicating that particle size variation within this range did not significantly impact workability. The standard Reactive powder concrete mix also noted a gradual decrease in density (kg/m^3) if the replacement percentage of recycled aggregate increased. However, when the particle size of recycled aggregate increases, the density increases, too, when compared to (600 μm) at constant replacement.[29]

Table (5) Density and workability results

Beam mix design	Density (kg/m^3)	Flow (mm)	Decrease in density (%)	Decrease in flow (%)
R0SS	2315.74	235	-	-
R20/0.6SS	2293	225	0.98%	4.3%
R40/0.6SS	2273	220	1.85%	6.4%
R60/0.6SS	2269	215	2.02%	8.5%
R40/1.18SS	2276	220	1.72%	6.4%
R40/2.25SS	2285	220	1.33%	6.4%
R40/4.75SS	2314	220	0.1%	6.4%

3.2 Hard Mechanical Properties of RPC

3.2.1 Compressive Strength

All the test specimens were examined using (100×100×100) mm cubes according to BS EN 12390-3:2019 [24] treated using heat treatment with a hot water bath curing type. Additional tests were conducted at 28 and 56 days under standard curing conditions.

For RPC testing cubes at hot water bath curing, at replacement levels of (0%, 20%, 40%, and 60%), with a maximum size of (0.6) mm, the compressive strength was enhanced if compared to the reference mix with compressive strength (79.14 MPa). The replacement mixes at (20%, 40%,and 60%) reached compressive strengths of (81.46 MPa, 84.64 MPa, and 80.78 MPa), respectively, representing increases of 2.9%, 6.9%, and 2.07%. there was a reduction in compressive strength at replacement 60% due to an increase in the porosity of the mix, which was caused by the high recycled aggregate replacement, same as a decrease in practical bond of aggregate with the cementation material in the RPC mixture

From Table (6), In terms of the effect of particle size on the compressive strength was also evaluated for recycled aggregate with different sizes (1.18 mm, 2.36 mm, 4.75 mm) at a 40% replacement level and compared with (0.6mm) at 40% replacement which is (R40/0.6SS). These mixes exhibited enhanced compressive strengths of 85.66 MPa, 87.56 MPa, and 89.10 MPa, respectively, compared to the 0.6 mm recycled aggregate at 40% replacement. The enhancement in compressive strength for these sizes was 1.2%, 3.4%, and 5.2%, respectively. Moreover, when comparing these results with the control RPC mix (R0SS), the enhancement is (8.2%, 10.63%, and 12.6%) respectively. all the reasons for the improvements in strength are mentioned in paragraph (3.2.4). [29]-[33]

Under normal curing at 28 days, the compressive strength was lower than that achieved with hot water curing, as the concrete's compressive strength had not fully developed, ranging up to 0.85 of the hot water curing value. This difference was attributed to the high dosage of superplasticizer and water. At 28 days, the results showed a similar effect of recycled aggregate, with the control mix (R0SS) achieving 66.57 MPa and the optimum replacement at 40% reaching 73.36 MPa. For particle sizes of 1.18 mm, 2.36 mm, and 4.75 mm, the compressive strengths at constant 40% replacement were 73.95 MPa, 76.98 MPa, and 87.94 MPa, respectively.

Under normal curing At 56 days, the results were close to those of 7-day hot curing, with similar enhancements observed. The optimum compressive strength was again found at 40% replacement, with the particle size variation (1.18 mm, 2.36 mm, 4.75 mm) yielding results above 90 MPa, surpassing the hot curing results. This was especially true for particle size 2.36, which reached 94.6 MPa, and it was the optimum result at day 56 with normal curing. The reason was that the extended hydration period provided by micropores in recycled aggregate contributed to the gradual release of retained water (water in the pores), acting as internal curing. This process leads to the formation of calcium silicate hydrate (C-S-H) gel, leading to increased compressive strength in the long-term

3.2.2 Splitting Tensile Strength

The splitting tensile strength of the RPC mix was examined using cylinders (200×100 mm) for various mixes. The results showed an enhancement in splitting tensile strength at the optimum, at a replacement of 40%, but a reduction at 60% replacement with recycled aggregate. The control mix achieved 10.9 MPa, while at 40%, the replacement mix reached 11.56 MPa. The highest splitting tensile strength for the particle size group was 13.36 MPa at a recycled aggregate size of 4.75 mm with 40% replacement (R40/4.75). When choosing a constant replacement and increasing the size of the recycled aggregate particles from 0.6 to 4.75mm, the split tensile strength keeps increasing, the same as the compressive strength. All the reasons for the improvements in strength are mentioned in paragraph (3.2.4). All split tensile test results listed below in Table (6).[29]-[33]

3.2.3 Flexural Strength

The flexural strength was examined using prisms with dimensions (100×100×400 mm) for all mixes at day 56 of standard treatment. An improvement was observed compared to the control mix, which had a flexural strength of 17.58 MPa. Regarding replacement, the flexural strength keeps increasing when recycled aggregate is added until 60%, reaching 24.57 MPa. In terms of the influence of the particle size group on flexural strength showed that the highest value of both groups was obtained with a particle size of 2.36 mm, achieving 26.46 MPa at 40% replacement (R40/2.36). All the reasons for the improvements in strength are mentioned in paragraph (3.2.4). all results listed below in Table (6).[29]-[33]

3.2.4 Reasons for overall mechanical properties enhancement of RPC.

When using fine recycled concrete aggregate as a partial replacement were because:
Filler Effect of Recycled Material: Recycled material, some finer than natural sand, fills the micro gaps in concrete. This densifies the concrete, reducing internal stresses and early crack propagation. Internal Curing Effect: Recycled materials exhibit an internal curing effect. Initially, absorbed water within pores becomes available later to hydrate cementitious materials.

Pozzolanic Reactions**:** Un-hydrated cement particles in recycled materials participate in pozzolanic reactions, resulting in higher strength. Role of Rough Recycled Fine Aggregates: The roughness and more irregular and angular shapes of recycled fine aggregate particles reinforce the recycled concrete's transition zone, leading to a stronger bond with the cement paste.[29]-[33]

Table (6) Hard properties of reactive powder concrete mixes

Beam mix	compressive strength (MPa) day 7 (Hot curing)	compressive strength (MPa) day 28 (normal curing)	compressive strength (MPa) day 56 (normal curing)	split tensile strength (MPa) day 56 (normal curing)	flexural strength (MPa) day 56 (normal curing)
R0SS	79.14	66.58	76.3	10.9	17.58
R20/0.6SS	81.46	68.32	80.41	11.12	18.38
R40/0.6SS	84.64	73.37	85.2	11.65	19.43
R60/0.6SS	80.78	71.53	78.52	11.05	24.57
R40/1.18SS	85.66	73.95	85.5	11.98	19.5
R40/2.25SS	87.56	76.98	94.6	12.59	26.46
R40/4.75SS	89.102	87.94	91.76	13.36	21.7

3.3 Torsional Behavior of RPC Beams

Beams were designed and tested to evaluate beam performance under pure torsion load. All beams are shaped with solid square beams, each reinforced with four main steel bars of 16 mm diameter, and stirrups are 10 mm diameter at 80 mm spaced along the beam length. Universal Testing Machines (UTMs) are essential in examining the mechanical properties of various materials, including the torsional behavior of beams. At our facility, we conducted torsion tests on beams with dimensions of 200*200*1200 mm to investigate their response to applied twisting forces. The UTM, equipped with a lever arm of 0.45m in length, was employed to apply a controlled torque to the beam. The machine measured the resulting twist angle and torsional moment during testing. The experimental results of beams tested under pure torsion revealed distinct behaviors based on curing methods and mix compositions. For RPC-beams under standard curing conditions, the torsion moments at the first cracking state for beams (R0SS, R20/0.6SS, R40/0.6, R60/0.6SS, R40/1.18SS, R40/2.36SS, R40/4.75SS) gives the result of (27 kN·m, 27 kN·m, 29.25 kN·m, 27 kN·m, 27 kN·m, 36 kN·m, 31.5 kN·m) respectively, the torsion moment at ultimate torsion state showed these results (58.5 kN·m, 60.75 kN·m, 62 kN·m, 60.75 kN·m, 63 kN·m, 74.2 kN·m, 67.5 kN·m), These results showed the effect of fine recycled aggregate replacement, and the particle size of fine recycled aggregate on the torsional As shown in Table (7). All RPC beams at failure state showed in (Fig.4)

Table (7) Experimental results of RPC beams of torsion behavior

Beam mix	Curing type	Cracking Torque moment (kN.m)	The angle of twist at the first crack (Radians/m)	Ultimate torque moment (kN.m)	The angle of twist at ultimate torsion (Radians/m)
R0SS	Standard curing	27	0.0045	58.5	0.008
R20/0.6SS		27	0.004	60.75	0.0088
R40/0.6SS		29.25	0.005	62	0.0095
R60/0.6SS		27	0.0048	60.75	0.011
R40/1.18SS		27	0.0055	63	0.0093
R40/2.25SS		36	0.005	74.25	0.0085
R40/4.75SS		31.5	0.0053	67.5	0.0097

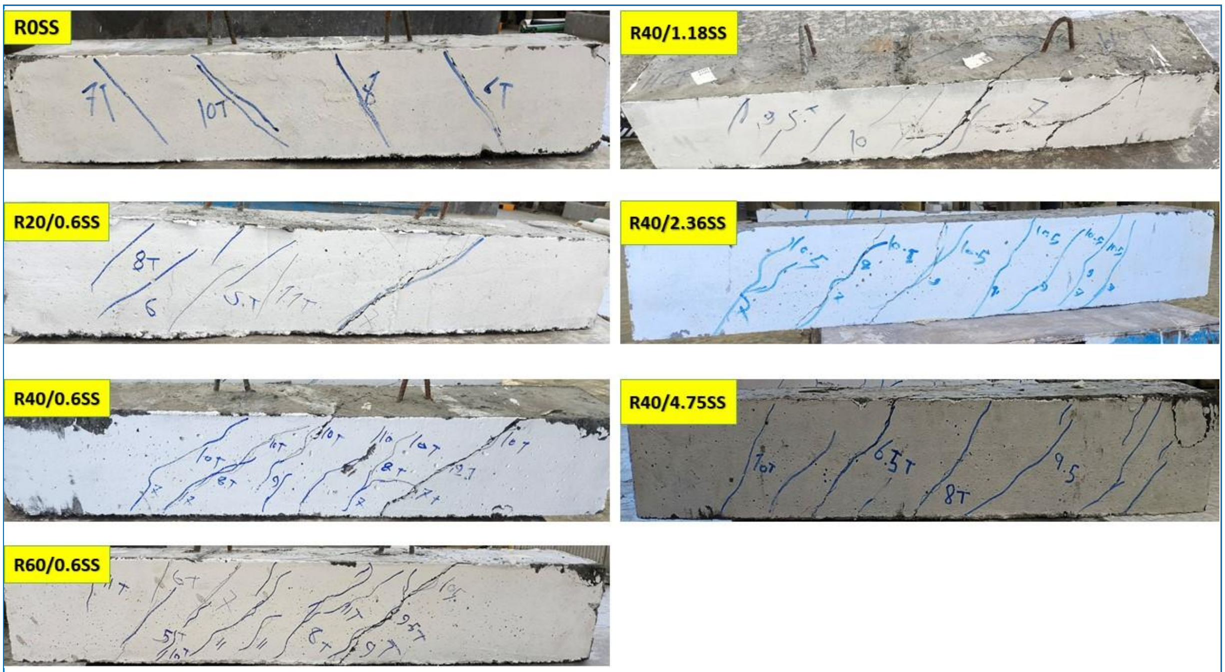

Fig. 4 RPC beams at failure mode

3.3.1 Effect of replacement ratios of fine recycled aggregates on RPC beams torque

At different replacement levels (0%, 20%, 40%, and 60%) with a constant particle size of 0.6 mm, the torsional behavior of beam groups (R0SS, R20/0.6SS, R40/0.6, R60/0.6SS) was evaluated. The control beam (R0SS) exhibited a torsion moment of 27 KN·m at the first crack stage, while the optimum result was observed at 40% replacement, with a first crack torque of 29.5 KN·m. The ultimate torsion moment is optimum with beam R40/0.6SS, giving a torsion moment of 62 KN·m.

These results show a slight enhancement in torsional moment strength when recycled aggregate is added, similar to the improvements seen in the mechanical properties of the RPC mixes, the reason for which is mentioned in section 3.2.4. However, as the replacement percentage increased, so did the angle of twist, which negatively impacted the beam's reliability. With a 60% replacement of fine recycled aggregate, the twist angle increased from 0.008 radians in the control beam to 0.011 radians in the R60/0.6SS beam.

(Fig.5) shows below the relation between the torsion moment at both states at first crack and at ultimate failure and the fine recycled aggregate replacement percentage. While (Fig.6) represents the impact of recycled aggregate replacement on a twist of angle at both states. The first group of RPC beams is shown together in (Fig.7), representing the reactive powder concrete's torsional behavior at various replacement ratios [31][32].

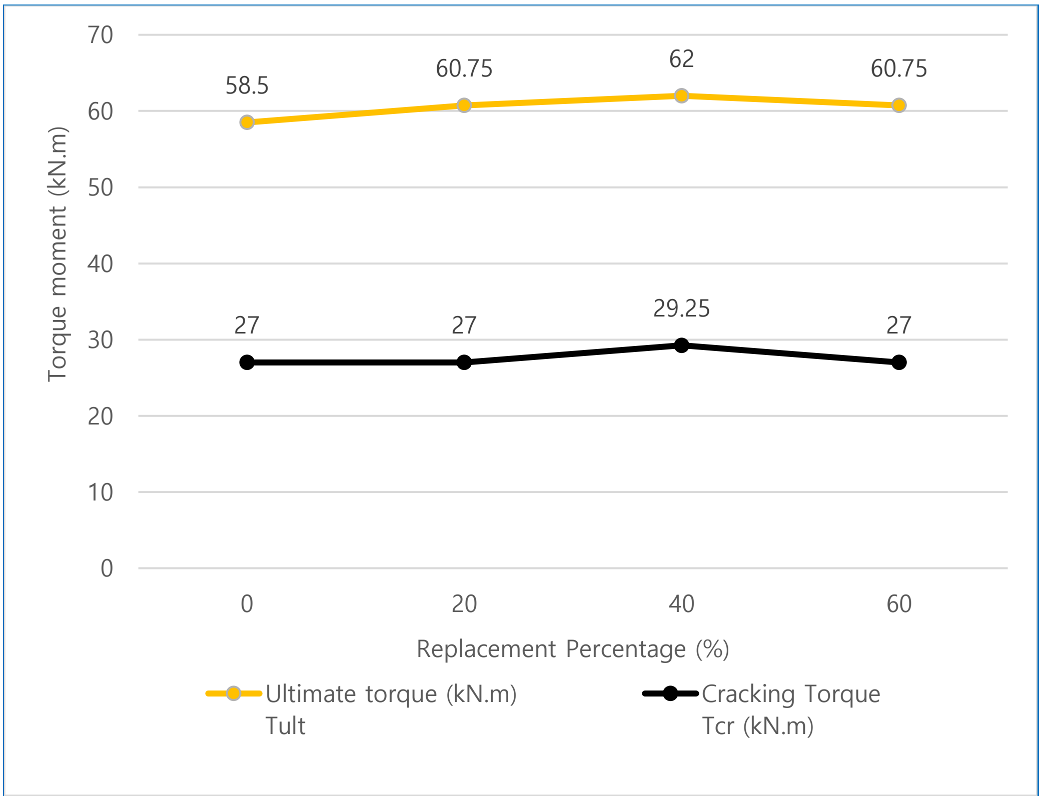

Fig.5 The effect of recycled aggregate replacement on torsion moment

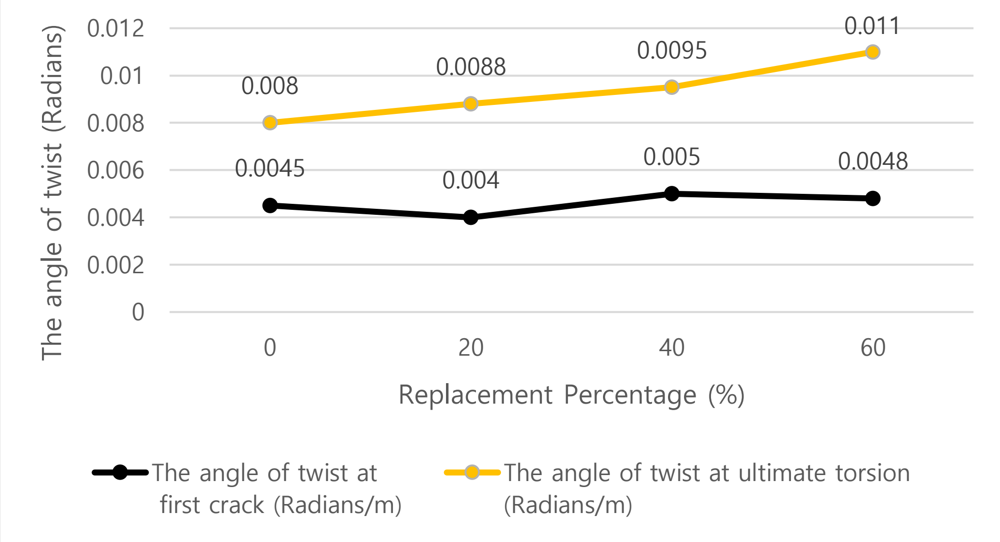

Fig.6 The effect of recycled aggregate replacement angle of twist

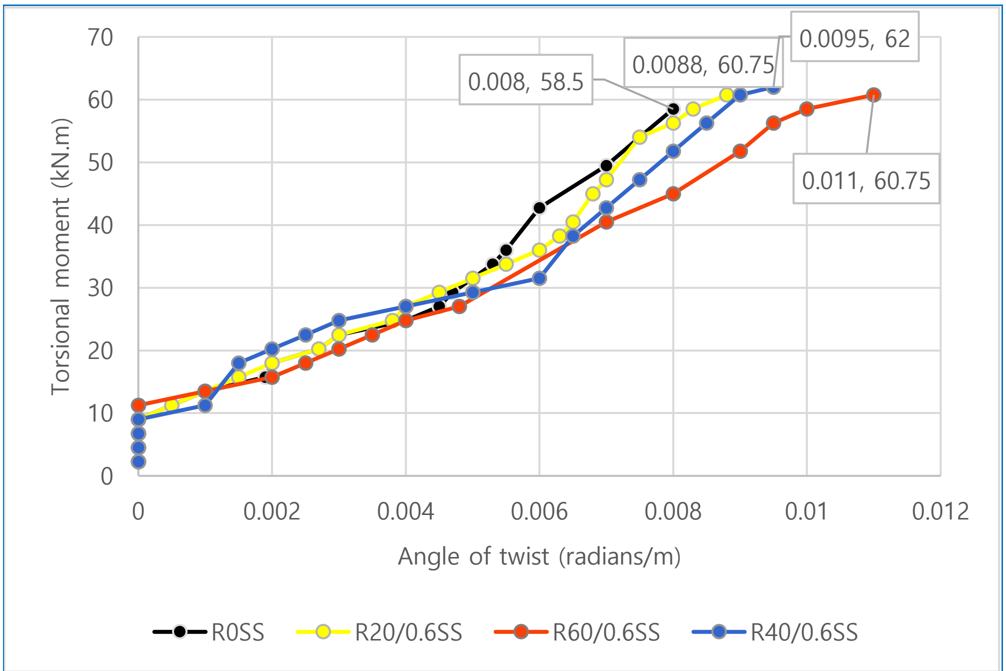

Fig.7 Torsion behavior of effect of recycled aggregate replacement

3.3.2 Effect of fine recycled aggregates particle size on RPC beams torque

In the second group which had these beams (R40/1.18SS, R40/2.36SS, R40/4.75SS), which focused on the effect of recycled aggregate particle size at constant replacement (40%), there was no significant difference between 1.18 mm and 600 µm at the same 40% replacement level for both ultimate and cracking torque. However, the beam with R40/2.36SS showed the optimum torsional behavior of all beams, with a first crack torque of 36 KN·m and an ultimate torsion of 74.25 KN·m. In contrast, the twist angle is (0.005) radians at the first crack and (0.0085) radians at ultimate failure. there was a noticeable increase in twist angle at the beam (R40/4.75SS) that has a 4.75mm size of recycled aggregate and 40% replacement. This increase in the twist angle at both states (first crack state and ultimate failure state) when increasing the recycled aggregate size is likely due to a bigger recycled aggregate, leading to more significant deformation under torsional loads. The reason for enhancement in torsion moment at both states (first crack, and ultimate) is the same reason for improving in mechanical properties of the RPC mix where mentioned in section (3.2.4) where the result showed better results in torsion strength if we compared it with the reference beam (R0SS). The (Fig.8) shows below the relation between the torsion moment at both states at first crack and at ultimate failure and the effect of the maximum size of fine recycled aggregate. While (Fig.9) represents the impact of recycled aggregate particle size on a twist of angle at both states. The second group of RPC beams is shown together (Fig.10) which represents the reactive powder concrete's torsional behavior at various maximum particle sizes of fine recycled aggregate [31][32].

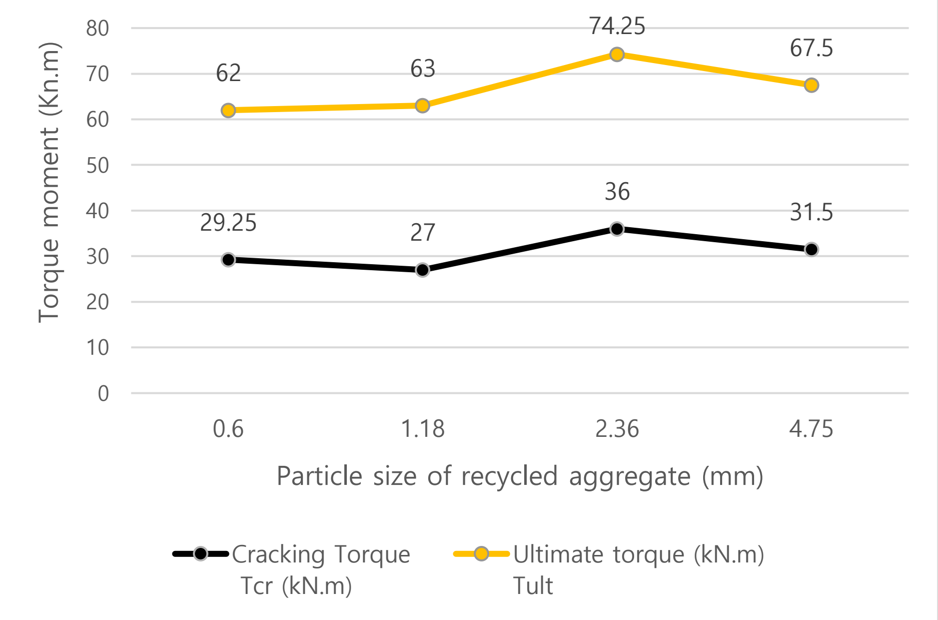

Fig.8 The effect of recycled aggregate replacement on torsion moment

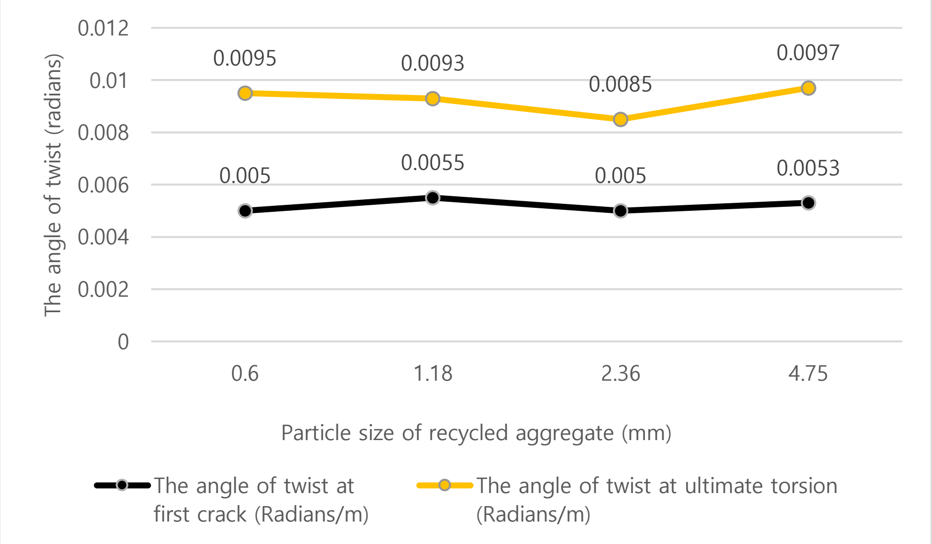

Fig.9 The effect of recycled aggregate replacement on torsion moment

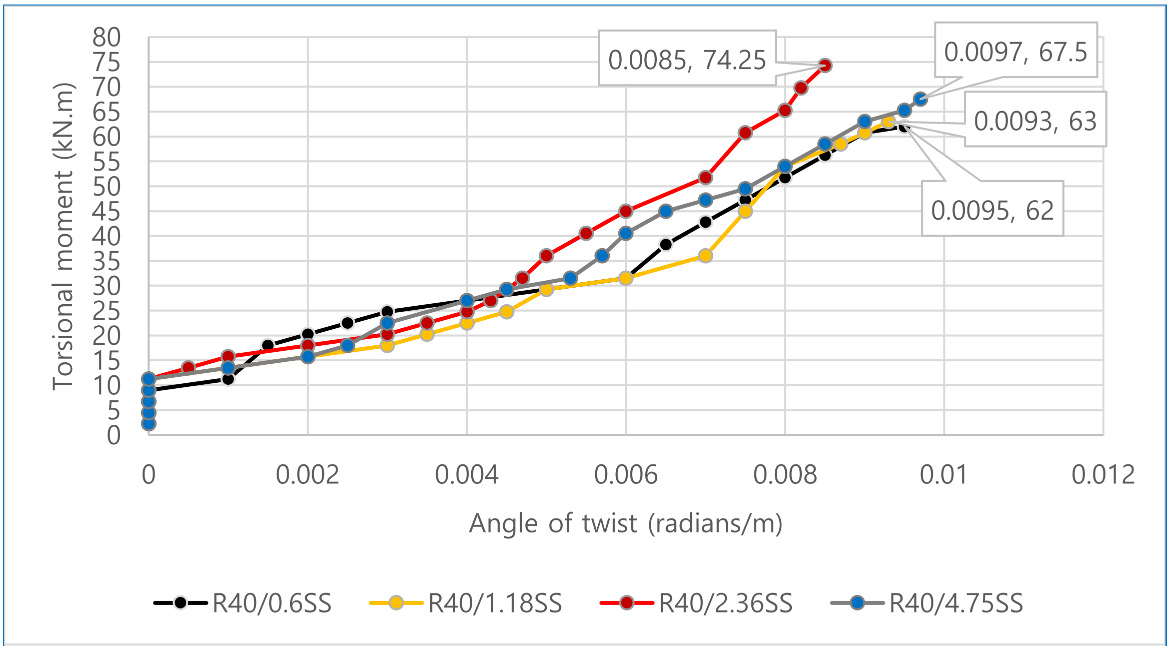

Fig.10 The torsion behavior of the effect of recycled aggregate particle size.

Conclusions

- Considering the superplasticizer percentage and water-to-cement ratio, a laboratory tilting drum mixer can be used in reactive powder concrete mixtures.
- For fresh properties, flow diameter decreases when replacement percentages are increased due to recycled aggregates'
- There is no effect on workability when increasing the size of fine recycled aggregate from (0.6 to 4.75mm) at constant replacement.
- The density of the RPC mix decreases when the replacement percentage of fine recycled aggregate is increased. However, at a constant replacement (40%), when the particle size of recycled aggregate increases the density increases too.
- The compressive strength and split tensile strength of RPC mix give the optimum result at 40% replacement, but for flexural strength, the optimum result is at 60% replacement with 600 µm.
- At day 56 of normal curing, the optimum result for compressive strength is (R40/2.36SS) mix, while at heat curing, the result shows (R40/4.75SS) is the optimum result for compressive strength.
- Compressive strength at day 28 of normal curing where the RPC mixes is not fully developed except for mix (R40/4.75SS), which is at 4.75 mm in size of recycled aggregate. Where the strength is near to day 56 of compressive strength.
- Increasing the particle size of fine recycled aggregates at constant replacement had no negative aspects; rather, quite the opposite, there was an enhancement in the mechanical properties,
- In terms of the effect of replacement, the torsion moment gives the highest result at the first crack state and ultimate state on 40% replacement with recycled aggregate at (600 µm). The twist angle increases gradually as the replacement percentage increases.
- Beam (R40/2.36SS), at 40% replacement with a fine aggregate size of 2.36 mm, gives the optimum torsion moment at both state.
- There is an increase in the twist angle of RPC beams when the recycled aggregate replacement percentage is increased.
- Using fine recycled aggregate made from old concrete as the partial replacement can enhance the strength of RPC mixes and can reduce the pollution of the environment and improve the sustainability of material.

Author Contributions: The authors contributed to all parts of the current study.

Funding: This study received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Halit Yazıcı, Engin Deniz, Bülent Baradan, "The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete", *Construction and Building Materials*, Volume 42,2013,Pages 53-63, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2013.01.003.

[2] Abdul-Hussain, S. T. (2013). Effect of elevated temperatures on compressive and tensile strengths of reactive powder concrete. *Journal of Engineering and Development, 17*(4), 259–266

[3] Sugathan, A. (2016). Steel reinforced reactive powder concrete. *International Journal of Advanced Engineering Research and Science (IJAERS)*, 3(7), 2349-6495(P) | 2456-1908(O). https://doi.org/10.22161/ijaers.3.7

[4] Grzeszczyk S, Matuszek-Chmurowska A, Vejmelková E, Černý R. Reactive Powder Concrete Containing Basalt Fibers: Strength, Abrasion and Porosity. Materials (Basel). 2020 Jul 1;13(13):2948. doi: 10.3390/ma13132948. PMID: 32630228; PMCID: PMC7372488.

[5] Salahuddin, H.; Qureshi, L.A.; Nawaz, A.; Abid, M.; Alyousef, R.; Alabduljabbar, H.; Aslam, F.; Khan, S.F.; Tufail, R.F. "Elevated Temperature Performance of Reactive Powder Concrete Containing Recycled Fine Aggregates". *Materials* 2020, 13, 3748. https://doi.org/10.3390/ma13173748

[6] Hammad Salahuddin, Liaqat Ali Qureshi, Adnan Nawaz, Syed Safdar Raza, "Effect of recycled fine aggregates on performance of Reactive Powder Concrete",*Construction and Building Materials,Volume* 243,2020,118223, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2020.118223.

[7] Borg RP, Cuenca E, Garofalo R, Schillani F, Nasner ML and Ferrara L (2021) "Performance Assessment of Ultra-High Durability Concrete Produced From Recycled Ultra-High Durability Concrete". *Front. Built Environ.* 7:648220. doi: 10.3389/fbuil.2021.648220

[8] Mizaal, A.M., Dawood, E.T. & Fakhri, R.S. Behavior of green reactive powder concrete exposed to aggressive solutions. *Innov. Infrastruct. Solut.* **9**, 380 (2024). https://doi.org/10.1007/s41062-024-01666-4

[9] Naser, Kadhim Z., Lafta, Yousif J., Alhussein, Thamer H., Effect of Steel Fiber Type and Curing Regimen on the Mechanical Properties of Reactive Powder Concrete, *Advances in Civil Engineering*, 2024, 6616375, 14 pages, 2024. https://doi.org/10.1155/2024/6616375

[10] Abdul-Hussein, W. (2010). "Behavior of reinforced reactive powder concrete beams in torsion". *University of Technology, Baghdad, Iraq. Retrieved from* https://uotechnology.edu.iq

[11] Waryosh, W. A., Al-Maliki, H. N., & Munaa, E. M. (2015). Torsional behavior of reinforced concrete hollow core beams. Journal of Engineering and Development, 20(2), 1813-7822.

[12] Ahmed, A. S., & Saad, R. H. (2016). *Behavior of composite-modified reactive powder concrete beams under pure torsion*. Journal of Engineering and Development, 18(3), 45-58.

[13] Alamli, A. S. A., & Abdulameer, S. H. (2017). "Behavior of hollow I-beams reactive powder concrete with opening for pure torque". *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD)*, 7(5), 67-76. ISSN (P): 2249-6866; ISSN (E): 2249-7978

[14] Ashour Al.Khuzaie, Hussein & Atea, Rafid. (2018). "Investigation of torsional behavior and capacity of reactive powder concrete (RPC) of hollow T-beam." Journal of Materials Research and Technology. 8. 10.1016/j.jmrt.2017.10.008.

[15] Mohammed, A. H., et al. (2020). "The influence of RPC thickness on hybrid beams under torsion." IOP Conference Series: Materials Science and Engineering, 737, 012027.

[16] Alamli, A. S., Mehdi, H. A., & Ahmed, R. H. (2020). "Torsional behavior of reactive powder concrete T-beam with web opening". *Journal of Engineering and Sustainable Development*. www.jeasd.org Vol. 21, No.03, May 2017 ISSN 2520-091

[17] Abdullah Adil Mahdi, Aqeel Hatem Chkheiwer, and Mustafa Shareef., " Torsional Behavior of Reactive Powder Reinforced Concrete Beams", *Advanced Engineering Science Journal*

[18] Iraqi Standards and Quality Control Organization. (1984). *Limit of IQ.S. No. 5/1984. Baghdad, Iraq*.

[19] Iraqi Standards and Quality Control Organization. (1984). *Aggregate from natural sources for concrete and construction (No. 45/1984). Baghdad, Iraq.*

[20] American Society of Testing and Material (ASTM) (2020), "Standard Specification for Silica Fume Used in Cementitious Mixtures", ASTM C1240/C1240M-20, ASTM International.

[21] American Society of Testing and Material (ASTM) (2020), "Standard Specification for Chemical Admixtures for Concrete", ASTM C494/C494M-20, ASTM International.

[22] American Society for Testing and Materials (ASTM). (2016). *Standard specification for steel fibers for fiber-reinforced concrete (ASTM A820/A820M-16)*. ASTM International.

[23] ASTM A615, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement", American Society for Testing and Materials, 2016.

[24] British Standards Institution (2019) BS EN 12390-3: 2019. Testing Hardened Concrete. Compressive Strength of Test Specimens. British Standards Institution, London.

[25] ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

[26] ASTM International. (1984). Standard test method for flexural strength of hydraulic-cement mortar and concrete. ASTM C78-84.

[27] American Society for Testing and Materials (ASTM). (2020). *Standard test method for flow of hydraulic cement mortar (ASTM C1437-20)*. ASTM International.

[28] ASTM International. (2023). *ASTM C1611/C1611M-23: Standard test method for slump flow of self-consolidating concrete*. ASTM International. https://doi.org/10.1520/C1611_C1611M-23

[29] Jinyang Jiang, Wenjing Zhou, Yun Gao, Liguo Wang, Fengjuan Wang, Hong-yan Chu, Guangyuan Xu, Brecht Vandevyvere, Zeger Sierens, Jiabin Li, "Feasibility of manufacturing ultra-high performance cement-based composites (UHPCCs) with recycled sand: A preliminary study", *Waste Management, Volume* 83, 2019, Pages 104-112, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2018.11.005.

[30] Yu, L., Huang, L., & Ding, H. (2019). "Rheological and Mechanical Properties of Ultra-High-Performance Concrete Containing Fine Recycled Concrete Aggregates". *Materials*, 12(22), 3717. https://doi.org/10.3390/ma12223717

[31] Salahuddin, H.; Qureshi, L.A.; Nawaz, A.; Abid, M.; Alyousef, R.; Alabduljabbar, H.; Aslam, F.; Khan, S.F.; Tufail, R.F. "Elevated Temperature Performance of Reactive Powder Concrete Containing Recycled Fine Aggregates". *Materials* 2020, 13, 3748. https://doi.org/10.3390/ma13173748

[32] Hammad Salahuddin, Liaqat Ali Qureshi, Adnan Nawaz, Syed Safdar Raza, "Effect of recycled fine aggregates on performance of Reactive Powder Concrete",*Construction and Building Materials,Volume* 243,2020,118223, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2020.118223.

[33] Borg RP, Cuenca E, Garofalo R, Schillani F, Nasner ML and Ferrara L (2021) "Performance Assessment of Ultra-High Durability Concrete Produced From Recycled Ultra-High Durability Concrete". *Front. Built Environ.* 7:648220. doi: 10.3389/fbuil.2021.648220