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# Structural Behavior of Reinforced Concrete One-Way Slabs Cast with Self-Compacting Concrete Containing Recycled Concrete as Coarse Aggregate

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## Abstract

**This work deals with the effect of using Recycled Concrete Aggregate (RCA) as a partial replacement of coarse aggregate in Self-Compacting Concrete (SCC), on the structural behavior (flexure and shear) of reinforced concrete one-way slabs. To the authors' knowledge, this study is one of limited studies concerning the behavior of recycled aggregate concrete one-way slabs subjected to line loading with significant replacement of conventional aggregates by recycled concrete aggregate (up to 75 %). Three replacement ratios were considered 25 %, 50 % and, 75 %. The mixes (with natural stone coarse aggregate, NCA) have an averaged compressive strength of (Fcu = 42 MPa) at the age of 28 days with a tolerance of (± 1.5 MPa). While, the mixes (with RCA) have an averaged compressive strength of (38.5, 36.5 and 34 MPa) for the three replacement ratios respectively, at the age of 28 days with a tolerance of (± 2 MPa). All the slabs were cast with length of (1600 mm), width of (600 mm), while the thickness was variable. For this purpose, sixteen reinforced concrete one-way slabs were cast and divided into five groups (G1 to G5). Different parameters that affect the behavior of one-way slabs were studied and include type of failure, replacement ratios of NCA by RCA, amount of main reinforcement, thickness and locations of line loadings along the span. Hardened concrete specimens results show that the compressive strength Fcu, tensile strength Ft, modulus of rupture Fr and modulus of elasticity E were decreased as the RCA replacement increased. The experimental results of slabs show that the ultimate capacity of slabs decreased as the RCA replacement increased, the deflection and strain increase as the RCA replacement increases and the crack width increases as the RCA replacement increases. From the results of ultimate capacity, cracking load and moment, deflections, crack width and pattern and concrete surface strains, it can be concluded that the recycled concrete aggregate can be used as a partial replacement of natural coarse aggregate to produce self-compacting concrete mixes. Also, the behavior of one way slabs cast with SCC containing RCA is acceptable.**



***Keywords:*** One-way slabs, Structural behavior, Self-compacting concrete, Recycled coarse aggregate.

## 1. Introduction

Concrete is considered as the second most used material in the world after water, because it uses a significant amount of non-renewable resources. The demand for concrete was very huge in the past and will continue to be in future. Concrete consumes a significant quantity of non-renewable materials especially natural stone aggregate. Also, the main element resulted from structure demolition is concrete. The rubbishes from demolition are increasing to a large level, which leads to an increase in landfill areas. This may cause groundwater pollution, which result in a negative environmental impact. Furthermore, millions of dollars paid yearly to:

1. Remove the concrete wastes from construction and demolition sites.
2. Transport the concrete wastes out of the major cities to the proposed landfill areas.
3. Perform needed procedures to bury the concrete wastes.

Sainz-Aja et al. [1] pointed that during 2016, a total of 2533 million tons of waste were generated in the European Union. Almost 36.4 % wt (weights were considered for comparisons) of which came from construction.

Poon et al. [2] estimated that in 8 years landfills in China will be saturated.

Yet, this amount of demolition wastes is increasing to vastly rates in Iraq and Middle East due to military actions at those countries. Unfortunately, the record on amount of demolition wastes is not available in those countries and there are no sufficient financial resources to get rid of the wastes, which are leading to a very negative impact on environment, human health and safety.

Therefore, making use of such wastes in concrete works will have economic and environmental benefits.

## 2. Behavior of RCA (Materials and Structural)

The structural behavior of reinforced concrete containing RCA is not as expressively affected by RCA incorporation as the material behavior of RCA (materials behavior refers to fresh and hardened concrete behavior containing RCA) since the flexural behavior of reinforced concrete is mostly controlled by the steel reinforcement and contribution of reinforcement in shear resistance.

Dong et al. (2019) [3], studied the interaction between steel bars and RAC. Fifteen (1100 × 300 × 150 mm) beams specimens were designed and tested to investigate the RAC-reinforcement bond behavior. They concluded that bond strength between reinforcements and concrete decreases with increasing of the RCA replacement percentage. However, the rate of decrease is reduced for specimens with low water-cement ratio compared to conventional concrete. The bond strength of RAC with a higher water-cement ratio (w/c = 0.42) decreased by 12 - 22 %, and decreased by 1 - 12 % for a water-cement ratio of 0.33.

Wu et al. (2018) [4], investigated the tensile-splitting behavior of the compound concrete. Two series of tests were conducted. In both of the series demolished concrete lumps DCLs were added. They found that: (1) the adverse effect of the DCLs on the combined tensile-splitting strength of the compound concrete did not increase significantly with the increase in the difference between the compressive strength of the fresh concrete and that of the demolished concrete; (2) for the compound concrete containing normal-strength FC I (41 - 43 MPa), the ratio of the combined tensile-splitting strength to the combined compressive strength was generally close to that for conventional normal-strength concrete, but for compound concrete containing high-strength FC II (53 - 65 MPa) (the ratio was approximately 1.1 times that for conventional high-strength concrete.

Ozbakkaloglu et al. (2018) [5], presented a study on mechanical and durability properties of concretes manufactured with recycled aggregates of different sizes and contents. Their results show that for a given w/c ratio, the compressive strength of RAC decreases with an increase in the recycled aggregate replacement ratio. Also, for the comparisons of the flexural and the splitting tensile strengths of both NSC and HSC mixes decreased with an increase in RCA %.

Schubert et al. (2012) [6], focused on the shear resistance of RCA one way slabs without shear reinforcement. The slabs made of recycled aggregate concrete showed similar crack distributions as the slabs made of natural aggregate concrete. During the tests the first flexural cracks formed in the middle of the slab. Some predictions based on different code formulas showed good correlation with the experimental results. They recommended to increasing the safety factor for the shear resistance for the slabs with RCA.

Maruyama et al. (2004) [7], their research comprises beams with varying main reinforcement ratios ranged between 2.4 % and 4.2 %. Also, they used water/cement ratios as a second variable, three different w/c were used (0.30, 0.45, and 0.60). Their study showed that the crack patterns and failure type of the RCA beams were identical with the NA concrete beams. The RCA beams without stirrups showed 10 % lower shear strength compared with the NA concrete beams.

Gonzalez-Fonteboa and Martinez-Abella (2007) [8], tested eight beams with 3 % longitudinal reinforcement ratio and 50 % recycled coarse aggregate. Results of their study showed that in terms of both deflection and ultimate shear strength, no significant difference was observed between the RAC and CC beams, but they observed notable splitting cracks along the tension reinforcement. They concluded that existing code provisions for shear can be used for the RAC beams.

## 3. Experimental Program

### *3.1. Materials*

Ordinary Portland cement and natural fine aggregate (sand) were used. Natural coarse aggregate was used with different replacement ratios of RCA. Both of NA RCA has same gradation zone and satisfying (Iraqi specification No.45/1984) [9] requirements. The recycled aggregate was prepared by manually crushing using concrete cubes belong to ongoing project in Basrah city. The crushed concrete was divided into two size (10 to 14 and 5 to 10 mm) by utilizing sieves, these two fractions were mixed in proportions to obtain grading comparable to that of natural aggregate, see Table 1 and Table 2. Tap water from the water-supply network was used. The high range water reducer (HRWR), Glenium 51, was used to get self-compacting concrete (SCC) property. Limestone powder locally named AL-Gubra was bought from local market and used as a filler material in the production of SCC. Ukrainian brand deformed steel reinforcing bars with different diameters (Ø 8 mm, Ø 10 mm and Ø 12 mm) were used, which satisfy the (ASTM A615/ A615M-05) [10].

### *3.2. Concrete Mixes*

Four types of SCC mixes were used, the first mix was made with natural coarse aggregate (0 % RCA) and the remaining three mixes were containing RCA as a partial replacement of NCA at replacement ratios of (25 %, 50 % and 75 %). Many trial mixes where prepared in order to meet fresh SCC requirements for mixes made with natural and with recycled concrete aggregates, the quantity of cement was the same for all mixes (0 %, 25 %, 50 % and 75 %) as shown in Table 1.

**Table 1** Mix design proportion ratios.

| Material | Content (kg/m$^3$) |
|---|---|
| Cement | 403 |
| Limestone Powder | 172 |
| Coarse Aggregate | 840 |
| Fine Aggregate | 803 |
| Water/cement ratio | 178 |
| Glenium 51 | 4 |

### *3.3. Mixing Procedure*

Rotary drum mixer was employed, prior to commence mixing. The mixer has been cleaned and moistened from inside. Mixing procedure developed by Jin [11] was adopted throughout this research. Fig. 1 shows the mixing procedure used along this study.

1. Powder (cement and limestone) and aggregate were mixed for one minute.
2. The water first part (W1) (80 %) of mixing water was added slowly while mixing and then mixed for further one minute.
3. The water second part (20 %) of mixing water plus super plasticizer, mixed together, was added slowly, while mixing for 4 minutes.
4. Rest for 3.5 minutes.
5. Remixing for 30 seconds for the mix to be ready.

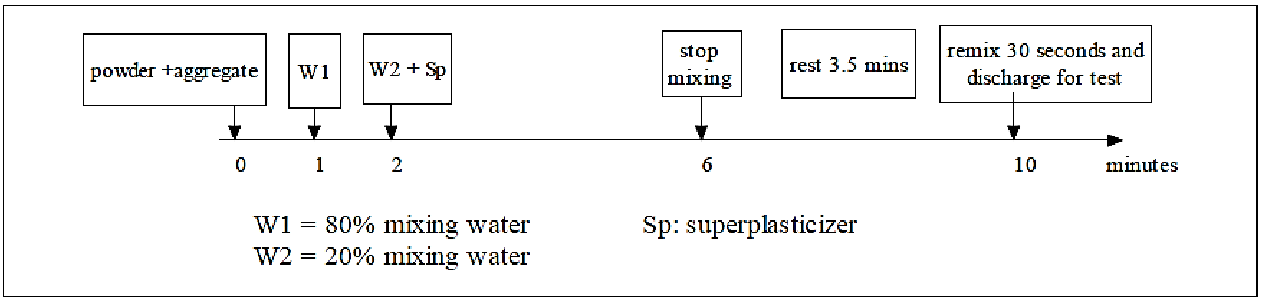


**Fig. 1** Concrete mixing procedure [11].

### *3.4. Slabs Details*

Sixteen slabs with and without RCA designed to failed in flexure and shear with a different (a/d) ratios (1, 2, 3 and 6) were cast. The slabs were cast with dimensions of total length of 1600 mm, width of 600 mm and variable thicknesses. The slabs were cast with different reinforcement ratios and three mixes were considered depending on RCA replacement percentages. Table 2 and Fig. 2 present the details of slabs.

**Table 2** Details of slabs.

| G | Slabs (%) | Reinf. | RCA (%) | a/d | Dimensions (mm) | | |
|---|---|---|---|---|---|---|---|
| G1 | 1W1 (0) | 5Φ10 | 0 | 2 | 1600 | 600 | 150 |
| | 1W2 (25) | | 25 | 2 | 1600 | 600 | 150 |
| | 1W3 (50) | | 50 | 2 | 1600 | 600 | 150 |
| | 1W4 (75) | | 75 | 2 | 1600 | 600 | 150 |
| G2 | 1W5 (0) | 7Φ12 | 0 | 6 | 1600 | 600 | 100 |
| | 1W8 (50) | | 50 | 6 | 1600 | 600 | 100 |
| | 1W6 (0) | 7Φ12 | 0 | 6 | 1600 | 600 | 120 |
| | 1W9 (50) | | 50 | 6 | 1600 | 600 | 120 |
| G3 | 1W14 (0) | 7Φ12 | 0 | 3 | 1600 | 600 | 200 |
| | 1W16 (50) | | 50 | 3 | 1600 | 600 | 200 |
| G4 | 1W7 (0) | 7Φ12 | 0 | 1 | 1600 | 600 | 150 |
| | 1W10 (50) | | 50 | 1 | 1600 | 600 | 150 |
| | 1W13 (0) | 7Φ12 | 0 | 1 | 1600 | 600 | 100 |
| | 1W15 (50) | | 50 | 1 | 1600 | 600 | 100 |
| G5 | 1W11 (0) | 13Φ12 | 0 | 3 | 1600 | 600 | 100 |
| | 1W12 (50) | | 50 | 3 | 1600 | 600 | 100 |

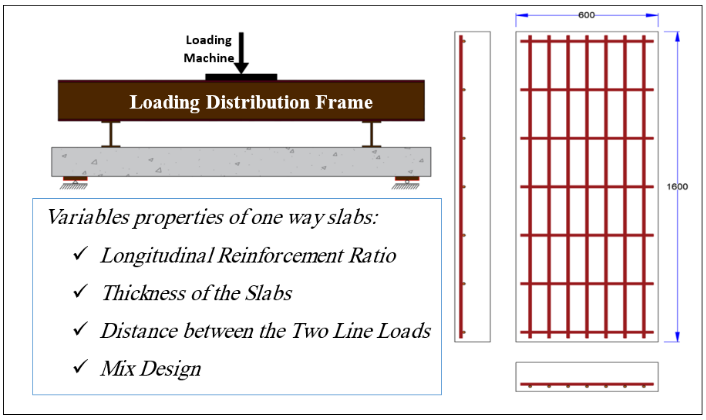


**Fig. 2** Slabs Details and considered loading system.

### *3.5. Casting, Curing and Testing of Slabs*

Slabs details and properties as in section 3.4. The steel reinforcement grids were fabricated and placed in their exact locations in the epoxy-painted plywood shutters. All molds were prepared for casting by oiling along the interior surfaces of the mold in order to prevent adhesion with concrete after hardening. No vibrator was used during concreting. Concrete was poured in one place inside the shutters and left to spread by its property of self-compacting, the surfacing done by using a steel trowel for the purpose of well finishing, the concrete finished to the same level of the shutter walls. Three cubes were cast for each patch, three flexural beams and six cylinders were cast for each concreting day, to evaluate the compressive strength, modulus of elasticity, splitting tensile strength. The slabs, cubes and cylinders were covered with wet canvas and polyethylene sheet for three weeks. All the slabs formworks were demolded after three weeks from casting date, as shown in Fig. 3.

**Fig. 3** Concreting and curing the slabs.

Before starting tests, the slabs were painted with white color, by using water solved paint, from bottom and both long sides for the cracks to be clear visible at earliest cracking loads. The location, where the loads applied and the supports were highlighted as well as the locations of the Demec points distribution was fixed. Using testing instruments and collecting measures and were as follows.

- Electronic dial gauges of 0.01 mm/div was used for deflection measurement at mid-span.
- Concrete surface strains were measured by using Demec points and mechanical strain gauge, digital type (Mitutoyo Absolute) with a maximum length of 100 mm and accuracy of one micron.

From the first appearance up to final development, the cracks were highlighted. Cracks width was measured by using electronic digital instrument up to linear portion of material behavior, as shown in Fig. 4.

**Fig. 4** testing of slabs.

## 4. Test Results and Discussion

### *4.1. Fresh and Hardened Properties of SCC with or without RCA*

The fresh and hardened properties of SCC are shown in Table 3 and Table 4 respectively. For fresh concrete three types of tests were conducted to satisfy SCC requirements. These tests include slump-flow, V-Funnel and L-Box test. It can be noticed that the properties of the fresh mixes are within the requirements for self-compacting concrete, (EFNARC-2005) [12] requirements. For hardened concrete, the compressive strength, tensile strength, modulus of elasticity and modulus of rapture were determined.

**Table 3** Tests results of fresh self-compacting concrete.

| RCA (%) | Slump flow (mm) | EFNARC Guideline | | T 500 (sec) | EFNARC Guideline | | V-funnel (sec) | EFNARC Guideline | | L-Box | EFNARC Guideline | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min. | Max. | | Min. | Max. | | Min. | Max. | | Min. | Max. |
| 0 | 710 | 650 | 800 | 2.76 | 2 | 5 | 8.47 | 8 | 12 | 0.96 | 0.8 | 1.00 |
| 25 | 700 | 650 | 800 | 2.79 | 2 | 5 | 8.55 | 8 | 12 | 0.92 | 0.8 | 1.00 |
| 50 | 690 | 650 | 800 | 2.90 | 2 | 5 | 8.86 | 8 | 12 | 0.89 | 0.8 | 1.00 |
| 75 | 640 | 650 | 800 | 3.40 | 2 | 5 | 9.81 | 8 | 12 | 0.89 | 0.8 | 1.00 |

**Table 4** Properties of hardened self-compacted concrete.

| SN | RCA % | $F_{cu}$ MPa | $F_t$ MPa | $F_r$ MPa | $E_c$ GPa |
|---|---|---|---|---|---|
| 1 | 0 % | 42.1 | 3.822 | 5.86 | 27.67 |
| 2 | 25 % | 38.47 | 3.322 | 5.80 | 24.99 |
| 3 | 50 % | 36.40 | 3.148 | 4.59 | 23.34 |
| 4 | 75 % | 34.05 | 2.849 | 3.85 | 23.07 |

It can be seen from Table 5 exhibited that, when the compressive strength of the RCA concrete is lower than that of the conventional concrete, the tensile strength (for both flexural and splitting tests) of the RCA concrete decreases gradually with the increase of RCA replacement ratios, and the decrease rate increase significantly with the increase of the strength difference between the conventional concrete and the RCA concrete. The decrease ratios of the modulus of elasticity, due to RCA replacements are generally close to compressive strengths.

**Table 5** Decrease in hardened concrete properties due to RCA content.

| SN | RCA % | $F_{cu}$ MPa | $F_t$ MPa | $F_r$ MPa | $E_c$ GPa |
|---|---|---|---|---|---|
| 2 | 25 % | 8.62 % | 13.08 % | 10.10 % | 9.69 % |
| 3 | 50 % | 13.54 % | 17.63 % | 21.67 % | 15.65 % |
| 4 | 75 % | 19.12 % | 25.46 % | 34.30 % | 16.62 % |

*4.2. Structural Behavior of Slabs*

Test results are presented in Table 6 and Table 7. The effect of different parameters such as replacement ratios of RCA, longitudinal reinforcement, slab thickness and location of loading along the span on the structural behavior of one-way slabs is discussed in the following paragraphs:

**Table 6** Cracking and ultimate moments of slabs failed in flexure.

| G | Slabs (%) | Reinf. | RCA (%) | a/d | Dimensions (mm) | | | $M_{cr}$ (kN.m) | $M_u$ (kN.m) | $M_{cr}$ / $M_u$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G1 | 1W1 (0) | 5F10 | 0 | 2 | 1600 | 600 | 150 | 8.75 | 22.81 | 0.38 | Flexure |
| | 1W2 (25) | | 25 | 2 | 1600 | 600 | 150 | 8.13 | 21.88 | 0.37 | Flexure |
| | 1W3 (50) | | 50 | 2 | 1600 | 600 | 150 | 7.50 | 20.94 | 0.36 | Flexure |
| | 1W4 (75) | | 75 | 2 | 1600 | 600 | 150 | 6.88 | 20.13 | 0.34 | Flexure |
| G2 | 1W5 (0) | 7F12 | 0 | 6 | 1600 | 600 | 100 | 6.75 | 27.00 | 0.25 | Flexure |
| | 1W8 (50) | | 50 | 6 | 1600 | 600 | 100 | 5.63 | 24.75 | 0.23 | Flexure |
| | 1W6 (0) | | 0 | 6 | 1600 | 600 | 120 | 9.00 | 34.50 | 0.26 | Flexure |
| | 1W9 (50) | | 50 | 6 | 1600 | 600 | 120 | 7.50 | 31.50 | 0.24 | Flexure |
| G3 | 1W14 (0) | 7F12 | 0 | 3 | 1600 | 600 | 200 | 18.00 | 69.00 | 0.26 | Flexure |
| | 1W16 (50) | | 50 | 3 | 1600 | 600 | 200 | 15.00 | 64.50 | 0.23 | Flexure |

**Table 7** Cracking and ultimate loads of slabs failed in shear.

| G | Slabs (%) | Reinf. | RCA (%) | a/d | Dimensions (mm) | | | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}$ / $P_u$ | Failure Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G4 | 1W7 (0) | 7Φ12 | 0 | 1 | 1600 | 600 | 150 | 130.00 | 610.00 | 0.21 | Shear |
| | 1W10 (50) | | 50 | 1 | 1600 | 600 | 150 | 120.00 | 580.00 | 0.21 | Shear |
| | 1W13 (0) | | 0 | 1 | 1600 | 600 | 100 | 90.00 | 480.00 | 0.19 | Shear |
| | 1W15 (50) | | 50 | 1 | 1600 | 600 | 100 | 85.00 | 450.00 | 0.19 | Shear |
| G5 | 1W11 (0) | 13Φ12 | 0 | 3 | 1600 | 600 | 100 | 45.00 | 210.00 | 0.21 | Shear |
| | 1W12 (50) | | 50 | 3 | 1600 | 600 | 100 | 40.00 | 195.00 | 0.21 | Shear |

*4.2.1 Load – Deflection Curves of Slabs*

The load versus deflection curves for SCC reinforced concrete slabs with and without RCA is needed as a part of description of structural behavior of slabs. One electronic dial gauge was used with a maximum capacity equal to 50 mm to measure the average deflection at the center of the bottom face of slabs.

The effect of parameters described in Table 6 and Table 7 are shown in Fig. 5. It can be indicated that the slabs with RCA show more deflection than slabs without RCA, because of the lower modulus of elasticity of concrete with RCA compared to concrete without RCA.

*4.2.2 Cracking and Ultimate Moments of Slabs Failed in Flexure*

The cracking and ultimate moment were decreased with the increase in the replacement ratio, as shown in Table 6. The decrease in ultimate moment ascribed to the reduction in concrete strength accompanying to the increase in replacement percentage. Consequently, concrete crushing in the compression zone would take place at smaller loads for those slabs. Whereas, the decrease in cracking moment was due to the smaller tensile strength of concrete attached to high replacement ratio.

The tested slabs can be classified into three groups based on (a/d) values, reinforcement amount, thickness and associated slabs failure. These slabs are elaborated as follows:

- G1 Slabs 1W1 0 %, 1W2 25 %, 1W3 50 % & 1W4 75 %

**Replacement Ratio:**

When RCA replacement percentage increase from 0 % to 25 %, the cracking moment decreased by 7 % and the ultimate moment decreased by 4 %. Further, increase in RCA replacement percentage to 50 %, the cracking moment decreased by 14 % and ultimate moment decreased by 8 %, while when RCA percentage becomes 75 %, the cracking moment and ultimate moment reduced by 21 % and 12 %, respectively.

Slabs in G1 showed (Mcr / Mu) ratios greater than that ratios in rest slabs. This observation reflects that slabs in G1 have less reinforcement ratio and greater slab thickness than G2 slabs. Whereas, the decrease in reinforcement ratio and the increase in the slab thickness proportionally increase (Mcr / Mu) ratio for slabs in G1.

- G2 Slabs (1W5 0 %, 1W8 50 %) and (1W6 0 %, 1W9 50 %)

**Replacement Ratio:**

For slabs 1W5 & 1W8, when RCA replacement percentage increase from 0 % to 50 %, the cracking and ultimate moment decreased by 17 % and 8 % respectively. For slabs 1W6 & 1W9 when RCA replacement percentage increase from 0 % to 50 %, the cracking and ultimate moment decreased by 17 % and 9 % respectively.

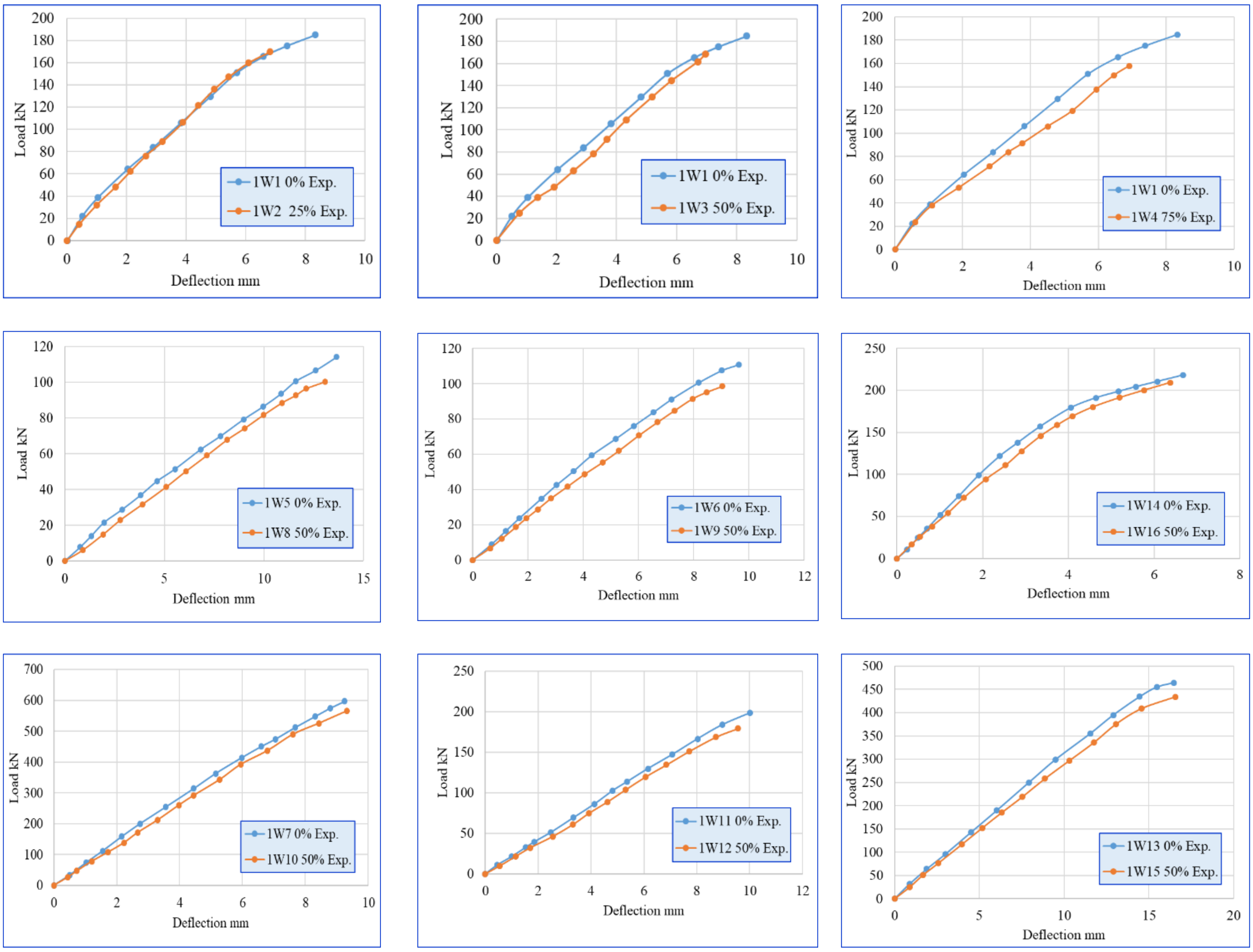


**Fig. 5** Experimental load versus mid-span deflection curve Slabs.

**Thickness:**

Although the slabs (1W5 0 % and 1W8 50 %) are differ from slabs (1W6 0 % & 1W9 50 %) in thickness, the decrease due to RCA replacement percentage was remained almost same. Therefore, it can be observed that changing slabs thickness does not affect "the reduction ratio".

Increasing the thickness from 100 mm (1W5 0 %) to 120 mm (1W6 0 %), increase Mcr and Mu by 33 % and 27 %, respectively. These percentages remain same when comparing results of 1W8 50 % to 1W9 50 %. Thus, the increase in moment capacity of the slabs due to increase slabs thickness does not change in case of adding RCA to the mix.

- G 3 Slabs (1W14 0 % and 1W16 50 %)

**Replacement Ratio:**

When RCA replacement percentage increase from 0 % to 50 %, the cracking and ultimate moment decreased by 17 % and 7 %, respectively.

By comparing the results of the three groups (G1, G2 & G3) detailed in Table 6, it was found that the change of thickness and a/d amount have no further effect on the effect of incorporating of RCA in reinforced concrete, i.e. the effect of these parameters on the behavior of slabs without RCA is identical to its effect on the slabs with RCA.

Comparing the values of Mcr and Mu for slabs of group G3 with those of group G2, it can be notice that G3 slabs showed higher Mcr and Mu due to greater slab thickness, which results in greater moment lever arm.

*4.2.3. Cracking and Ultimate Loads of Slabs Failed in Shear*

Slabs of this section are detailed in Table 7.

- G 4 Slabs (1W7 0 %, 1W10 50 %) and (1W13 0 %, 1W15 50 %)

**Replacement Ratio:**

When RCA replacement percentage increase from 0 % 50 %, the cracking load decreased by 7.7 % and ultimate load decreased by 5 %, for slabs 1W7 and 1W10, respectively. When RCA replacement percentage increase from 0 % to 50 %, the cracking and ultimate load decreased by 6.25 % and 4 %, for slabs 1W13 and 1W15, respectively.

**Thickness:**

Same observation that made for slabs failed in flexure, the slabs (1W7 0 % and 1W10 50 %) are differ from slabs (1W13 0 % and 1W15 50 %) in thickness, the decrease due to RCA replacement percentage was remained almost same. So, it can be stated that changing slabs thickness does not affect "reduction ratio".

Increasing the thickness from 100 mm (1W13 0 %) to 150 mm (1W7 0 %), increase Pcr and Pu by 43 % and 27 %, respectively. These percentages remain almost same when comparing results of 1W15 50 % to 1W10 50 %. Thus, the increase in shear resistance of the slabs due to increase slabs thickness does not change in case of adding RCA to the mix.

- G 5 Slabs (1W11 0 % and 1W12 50 %)

**Replacement Ratio:**

When RCA replacement percentage increased from 0 % to 50 %, the cracking load and ultimate load decreased by 11 % and 7 %, respectively.

Slabs in G5, which have the greatest reinforcement ratio and greatest (a/d) value, show the greatest decrease ratios in cracking and ultimate loads due to adding RCA. Therefore, it can be observed that (a/d) value is the most significant parameter that can affect decrease ratios due to adding RCA replacement rather than reinforcement ratio and slab thickness for slabs failed in shear as well.

Slabs in G4, which have a reinforcement ratio range from 0.9 % to 1.3 % and relatively least (a/d) value, show the least decrease ratios in cracking and ultimate loads due to adding RCA. Therefore, that the previous observation of G5 can be confirmed through G4 slabs results.

Slabs in G4 show results vastly close results (reduction ratios), despite the former have the greatest thickness and the least reinforcement ratio, but same (a/d) value. This is a second confirmation for predomination of (a/d) values on the decrease ratios of cracking and ultimate loads of slabs containing RCA as a portion of coarse aggregate.

### *4.2.4. Crack Behavior and Failure Pattern*

#### *4.2.4.1. Slabs Failed in Flexure*

At the load level below crack load, flexural cracks predominantly spread and developed perpendicularly toward the top surface of slabs in the direction of maximum principal stress that induced by pure moment. As the load increased, more cracks beyond the flexure zone were developed in a similar manner of flexural cracks. As the shear stresses became more significant, more inclined cracks appear outside the pure bending zone.

In the context of comparing the crack behavior of slabs with and without RCA replacements, it can be seen that the general behavior of the cracks is almost the same except the cracks of slabs with RCA replacement are slightly wider and the number of cracks is higher. This is due to higher strain produced in slabs with RCA replacement compared to slabs without RCA replacement, also the strength of concrete in tension. However, it is important to observe cracks at service loads (ACI318-14) [13]. Figs. 6 and 7, show failure pattern and load-flexural cracks relations, respectively. These Figures show that RCA slabs have cracks width slightly greater than same NCA slabs in the same load stage. This may be caused by the first crack load of RCA slabs less than that of NCA slabs. However, the crack width increases as concrete compressive strength decreases in RCA concrete. This is attributed to the lower modulus of rapture, tensile strength and lower modulus of elasticity of higher strength concrete.

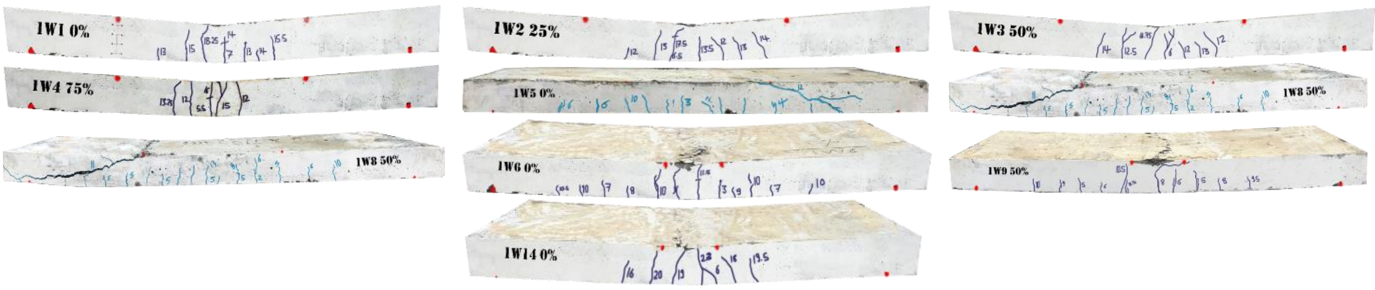


**Fig. 6** Cracks pattern of slabs failed in flexure.

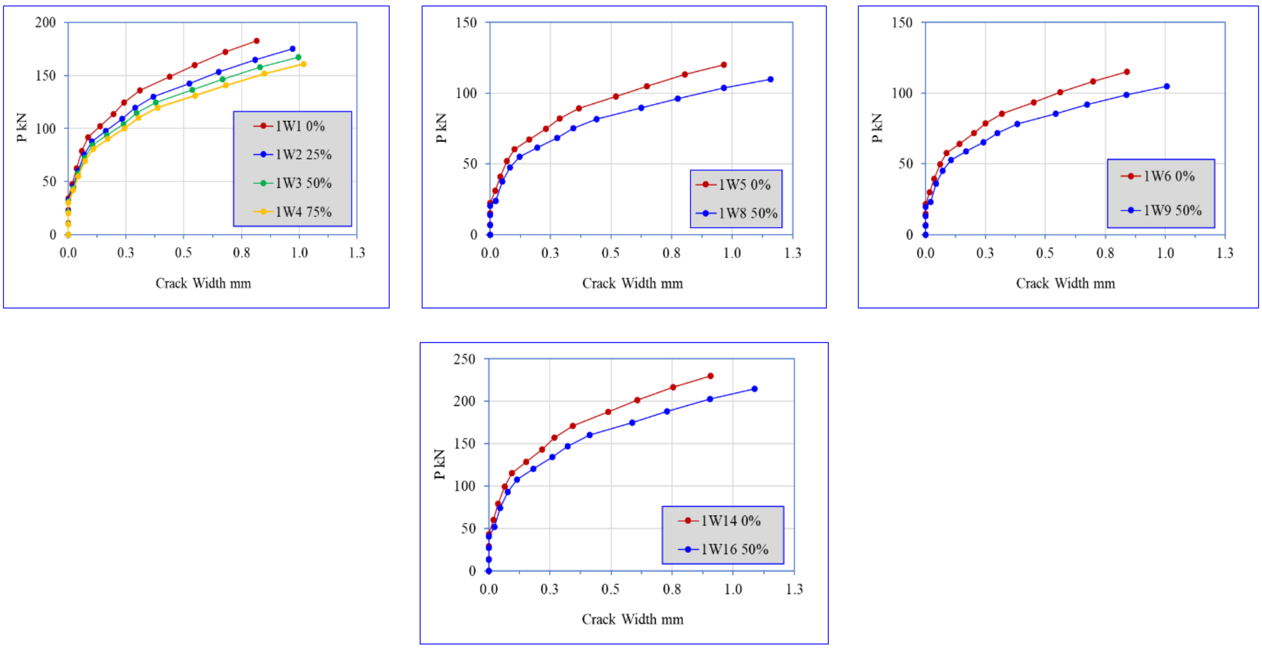


**Fig. 7** Load-flexural cracks relations for slabs failed in flexure.

#### *4.2.4.2. Slabs Failed in Shear*

At the load level below crack load, flexural cracks predominantly spread and developed perpendicularly toward the top surface of slabs in the direction of maximum principal stress induced by pure moment. As the shear stresses became more significant, more inclined cracks appear.

The diagonal cracking (at which particular slab failed) load was close to the ultimate load, the diagonal crack that causing failure started suddenly from the last flexural crack that became inclined and crossed mid-depth, and then such a crack propagated simultaneously towards the load-point and towards the support along the tensile reinforcement (due to dowel action) causing a loss of bond and failure of the slab.

In term of crack behavior, a comparison between slabs with and without RCA replacements was made. It can be seen that the general behavior of the cracks is almost the same except the cracks of slabs with RCA replacement, which is slightly wider and higher in number. This is due to higher produced in slabs with RCA replacement compared to slabs without RCA replacement. Figs. 8 and 9, show failure pattern and load-flexural cracks relations, respectively. The flexural cracks were the first to appear, but their height and width stopped after the rise of inclined shear crack. These Figures show that RCA slabs have flexural cracks width and number of cracks slightly greater than same NCA slabs.

**Fig. 8** Cracks pattern of slabs failed in shear.

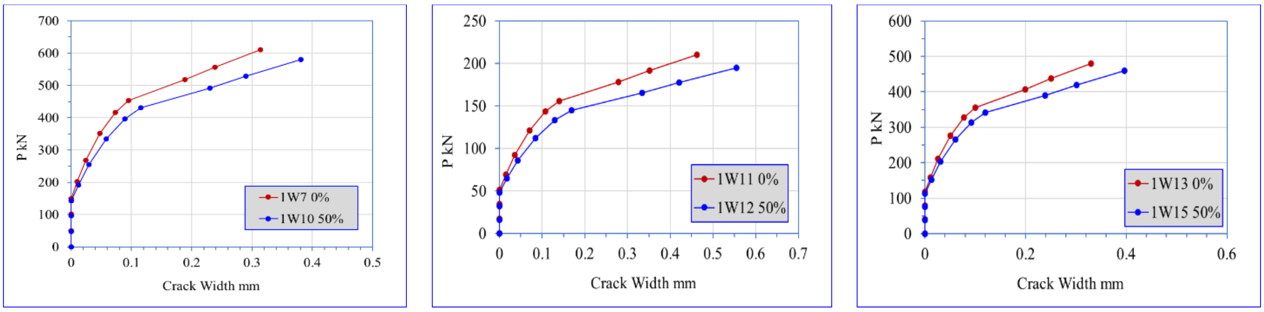


**Fig. 9** Load-flexural cracks relations of slabs failed in shear.

### *4.2.5. Concrete Strains*

To measure surface strain of concrete slabs, Demec points were used, which were located at both sides of centerline of load application, as shown in Fig. 10. The strains were measured by using mechanical strain gauge at every loading stage up to cracking load. From the first loading step up to cracking load, elastic stage, the slabs show the same behavior. Therefore, the strains measured at cracking load (near cracking load) considered to be expressing the behavior of the slabs for all load levels prior to the cracked stage. Fig. 11 present strains distribution along the slab's depth at Pcr.

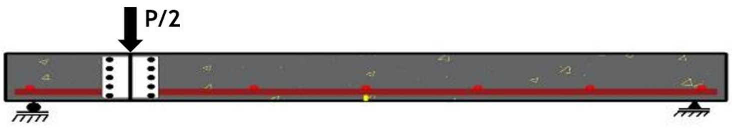


**Fig. 10** Demec points locations for all slabs.

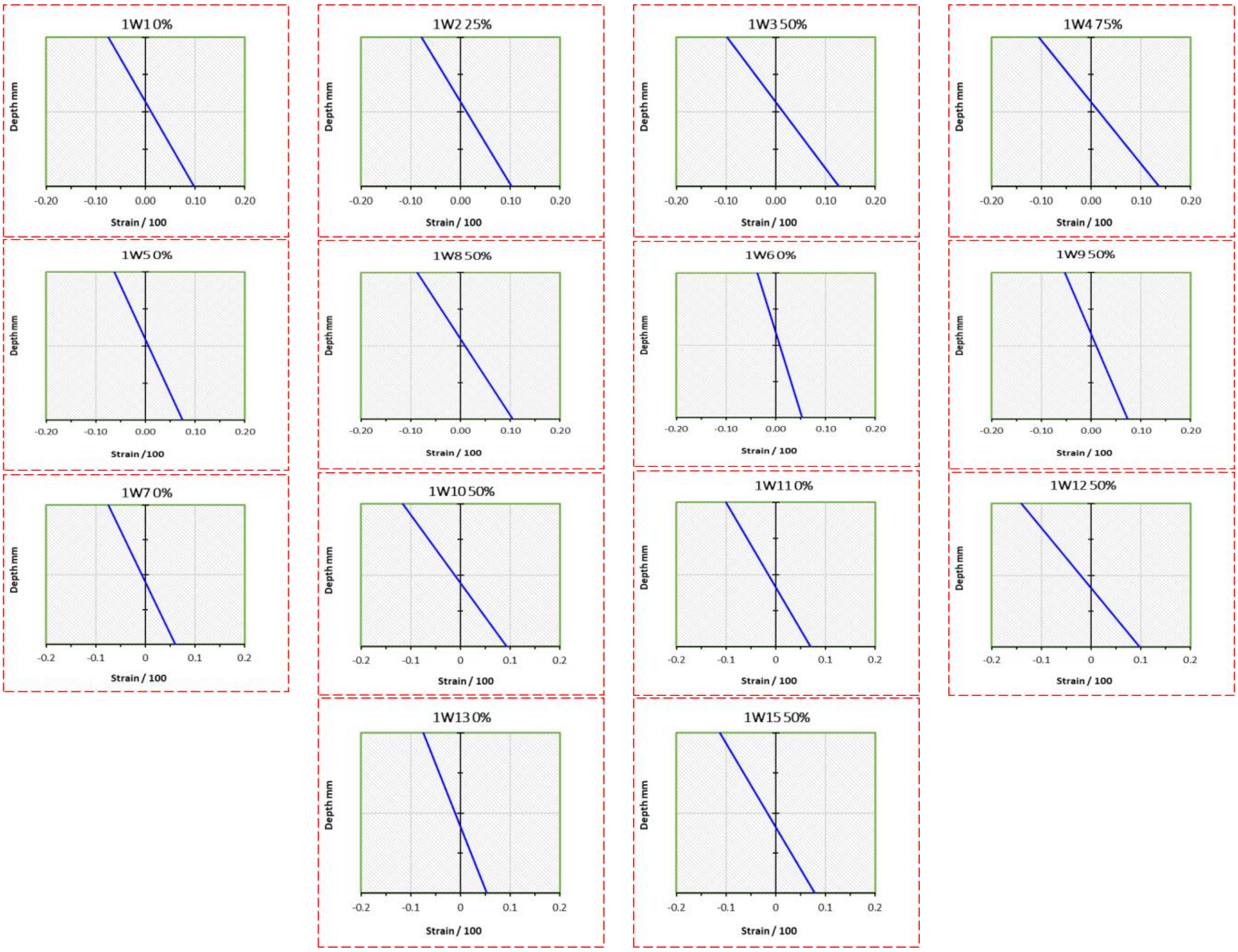


**Fig. 11** Strain distribution of slabs at near cracking load.

## 5. Conclusions

Based on the gained experimental results, it can be concluded that:

1. From Slump Flow, V-Funnel and L-Box tests, it was observed that the flowability, filling ability and passing ability of self-compacted concrete decreased as RCA replacement increased.
2. Fcu, Ft, Fr and E values, decreased as the RCA replacement increased.
3. Including of RCA in concrete mixes cause the first crack appear earlier in comparison to slabs made of NCA concrete.
4. The cracking and ultimate moment capacity of slabs failed in flexure decrease when adding RCA to the mixes in comparison to slabs made of NCA concrete. The maximum decrease ratio was for slabs 1W4 75 %, where the cracking moment and ultimate moment decreased by 21 % and 12 % respectively.
5. The cracking and ultimate load of slabs failed in shear decrease when adding RCA to the mixes in comparison to slabs made of NCA concrete. The maximum decrease ratio was for slabs 1W11 50 %, where the cracking and ultimate loads decreased by 11.11 % and 7.14 % respectively.
6. Impact of changing thickness, reinforcement amount and a/d on RCA concrete is same as NCA concrete, i.e. the thickness, reinforcement amount and a/d parameters have no effect on the decrease ratios due to replacing NCA by RCA concrete.
7. Slabs containing RCA induce higher deflection. The maximum increase ratio was for slabs 1W4 75 %, where the ultimate deflection increased by 9 % at the same load level of 1W1 0 %.
8. For both concrete types (with and without RCA), the general behavior of the cracks is almost same, except the cracks of slabs with RCA replacement, which is slightly wider. The maximum increase ratio was for slabs 1W8 50 % where the flexural crack increased by 20 %.
9. Strains at cracking load and below (elastic stage), increased as the RCA replacement ratio increase.

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