Reinforced Concrete Slabs Containing Recycled Concrete as Coarse Aggregate

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Abstract. This research presents an experimental study on the performance of reinforced recycled aggregate concrete (RAC) that contains one of two types of recycled coarse aggregate, one from normal concrete and another from self – compacting concrete (SCC). The replacement percentages (by weight) of natural coarse aggregate with the recycled coarse aggregate are (0, 33.3, 66.7 & 100) % by weight. Moreover, Silica Fume was used as an admixture for all (RAC) mixtures. Concrete compressive strength, split tensile strength, and flexural strengths were studied for all of the reference and (RAC) mixtures at (28) days age, by testing concrete cubes, cylinders and reinforced concrete slabs specimens respectively. The results showed that the using of recycled waste concrete as concrete as aggregate will largely decreasing the slabs flexure strength while using of recycled (SCC) mixtures have relatively small effect in reducing the slabs flexure strength. The adding of silica fume to the concrete mix will increasing the slabs flexural strength and that increase is larger for recycled (SCC) aggregate mixes than the recycled concrete aggregate mixes. The results also indicate that the compressive strength and tensile strength are decreased by different ratio when using of recycled waste concrete as aggregate, while using of recycled (SCC) aggregate will also reduce the tensile strength and the modulus of rupture while the compressive strength increased when using this type of recycled aggregate. On the other hand, the mixtures with the Silica Fume showed a significant enhancement in the mechanical properties compared to those without the Silica Fume.

Keywords: Recycled Aggregate Concrete (RAC); Recycled Concrete Aggregate (RCA); Slabs; Strength; Flexure.

1.Introduction

Since the coarse aggregate forms the largest portion in concrete, the strength and durability of the concrete is directly affected by the strength and durability of its coarse aggregate. As a practical fact, using recycled concrete aggregate (RCA) to produce a new concrete involves sequent stages starting with breaking, removing and then crushing the original concrete into a new material with specified properties such cleanliness, size and quality.

Rao et al. (2011) defined recycled concrete aggregate (RCA) as the aggregate which is produced by the crushing of sound and clean demolition contains at least (95) % by weight concrete, and has a
contamination level lower than (1) % of the bulk mass. Recycled concrete aggregate obtained from construction and demolition (C&D) waste has received an increasing attention recently, due its promising potential use in environmentally friendly concrete structures.

The basic method of recycling concrete is the crushing of (C&D) waste materials into a granular nature materials of a selected particle size distribution. The level of contamination of the recycled waste determines the quality of the (RCA). For the crushing process, many types of crushers can be used, but the main crushers are: jaw crusher, cone crusher and impact crusher. Most recycling plants use the jaw crusher as a primary crusher since it has the capability to process the large pieces of concrete as well as the residual reinforcement if existed. This crusher generally reduces the materials down to the size of (60 - 80) mm. In addition, some plants also use the impact crusher as a secondary crusher to produce more of aggregate without adhered mortar. The products of the secondary crusher are then screened to separate the aggregate into different sizes.

Anderson et al. (2009) stated that recycled aggregate – as compared to conventional or natural aggregate – has higher water absorption and lower specific gravity. Also, its density is lower than normal aggregate. For porosity, recycled aggregate has much higher porosity. It is a general fact that recycled aggregate's strength is lower than its corresponding value of natural aggregate, the grading curves for recycled aggregate are generally having a continuous form with a similar fineness modulus for the equivalent fracture.

For the fresh state of concrete, Obla et al. (2007) found that with the increase in (RCA) content in concrete mixtures, their workability decreases. They also stated that in order to produce a similar workability as that of natural aggregate concrete, (5) % more of mixing water was required when only the coarse (RCA) was used, and up to (15) % when both of fine and coarse (RCA) were used.

In the field of structural behaviour of reinforced (RAC), few investigations have been conducted. Maruyama et al. (2004) examined the flexural behaviour of (RRC) beams and reported that the crack width in (RRC) was wider than that of the conventional reinforced concrete. The deflection of the (RRC) beams was greater than the case of conventional concrete beams. Finally, they concluded that the use of (RAC) did not significantly decrease the flexural capacity, providing that the reinforcing steel was sufficiently anchored to yield before the concrete fails. Xiao et al. (2006) studied the seismic performance of (RAC) frame structures of (1/2) scale specimens made of (0,30, 50 &100) % replacement of (RCA). The specimens were subjected to a constant gravity load and a low - frequency cyclic lateral load. They reported that the failure pattern was similar for all frames, but the yield and ultimate load capacities of (RAC) frames were smaller. Their final conclusion was that a properly mixed (RAC) frame behaves well enough to stand an earthquake.

2. Aim of the study

This study aims to Using the produced self – compacting and waste concrete as recycled coarse aggregate to produce recycled aggregate concrete specimens containing different percentages of recycled aggregates.

Also, this research aims to studying the flexural behavior of the two-way reinforced concrete slabs which contain the recycled concrete aggregate.

3. The Experimental Program

The aim of this research is to compare the flexural strength of the reinforced reference concrete slab which is made with natural aggregate only, and the flexural strengths of reinforced concrete slabs made with different types and contents of recycled concrete as coarse aggregate. Five concrete types were tested in this research; mixture proportions of the tested concretes were determined as follows:

- Constant cement content,
- Constant maximum aggregate size of (14) mm,
• Constant type but variable content of fine aggregate,
• Constant workability about (75) mm,
• Variable type and content of coarse aggregate,
• Variable content of silica fume.

3.1. Concrete Mixtures

The reference concrete mixture was proportioned to obtain the slump of (75) mm, and the contents of this concrete are shown in Table (1) below.

| Cement (kg) | Water (kg) | Coarse aggregate (kg) | Fine aggregate (kg) |
|------------|------------|-----------------------|--------------------|
| 471        | 194        | 1019                  | 598                |

The recycled aggregate concrete mixtures were twelve mixtures, where the (RCA) was used with different type and percentage. In addition, silica fume was added with a constant amount of (10%) of the cement's weight to enhance the strength of the reinforced (RAC) slabs (Abdul-Rahman, M. et al., 2018, Abdul-Rahman, M. et al. 2020, and Al-Attar et al., 2020). The details of the variables of each mixes are shown in Table (2), while Table (3) presents the materials quantities information of these mixtures. The replacement ratio of recycled coarse aggregate (for normal or self-compacted concrete aggregate) is considered by weight of the normal used aggregate.

| Mix Designation | Mix details |
|-----------------|-------------|
| N33             | Concrete with 33.3 % of recycled normal concrete as coarse aggregate |
| Ref             | Reference concrete (no recycled aggregate or silica fume) |
| N66             | Concrete with 66.7 % of recycled normal concrete as coarse aggregate |
| N100            | Concrete with 100 % of recycled normal concrete as coarse aggregate |
| N33S            | Concrete with 33.3 % of recycled normal concrete as coarse aggregate and added silica fume |
| N66S            | Concrete with 66.7 % of recycled normal concrete as coarse aggregate and added silica fume |
| N100S           | Concrete with 100 % of recycled normal concrete as coarse aggregate and added silica fume |
| S33             | Concrete with 33.3 % of recycled Self-compacting concrete as coarse aggregate |
| S66             | Concrete with 66.7 % of recycled Self-compacting concrete as coarse aggregate |
| S100            | Concrete with 100 % of recycled Self-compacting concrete as coarse aggregate |
| S33S            | Concrete with 33.3 % of recycled Self-compacting concrete as coarse aggregate and added silica fume |
| S66S            | Concrete with 66.7 % of recycled Self-compacting concrete as Coarse aggregate and added silica fume |
| S100S           | Concrete with 100 % of recycled Self-compacting concrete as coarse aggregate and added silica fume |
### Table 3. Contents of recycled aggregate concrete mixtures for one cube meter

| Mixture Designation | Contents for a cubic meter (kg) |
|--------------------|---------------------------------|
|                    | Cement | Water * | Fine Aggregate | Natural coarse Aggregate | Recycled coarse Aggregate (type-weight) | Silica Fume |
| N33                | 471.26 | 206.41  | 612.7          | 631.74                  | NC-332.86                              | -          |
| N66                | 471.26 | 205.51  | 643.4          | 292.35                  | NC-618.0                               | -          |
| N100               | 471.26 | 195.90  | 690.7          | -                       | NC-853.24                              | -          |
| S33                | 471.26 | 206.4   | 610.9          | 629.13                  | SCC-331.49                             | -          |
| S66                | 471.26 | 194.28  | 650.4          | 289.75                  | SCC-620.45                             | -          |
| S100               | 471.26 | 192.83  | 689.3          | -                       | SCC-852.40                             | -          |
| N33S               | 471.26 | 217.14  | 567.4          | 631.74                  | NC-332.86                              | 47.1       |
| N66S               | 471.26 | 215.24  | 598.8          | 292.35                  | NC-618.0                               | 47.1       |
| N100S              | 471.26 | 214.26  | 636.6          | -                       | NC-853.72                              | 47.1       |
| S33S               | 471.26 | 217.17  | 565.3          | 629.13                  | SCC-335.84                             | 47.1       |
| S66S               | 471.26 | 215.73  | 596.2          | 289.75                  | SCC-620.54                             | 47.1       |
| S100S              | 471.26 | 214.29  | 635.1          | -                       | SCC-852.40                             | 47.1       |

* the w/c ratio is adjusted to achieving the requirements of workability limits.

#### 3.2. Slabs Flexural Strength Test

This test was performed using a digital flexural testing machine of (200) kN capacity. Reinforced concrete slabs of dimensions \((500 \times 500 \times 50)\) mm were subjected to a concentrated load by steel disc of \((40)\) mm diameter. These slabs were simply supported in all directions by a steel frame, then a load- deflection curve was plotted with a precision of \((1)\) kN. Details of the slab's supporting system, load and reinforcement are shown in Figure 1.
4. Results and Discussion
For an inclusive presentation of the results, they are discussed as follows:

4.1 Mechanical Properties of Concrete

4.1.1 Compressive Strength

The tests result of the recycled coarse aggregate concrete along with the types, percentages of the recycled aggregates with the presence of the silica fume are presented in Table (4).

It can be seen that the waste aggregate concretes with (33.3, 66.7 and 100) % replacement of coarse aggregate exhibited a decrease in the compressive strength (compared to the reference concrete) by the amount of (3.18, 5.05 and 6.12) % respectively. These results may be attributed to a number of reasons. First, the crushed waste (RCA) possesses a higher porosity and a lower density of about (20) % than the natural coarse aggregate. Therefore, lower density of the coarse aggregate (which has the largest contribution to the concrete mass) leads to a lower strength of coarse aggregate and consequently, lower strength of the concrete.

On the other hand, the replacement of recycled (SCC) coarse aggregate led to a significant increase in the compressive strength by (2.85, 6.45 and 9.95) % for the aggregate replacement percentages of (33.3, 66.7 and 100) % respectively when compared to the reference concrete. The above results can be interpreted as follows; the (SCC) has much more resistance to mechanical action than the ordinary concrete, hence a better recycled aggregate is gained. Also, the recycled (SCC) coarse aggregate consists of strong angular particles which tend to improve the interlocking action of the coarse
aggregate and increase the strength. In addition, it is important to mention that the (SCC) has stronger mortar attached to coarse aggregate, due to the increased fine aggregate content and the use of powders and super plasticizers that produce denser and stronger mortar than other types of concrete.

Table 4. Compressive strength values for different concrete mixes

| Symbol Designation | Compressive strength \( f'c \) at (28) days (MPa) | Difference from Ref. (%) | Splitting tensile strength \( f't \) (MPa) | Difference from Ref. (%) |
|--------------------|---------------------------------|--------------------------|---------------------------------|--------------------------|
| Ref                | 39.336                          | -                        | 3.442                           | -                        |
| N33                | 38.085                          | - 3.18                   | 3.43                            | - 0.348                  |
| N66                | 37.349                          | - 5.05                   | 3.396                           | - 1.34                   |
| N100               | 36.93                           | - 6.12                   | 3.332                           | - 3.46                   |
| S33                | 40.458                          | 2.85                     | 3.559                           | 3.4                      |
| S66                | 41.874                          | 6.45                     | 3.522                           | 2.33                     |
| S100               | 43.25                           | 9.95                     | 3.405                           | - 1.07                   |
| N33S               | 40.937                          | 4.07                     | 3.647                           | 9.56                     |
| N66S               | 40.536                          | 3.05                     | 3.491                           | 1.42                     |
| N100S              | 39.87                           | 1.36                     | 3.358                           | - 2.44                   |
| S33S               | 41.464                          | 5.41                     | 3.811                           | 10.7                     |
| S66S               | 42.159                          | 7.17                     | 3.694                           | 7.32                     |
| S100S              | 43.73                           | 11.17                    | 3.438                           | - 0.11                   |

4.1.2 Splitting Tensile Strength

The splitting tensile strength test results of all concrete mixtures are shown in Table (4). These results show a slight decrease in strength when waste concrete aggregate is used with (33.3) % of replacement, this decrease is of (0.35) % compared to the reference concrete. This decrease may be attributed to that the recycled aggregate contains a high percentage of natural aggregate particles with a less percentage of mortar attached on the aggregate particles forming angular particles that limitedly enhanced the interlocking and gave a similar strength (Hansen, 1986).

When the recycled (SCC) aggregate was used, the splitting tensile strength witnessed an increase of (3.4 and 2.33) % for (33.3 and 66.7) replacement percentages respectively. While for (100) % replacement, the tensile strength decreased for about (1.07) %. These results can be explained when the nature of (SCC) is considered.

Nevertheless, compared to the mixtures without the silica fume, the use of this admixture resulted in an increase in the splitting tensile strength of (5.1, 2.8 and 1.05) % for (33.3, 66.7 and 100) % replacement of waste (RCA) in the same order. These results show that the use of the silica fume could result the same tensile strength of the reference concrete when the replacement of waste (RCA) is raised up to (66.7) %.

4.2 Ultimate Loading

The first crack and ultimate (failure) loads results of the (RAC) slabs are presented in Table (5). Also, the (load-deflection) relationships for the all tested concrete slabs are shown in Figures (2, 3, 4 and5). The test results showed a reduction in flexural strength of (2.19, 4.96 and 13.97) % for the replacement of normal (RCA) of (33.3, 66.7 and100) % respectively. The results confirmed that the flexural strength of concrete undergoes a reduction of less than (10) % and maximum of (20) % when the concrete is made of recycled coarse aggregate and natural fine aggregate as stated by ACI.
committee 555R-01 report (2001). The low reduction took place because the reinforced concrete is a composite material. Hence, weaker aggregate has low effect on its ultimate strength. Another reason for this reduction in strength is that the recycled coarse aggregate has a lower resistance to the mechanical action than the natural aggregate, so a weaker concrete is produced (Ravindrajah and Tam, 1985). In addition, the recycled aggregate concrete (RAC) has significantly weaker bond areas than the corresponding normal concrete since it has bonding areas between the round gravel and old or new mortar in addition to the bonding areas between the old and the new mortar (AlHussainy, 2011).

Oppositely, the recycled (SCC) aggregate showed an enhancement of the flexural strength of (6.23 and 4.58) % for (33.3 and 66.7) % of replacement, but for (100) % of replacement, a reduction of (2.09) % compared to the reference concrete occurred. When silica fume was added to the normal (RAC) mixtures, the flexural strength increased even beyond that of the reference concrete for (33.3 and 66.7) % of replacement with an increase of (7.94 and 8.9) % respectively, but for (100) % of replacement, the strength was still less than that of the reference concrete but with (10.2) % greater than that value of the concrete without the silica fume. Also, all concretes containing recycled (SCC) aggregate and silica fume gave flexural strength values more than the reference value, and the enhancements were (4.06, 1.05 and 4.72) % for the replacements of (33.3, 66.7 and 100) % respectively.

The first crack loads for all normal (RAC) slabs were lower than that of the reference concrete slab, where the maximum reduction was (29.62) %, while for the recycled (SCC) slabs, the maximum reduction was (18.66) %. The addition of silica fume showed an increase in the first crack loads compared to those without it, and the differences were (20.52 & 15.34) % for the normal (RAC) and recycled (SCC) slabs respectively, compared to the reference slab.

Table 5. Ultimate loading results of the reinforced concrete slabs

| Concrete Symbol | Load at first crack (kN) | Difference from Ref (%) | Failure load (kN) | Difference from Ref (%) |
|-----------------|---------------------------|-------------------------|-------------------|-------------------------|
| Ref             | 10.82                     | -                       | 29.21             | -                       |
| N33             | 8.6                       | -20.52                  | 28.57             | -2.19                   |
| N66             | 8.2                       | -24.21                  | 27.76             | -4.96                   |
| N100            | 7.615                     | -29.62                  | 25.13             | -13.97                  |
| S33             | 9.4                       | -13.12                  | 31.03             | 6.23                    |
| S66             | 9                         | -16.82                  | 30.55             | 4.59                    |
| S100            | 8.8                       | -18.66                  | 28.6              | -2.09                   |
| N33S            | 11.6                      | 7.21                    | 30.84             | 5.58                    |
| N66S            | 10.41                     | -3.79                   | 30.23             | 3.49                    |
| N100S           | 8.6                       | -20.52                  | 27.69             | -5.20                   |
| S33S            | 9.57                      | -11.55                  | 32.92             | 12.70                   |
| S66S            | 9.3                       | -14.05                  | 30.87             | 5.68                    |
| S100S           | 9.16                      | -15.34                  | 29.95             | 2.53                    |
Figure 2. Load-deflection curves of the normal (RAC) slabs

Figure 3. Load-deflection curves of the self-compacting (RAC) slabs

Figure 4. Load-deflection curves of the normal (RAC) slabs with SF
4.3. Modes of Failure

In order to classify the failure, the (load-deflection) curves were used. According to Marzouk and Hussein (1991), modes of failure can be classified into three types: pure flexural failure, ductile shear failure and pure punching failure. The pure flexural failure occurs in the slabs in which most of their reinforcement yields before the punching takes place, hence; these slabs exhibit large deflection values prior to the failure. This type can be seen in Figure 6 for (Ref) slab and Figure 8 for (S33) slab, where the main wide cracks are located at the center of the slab. As the cracks spread towards the corners, they gradually decrease in width until they reach the edges as hair line cracks.

![Figure 6. Failure pattern of the reference concrete slab](image)

Pure punching failure takes place when the slab shows small deflection values with the yielding of the reinforcement steel is being very localized at the loaded central area. The (N33S) and (N66S) slabs in Figure 7 are examples of this failure. The cracks first occurred at the center, followed by radial extending from the center. As the load was increased, the final failure developed by the punching of the loading column through the slab.

Finally, the ductile shear failure is a transition between the previous cases of pure flexural and pure punching failures. The (N100S) and (S100S) slabs showed the ductile shear failure where they failed before the flexural strength was exceeded. See Figures 7 and 8.
Figure 7. Failure pattern of the normal (RAC) slabs

Figure 8. Failure pattern of the self-compacting (RAC) slabs
5. Conclusions

Based on the adopted experimental program, the following conclusions can be made:

1. Recycled aggregate concrete (RAC) made from waste coarse (RCA) showed a gradual decrease in the compressive strength for (33.3, 66.7 and 100) % of replacement. While (RAC) made from recycled (SCC) aggregate exhibited a gradual increase in the compressive strength compared to the reference concrete.

2. The splitting tensile strength decreased when waste (RCA) was used. The use of recycled (SCC) aggregate presented an increase and a slight reduction for (100) % of replacement, compared to the reference concrete. When the silica fume was used, the

3. The flexural strength of the reinforced concrete slabs decreased when only waste (RCA) was used. While the flexural strength increased for (33.3 & 66.7) % replacement of recycled (SCC) where only the (100) % of recycled (SCC) showed a slight decrease in the flexural strength.

4. The addition of Silica Fume improved the mechanical properties as well as the flexural strength of all mixtures for recycled (SCC) mixtures, and for (33.3 & 66.7) % of waste (RCA) mixtures, except for the (100) % replacement of waste (RCA) mixture where a reduction occurred compared to the reference concrete.

5. In general, reinforced (RAC) slabs showed less deflections at the ultimate load than that of the reference slab.

6. The addition of Silica Fume resulted even less deflections than the cases of its absence.

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