Behaviour of recycled aggregates RC columns strengthened with CFRP under uniaxial compressive loadings

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Abstract. The recent development in the construction industry has significantly influenced the socio-economic growth and the built environment of the mega cities around the globe. However, these developments have also resulted in millions of tonnes of construction demolition waste, which is mainly dumped, in the already populated landfills. As a result, the construction waste is not only causing a threat to the natural resources but also to the already deteriorating environment. Over recent past, studies have been conducted which investigated the use of concrete based construction waste as recycled coarse aggregates in preparing concrete for structural purposes. Based on these studies, in general it was found that the concrete compressive strength decreases with the increase in the percentage of recycled aggregates. Furthermore, studies have also been carried out in which use of Carbon Fiber Polymers wrapped along the outer surfaces of the structural elements resulted in significant increase of load carrying capacity. Therefore, in this study, investigation aims at the behaviour of reinforced concrete columns made with recycled aggregates and wrapped with Carbon Fiber Reinforced Polymers under uniaxial static compressive loading. For this purpose, 12 rectangular specimens having cross section dimensions of 150mm x 300mm and height of 600mm reinforced both longitudinally and transversely were used. The specimens were made with three different mixes of concrete having 0%, 30% and 50% of recycled aggregates. It was found that the recycled aggregates reinforced concrete specimens wrapped with CFRP exhibited higher compressive loads as compared to their corresponding specimens made with natural aggregates.

1. Introduction
The development of the infrastructure according to the modern era is of prime importance to ensure smooth economic growth of any developing nation. However, these developments may outcome problems which not only threat the environment as well as natural resources. Construction demolition waste which is one of the negative outcomes of the ongoing urban developing activities around the globe has become the major concern. The major part of the construction waste goes to solid waste landfills which in turn are requiring more sites and ultimately influencing the already polluted ambience.

Over past recent decades studies have been conducted which focuses on the use of the concrete demolition waste as recycled coarse aggregates in preparing concrete for structural purposes. Zhou and Chen [1] studied the mechanical properties of concrete made with different types of recycled coarse aggregates under static loading. For that purpose, Natural Aggregate Concrete (NAC) was made with coarse aggregates extracted from crushed rock and pebbles. For comparison purposes, the Recycled Aggregates Concrete (RAC) was also made with parent concrete having same type of crushed rock and
pebbles aggregates as used for the NAC. The specimens were made with concrete having different percentages of recycled crushed rock aggregates (RCRA) and recycled pebbles aggregates (RPA). The percentage of both types of recycled aggregates (RCRA and RPA) used for making concrete varied between of 0% to 100% with water to cement ratio of 0.49 for concrete made with natural and recycled crushed rock aggregates and 0.47 for concrete made with natural and recycled pebble aggregates. In general, it was observed that the relationship of concrete compressive strength with respect to replacement percentage (RP) is scattered and no definite relationship can be formed between concrete compressive strength and percentage of recycled aggregate used irrespective of type of recycled aggregates used for making concrete. Furthermore, it was observed that when using 100% RP of recycled pebbles concrete (RPC), the compressive strength shows slight improvement when compared to its counterpart concrete having 0% recycled aggregates.

Etxeberria and Mari et al. [2] carried out an investigation to study the influence of amount of RCA and its production process on the properties of concrete made with recycled aggregates (RAC). For this purpose, four different concrete mixes were used to study the behavior of concrete made with RCA under uniaxial static loading. In general, it was observed that with the increase in the curing period the concrete compressive strength also increases irrespective of the production type. It was also observed that for the case of specimens made with 25% (RC25) and 50% (RC50) of RCA, the concrete compressive strength decreases as compared to natural aggregate concrete irrespective of curing period.

Based on the experimental studies, it has been generally observed that the concrete having replacement percentage of recycled aggregates above 30% showed decline in its compressive strength. Therefore, this study focuses on investigating the use of the concrete made with recycled aggregates in the reinforced concrete columns. Furthermore, study also aims at rectifying the decline compressive strength trend of the recycled aggregate concrete using Carbon Fiber Polymers (CFRP) wraps as studies [3-6] have also been carried out in which use of Carbon Fiber Polymers wrapped along the outer surfaces of the structural elements resulted in significant increase of load carrying capacity. For this purpose, 12 rectangular specimens having cross section dimensions of 150mm x 300mm and height of 600mm reinforced both longitudinally and transversely were tested under static uniaxial compressive loads. The specimens with and without wraps were made with three different mixes of concrete having 0%, 30% and 50% of recycled aggregates.

2. Experimental Programme
In order to investigate the behavior of reinforced concrete columns made with recycled aggregates wrapped with and without CFRP, 12 specimens were tested under static uniaxial compressive loads. The specimens were made with concrete having 0%, 30% and 50% of recycled aggregates. Four specimens (two each with and without wraps) were casted for each percentage of recycled aggregates and the results were averaged out to investigate its behaviour under uniaxial compressive loading.

Figure 1. (a) Specimen cross sectional dimensions and (b) reinforcement details.
2.1. Specimen details
The rectangular shape specimens having cross section dimensions of 150mm x 300mm and height of 600mm as shown in Figure 1(a) were used. The specimens were reinforced with six longitudinal bars of 12.5mm diameter with longitudinal steel ratio of 1%. The shear reinforcement was provided in the form of stirrups having diameter of 11mm spaced at 152.4 mm centre to centre therefore having a concrete cover of 25.4mm as shown in Figure 1(b).

2.2. Material Properties
The specimens were prepared with three different mixes of concrete having a constant mix and water cement ratios of 1:1.24:2.60 and 0.43 respectively. Four out of twelve specimens used in this investigation were prepared for each mix having 0% (NAC), 30% (RAC-30) and 50% (RAC-50) of recycled aggregates. For preparing concrete, the total weight of coarse aggregates (both natural and recycled) consist of 60% of aggregates retained on 9.5mm and 40% retained on 12.7mm sieves. The details of constituent used for each mix for preparing specimens are provided in Table 1.

3. Results and discussions
3.1. Peak load exhibited
Figure 2 shows the peak loads exhibited by specimens made with different percentages of recycled aggregate concrete (RAC) wrapped with and without CFRP under uniaxial static compressive loading. In general, it was observed that for the case of specimens without CFRP wrapping the peak load exhibited by specimens decreases with the increase in the percentage of the recycled aggregates. However, for the case of specimens with CFRP wrapping no definite relationship can be formed as initially specimens having up to 30% of recycled aggregates the peak load increases, which then decreases, for the specimens made with 50% of recycled aggregates. It was also observed that for the case of specimens made with 0% recycled aggregates, the CFRP wrapping does not influence the peak load response as similar peak load was observed for both wrapped and unwrapped specimens (see Figure 2).

| Mix   | OPC cement (kg/m³) | Fine Aggregates (kg/m³) | Natural Coarse Aggregates (kg/m³) | Recycled Coarse Aggregates (kg/m³) | water (kg/m³) |
|-------|--------------------|-------------------------|-----------------------------------|-----------------------------------|---------------|
| NAC   | 454.01             | 567.51                  | 1183.26                           | 0                                 | 195.22        |
| RAC-30| 454.01             | 536.34                  | 782.79                            | 335.48                            | 195.22        |
| RAC-50| 454.01             | 517.40                  | 539.39                            | 539.39                            | 195.22        |
When comparing the peak loads exhibited by specimens with and without CFRP wrapping, it was observed that the specimens with CFRP exhibited higher compressive loads as compared to its counterpart for the case of specimens without CFRP wrapping irrespective of the percentage of aggregates used. Furthermore, it was also observed that CFRP significantly increased the peak load capacity of the specimens made with recycled aggregates as higher load was recorded for the case of specimens made with 30% recycled aggregates and similar load was also recorded for the case of 50% specimens when compared with specimens made with 0% recycled aggregates.

Table 2 gives the increase in load carrying capacity of recycled aggregate reinforced concrete specimens with and without CFRP wrapping. It can be seen from Table 2 that use of CFRP with recycled aggregate reinforced concrete columns proved to be beneficial as the decline strength effect of compressive strength with increase in the percentage of the recycled aggregates was overcome as significant increase in the load carrying capacity was observed.

Table 2. Increase in load carrying capacity of recycled aggregate reinforced concrete specimens with and without CFRP wrapping.

| Specimens | Maximum load (kN) | Increase in load carrying capacity (%) |
|-----------|-------------------|---------------------------------------|
|           | Without CFRP | With CFRP |                               |
| NAC       | 1167          | 1221      | 4.42                           |
| RAC-30    | 1019          | 1400      | 27.21                          |
| RAC-50    | 950           | 1201      | 20.89                          |

3.2. Failure pattern

Figure 3 shows the damage caused to the specimens made with different percentages of recycled aggregate concrete (RAC) wrapped with and without CFRP under uniaxial compressive loading. For the case of specimens without CFRP wrapping and made with 0%, 30% and 50% of recycled aggregates, it was observed that the failure initiated due to the formations of crack at the outer edges of the cross...
section which extends along the whole length. For the case of unwrapped specimen with 50% recycled aggregates, the cracks initiated at the mid-height of the specimens then extending along the top and bottom, similar to the behaviour of cylindrical specimen under uniaxial compression test. It was also observed that the damage caused to the specimens without CFRP wrapping only caused damage to the concrete in the cover region as reinforcement was not exposed.

For the case of specimens having CFRP wrapping, in general, it was observed that the failure occur due to crushing of the concrete cover and CFRP rupture irrespective of the percentage of recycled aggregate used for preparing the specimen. It was also observed that except for the specimen made with 0% recycled aggregates, the damage was only limited to the concrete cover as reinforcement were not exposed. Furthermore, the use of CFRP, also limited the failure to very localized area as compared to the case of specimens without CFRP wrapping.

![Figure 3](image)

**Figure 3.** Damage caused to the specimens made with different percentages of recycled aggregate concrete (RAC) wrapped with and without CFRP under uniaxial compressive loading.

4. **Conclusions**

Based on the experimental investigation carried out herein which investigates the behaviour of recycled aggregate reinforced concrete columns under uniaxial static compressive loadings following conclusions can be deduced:

- The peak load exhibited by specimens without CFRP wrapping decreases with the increase in the percentage of the recycled aggregates.
- The specimens with CFRP exhibited higher compressive loads as compared to its counterpart for the case of specimens without CFRP wrapping irrespective of the percentage of aggregates used.
- The use of CFRP, also limited the failure to very localized area as compared to the case of specimens without CFRP wrapping.
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