# EXPERIMENTAL INVESTIGATION ON THE EFFECT OF STEEL FIBRES ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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## Abstract

*This paper presents an experimental investigation into the effect of steel fibres on the mechanical properties of recycled aggregate concrete. Steel fibres (DRAMIX 3D 65/35BG) were added to the mixes and washed construction and demolition wastes (size 20mm) as a coarse recycled aggregate were used. The variables of this study were: different steel fibre contents; ($V_f$) = 0, 0.5, 1.0 and 1.5% and replacement percentages of recycled aggregate; (RP) = 0, 50 and 100%. Cubes (100×100×100mm), cylinders (150×300mm) and prisms (100×100×500mm) were cast and tested at an age of 28 days. The results showed that the addition of steel fibres enhanced the cube compressive strength, splitting tensile strength, flexural strength and the modulus of elasticity by 1-5%, 11-55%, 16-53% and 4-15%, respectively, in comparison to the specimens without fibres. Interestingly, the results of the cylinder compressive strength tests were 5-25% greater than those results recorded from the cube tests.*

**Keywords: steel fibre, recycled aggregate concrete, compressive strength, splitting tensile strength, flexural strength and the modulus of elasticity.**

## 1. Introduction

Recently, it has been reported that about 850 million tonnes of construction and demolition wastes (CDW) are generated in the EU per year, which represents 31% of the overall waste generation [1]. Using CDW as a coarse recycled aggregate in the production of new concrete has attracted much interest in the research community due to its potential for improving the environmental performance of concrete. However, in comparison to natural aggregate (NA), the quality of recycled aggregate (RA) is poorer which makes its use in various construction applications restricted.

It was stated in previous studies that the adhered mortar content in recycled aggregate as well as the presence of other material such as clay bricks and tiles can make it more porous and more liable to absorb a high amount of water [2]. The high porosity and water absorption capacity of recycled aggregate can substantially reduce the various properties of the resulting concrete [2,3].

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Existing results in the literature concluded that all the strength properties and the modulus of elasticity of concrete decreased with the incorporation of recycled aggregate. The reductions in compressive strength, splitting tensile and flexural strength were 25, 15 and 20%, respectively, while there was a reduction of up to 45% for the modulus of elasticity [4-6].

Steel fibre reinforced concrete (SFRC) has become a very useful structural material in various applications. Adding steel fibres to concrete significantly enhances its mechanical properties. Many researches have investigated the use of SFRC, particularly its mechanical properties. They indicated that steel fibres do little to enhance the compressive strength of concrete (increases ranging from 0 to 20%) [7-9].

It is well known that the presence of steel fibres in the concrete matrix leading to an improvement in the tensile behaviour of concrete, especially after cracking. Increases of 60% and up to 80% in splitting tensile and flexural strength of concrete, respectively, were recorded due to adding 2% of steel fibres; an increment of 30% was indicated in the results of modulus of elasticity [7-9].

A review of the concrete literature showed that the effect of glass and polypropylene fibres on recycled aggregate concrete (RAC) have been investigated. These studies showed how fibres have a considerable influence on the properties of RAC [10,11]. The replacement percentage (RP) of recycled aggregate and the volume fraction of fibre ($V_f$) have been found to have a considerable influence on the mechanical properties of concrete.

Therefore, adding steel fibres to RAC in order to produce steel fibre recycled aggregate concrete (SFRAC) may improve its mechanical properties and make it a suitable structural material, thereby reducing its limited use.

## 2. Research significance

This experimental investigation aims to assess the effect of adding four different percentages of steel fibre content, i.e. ($V_f$) = 0, 0.5, 1.0 and 1.5%, on the mechanical properties of recycled aggregate concrete, which itself is made of three different levels of replacement percentage of CDW aggregate, i.e. (RP) = 0, 50 and 100%. The results for compressive strength, splitting tensile, flexural strength and modulus of elasticity of SFRAC specimens are compared to normal concrete.

## 3. Experimental programme

A total of 12 groups of specimens, each consisting of four cubes (100×100×100 mm), four cylinders (150×300 mm) and three prisms (100×100×500 mm), were prepared, cast and tested at an age of 28 days. The properties of the materials, mix proportions, specimen preparation, curing and test methods are described in the following sections.

### 3.1 Materials and mix proportions

**Cement:** high strength cement (C52.5) was used in all mixes for casting the specimens of this study. The cement is manufactured to conform to the requirements of BS EN 197-1.

**Fine aggregate:** natural fine aggregate with a maximum particle size of 5 mm was used in the experimental work of this study. The properties and grading of the fine aggregate conformed to the standard requirement limits of BS EN 882.

**Coarse aggregate:** un-crushed natural aggregate with a maximum size of 20 mm was used as a coarse aggregate in this study. The properties and grading of the coarse aggregate conformed to the standard requirement limits of BS EN 882.

**Recycled aggregate:** crushed washed construction and demolition waste with a maximum size of 20 mm was used as a coarse recycled aggregate in this study. The properties and grading of the recycled aggregate are according to BS EN 8500.

**Water:** according to BS EN 3148, Leeds tap drinking water was used as mixing water in all the mixes of this study.

**Superplasticiser:** a high range water-reducing concrete admixture (Sika ViscoCrete) was used as a superplasticiser to control the workability requirements for all mixes.

**Steel fibres:** glued discontinued hooked-end steel fibres (DRAMIX 3D 65/35BG) from Bekaert as shown in Figure 1 were used in this study. The fibres have an aspect ratio of 65, length of 35 mm and diameter of 0.55 mm. The ultimate tensile strength of these fibres is 1180 MPa.

**Table 1:** Properties of natural and recycled aggregate

| Properties | Fine natural aggregate (FA) | Coarse natural aggregate (CA) | Coarse recycled aggregate (RA) |
|---|---|---|---|
| **Specific gravity** | 2.64 | 2.62 | 2.48 |
| **Bulk density (Kg/m$^3$)** | 1580 | 1600 | 1360 |
| **Water absorption ratio (%)** | 1.06 | 0.49 | 4.78 |
| **Porosity (%)** | - | 38 | 46 |


**Figure 1:** Hooked-end steel fibres (DRAMIX 3D)

A total of 12 concrete mixes were designed to study the effect of steel fibres on the mechanical properties of recycled aggregate concrete. The natural coarse aggregate was used in the first 4 mixes to produce control specimens; while in the other 8 mixes, recycled coarse aggregate was used by 50 and 100% of replacement. Steel fibres were added to all mixes in different contents; 0, 0.5, 1.0 and 1.5%.

All concrete mixes had the same effective water-to-cement ratio. Additional water was added to the RAC mixes for compensating the high water absorption capacity of RA and obtaining the required level of workability. The amount of additional water was calculated by accordance with the amount of aggregate in the mix and its water content. The designation and details of the mixes proportions are summarized in Table 2.

**Table 2:** Mixes designation and proportions

| Mix | Designation | Mix proportions (Kg/m$^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | W/C | W | C | FA | CA | RA | SP | SF |
| **M1** | **NC** | 0.42 | 177 | 422 | 754 | 1024 | - | - | - |
| **M2** | **SFRC-0.5** | 0.42 | 177 | 422 | 754 | 1024 | - | 0.5 | 40 |
| **M3** | **SFRC-1.0** | 0.42 | 177 | 422 | 754 | 1024 | - | 1.0 | 80 |
| **M4** | **SFRC-1.5** | 0.42 | 177 | 422 | 754 | 1024 | - | 1.5 | 120 |
| **M5** | **RAC-50** | 0.42 | 177 | 422 | 754 | 512 | 512 | - | - |
| **M6** | **SFRAC-50-0.5** | 0.42 | 177 | 422 | 754 | 512 | 512 | 0.5 | 40 |
| **M7** | **SFRAC-50-1.0** | 0.42 | 177 | 422 | 754 | 512 | 512 | 1.0 | 80 |
| **M8** | **SFRAC-50-1.5** | 0.42 | 177 | 422 | 754 | 512 | 512 | 1.5 | 120 |
| **M9** | **RAC-100** | 0.42 | 177 | 422 | 754 | - | 1024 | - | - |
| **M10** | **SFRAC-100-0.5** | 0.42 | 177 | 422 | 754 | - | 1024 | 0.5 | 40 |
| **M11** | **SFRAC-100-1.0** | 0.42 | 177 | 422 | 754 | - | 1024 | 1.0 | 80 |
| **M12** | **SFRAC-100-1.5** | 0.42 | 177 | 422 | 754 | - | 1024 | 1.5 | 120 |

Note: W/C = water-to-cement ratio, W = water, C = cement, FA = fine natural aggregate, CA = coarse recycled aggregate, RA = recycled coarse aggregate, SP = superplasticiser, SF = steel fibres content.

## 3.2 Specimen preparation and test methods

For each mix, four cubes (100×100×100 mm), four cylinders (150×300 mm) and three prisms (100×100×500 mm), were prepared and cast according to standards BS EN 1881-125 and BS EN 12390-1 using a mechanically driven drum mixer. The workability of the fresh concrete was evaluated using the slump test according to BS EN 12350-2.

The concrete was poured into the prepared moulds directly after measuring the slump according to BS EN 12390-2. The cubes and prisms were filled with two layers whereas the cylinders were filled with three layers of concrete. Compaction took place immediately after filling each layer using a vibrating table; samples were compacted for a few seconds to avoid segregation of the concrete. The specimens were then left for at least 24 hours. After this period, the concrete specimens were removed from the moulds and transferred to the curing room for 28 days. After 28 days, the specimens were tested for compressive strength, splitting tensile strength, flexural strength and modulus of elasticity according to standards BS EN 12390-3, 4, 5, 6 and ASTM C39, C496, C78 and C469 as shown in Figure 2.

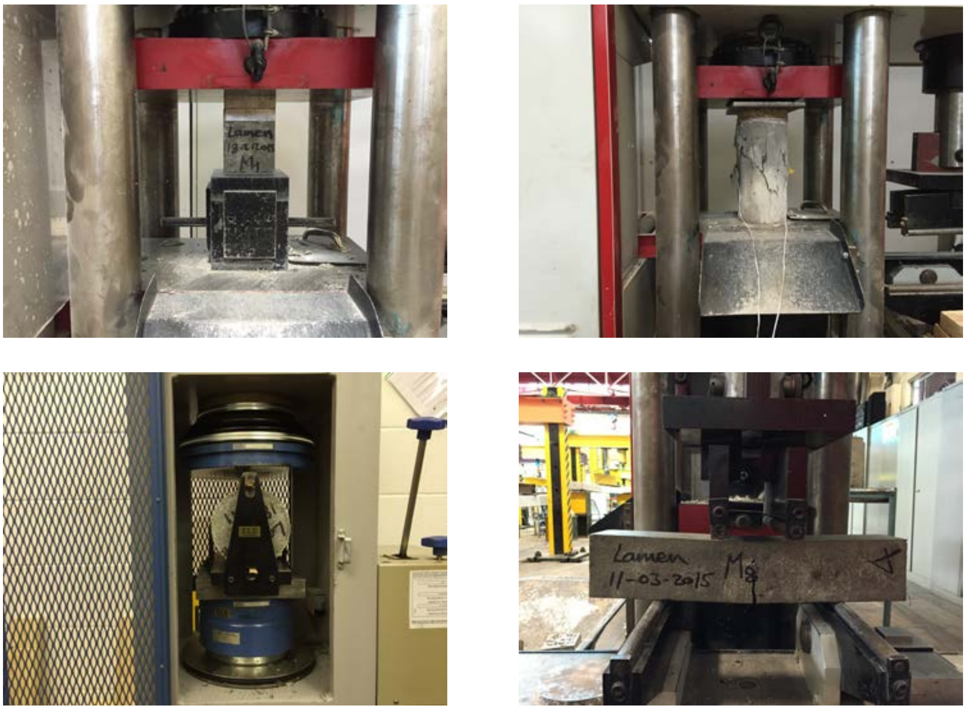


**Figure 2:** Experimental tests

## 4. Results and discussion

The experimental results obtained for the normal and recycled concrete are presented in Table 3. Figures 3-6 show the effect of steel fibres and recycled aggregate content on the different properties of concrete.

**Table 3:** Experimental results of concrete properties

| Specimen | $f_{cu}$ (MPa) | $f_c$ (MPa) | $f_{spt}$ (MPa) | $f_{ft}$ (MPa) | $E_c$ (GPa) |
|---|---|---|---|---|---|
| **NC** | 51.57 | 41.50 | 4.17 | 5.25 | 30.55 |
| **SFRC-0.5** | 52.92 | 43.72 | 4.68 | 6.12 | 31.84 |
| **SFRC-1.0** | 54.20 | 47.12 | 5.62 | 6.98 | 33.47 |
| **SFRC-1.5** | 53.16 | 51.45 | 6.23 | 7.89 | 34.63 |
| **RAC-50** | 49.15 | 39.00 | 3.65 | 4.75 | 25.24 |
| **SFRAC-50-0.5** | 49.98 | 41.56 | 4.08 | 5.54 | 26.33 |
| **SFRAC-50-1.0** | 50.78 | 44.18 | 5.02 | 6.42 | 27.60 |
| **SFRAC-50-1.5** | 49.85 | 48.82 | 5.53 | 7.28 | 28.32 |
| **RAC-100** | 47.32 | 37.43 | 3.23 | 4.28 | 23.46 |
| **SFRAC-100-0.5** | 48.67 | 39.88 | 3.64 | 4.98 | 24.78 |
| **SFRAC-100-1.0** | 49.29 | 42.04 | 4.43 | 5.81 | 26.02 |
| **SFRAC-100-1.5** | 48.66 | 46.23 | 5.03 | 6.56 | 26.89 |

## 4.1 Compressive strength

All compressive strength results for normal and RAC with or without fibres were obtained after 28 days of curing. The test was performed on cubes and cylinders and the results are shown in Figure 3. The results indicated almost the same trend for both specimens with and without recycled aggregate. There was the same reduction of about 5 and 10% in both types of specimens (cubes and cylinders) when 50 and 100% of the natural coarse aggregate was replaced, respectively.

As reported in the literature, adding steel fibres to normal and RAC revealed no significant effect on its compressive strength when it was tested on cube specimens. An increment of 1 and 5% was obtained by adding 0.5 and 1.0%, respectively, of steel fibres at all replacement percentages of RA. However, a fibre content of 1.5% recorded a negative effect. This may probably be explained by the effect of high fibre content in a small volume (cube 100×100×100 mm) which prevents the mixture from being homogenous and well compacted.

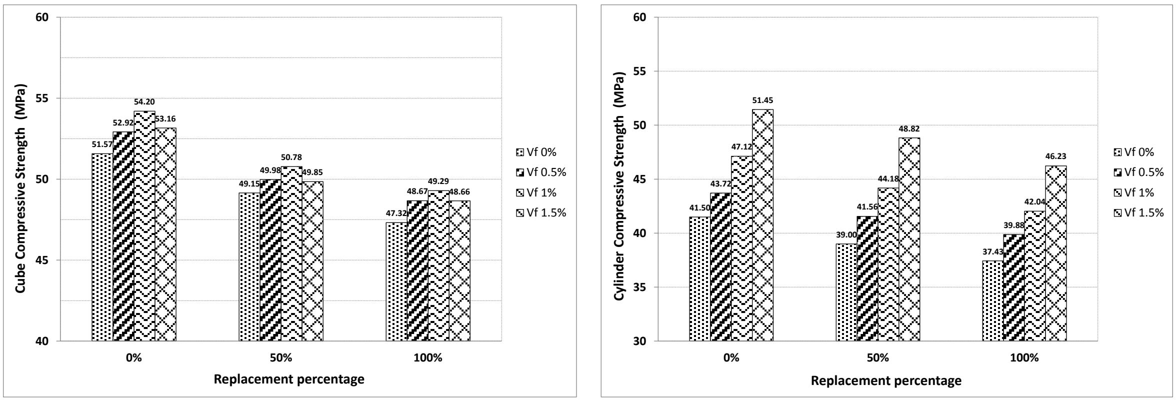


**Figure 3:** Results of cube and cylinder compressive strength

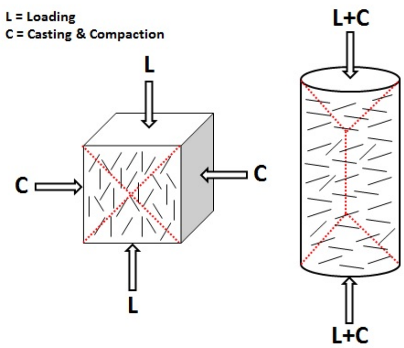


**Figure 4:** Effect of steel fibres on bridging cracks during the loading of cube and cylinder specimens

Interestingly, the results for the cylinder specimens showed an increase of 5, 15 and 25% by adding 0.5, 1.0 and 1.5%, respectively, of steel fibres to all specimens of normal and RAC. Figure 4 suggests a reason for the disparity in behaviour of the cube and cylinder samples when reinforced with steel fibres. For cubes, casting and compaction will most likely lead to the load being applied parallel to the orientation of most fibres. The tensile forces governing cube failure are therefore perpendicular to the direction of the steel fibres and will not therefore be resisted by the steel fibres. The opposite case is observed in the cylinders where it is likely that the steel fibres will the resist the tensile forces and help to bridge any cracking, thus compressive strength increases with an increase in steel fibre content (see Figure 3), at least up to 1.5%. The different failure patterns evident for cubes and cylinders will also mean that the steel fibres work better in the cylinder samples to enhance compressive strength.

## 4.2 Splitting tensile strength

The splitting tensile test of this study was performed using a line compressive force along the sides of the cylindrical test specimens. Figure 5 shows the effect of steel fibres and RA replacement levels on the splitting tensile strength. The results clearly demonstrated a gradual reduction in splitting tensile strength of 15-30% with increasing RA content.

As was expected, steel fibres significantly enhanced the splitting tensile strength of normal and RAC. The increase was strongly dependent on the fibre content, i.e. adding 0.5, 1.0 and 1.5% of fibres increased the splitting tensile strength by 11, 35 and 55%, respectively, for all RA replacement levels. Furthermore, the experimental results revealed that the ratio of tensile to compressive strength ($f_{spt}/f_c$) for all specimens was about 9-11%.

## 4.3 Flexural strength

Similar to the splitting tensile strength, the flexural strength also reduced (see Figure 5). A decrease of 10 and 22% was observed by replacing 50 and 100% of the aggregate, respectively.

Incorporation of steel fibres into the normal and RAC caused a considerable increase in flexural strength. Increments of 16, 35 and 53% were recorded by adding 0.5, 1.0 and 1.5% of steel fibres, respectively, for all replacement percentages. Moreover, the ratio of flexural to compressive strength ($f_{ft}/f_c$) varied from 12-15%.

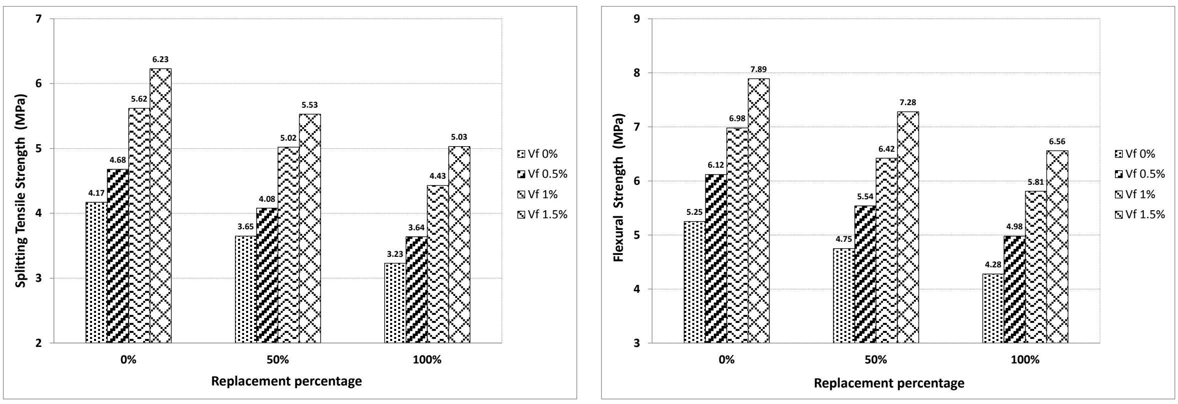


**Figure 5:** Results of splitting tensile and flexural strength

### 4.4 Modulus of elasticity

Cylinder specimens were tested for static modulus of elasticity at an age of 28 days according to ASTM C469. The values were calculated as the average of two strain gauges in each sample (see Figure 2) by using the following equation:

$$E_c = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 50 \times 10^{-6}}$$

Where: $\sigma_2$ is the stress corresponding to 40% of the ultimate load, $\sigma_1$ is the stress corresponding to a longitudinal strain = $50 \times 10^{-6}$ and $\varepsilon_2$ is the longitudinal strain produced by stress $\sigma_2$.

In comparison to the normal concrete, the moduli of elasticity of the RACs were lower by 20-30%. This was expected due to the higher porosity and lower stiffness of the recycled aggregate. Figure 6 shows the influences of the inclusion of steel fibres on the modulus of elasticity of normal and RAC specimens.

The addition of steel fibres by 0.5, 1.0 and 1.5% increased the modulus of elasticity of normal and RAC by 4, 10 and 15%, respectively. The higher modulus of elasticity of the steel fibres (210 GPa) appears to have an important role in changing the elasticity of the researched specimens.

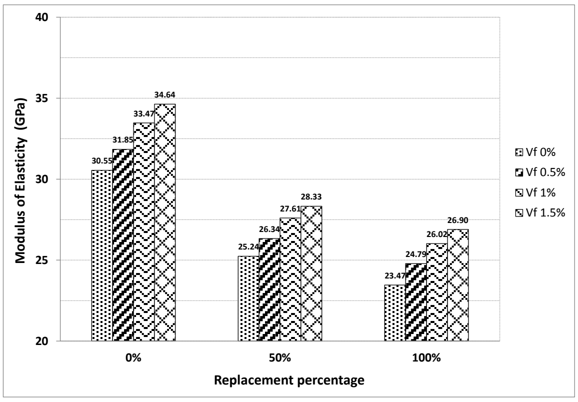


**Figure 6:** Results of modulus of elasticity

## 5. Conclusions

The effect of adding different contents of steel fibre to the mechanical properties of recycled aggregate concrete made of different replacement percentages of RA was studied. Based on the test results, the following conclusions can be drawn:

- In general, the quality of recycled aggregate is poorer than that of natural aggregate. However, the results revealed that the CDW aggregate used in this study was considered to be of good quality in comparison to the results in the literature.
- Due to the high water absorption capacity of RA, additional water or pre-saturated RA is necessary to compensate the absorption and control the requirements of

workability. However, the results in the literature showed that concrete produced using pre-saturation method exhibited slightly worse results of fresh and hardened properties.

- All strength properties and the modulus of elasticity of concrete deteriorated with the incorporation of RA. This is attributed to the presence of adhered mortar, clay brick and tiles in RA, which have reduced properties to that of natural stones. A reduction of 5, 15, 10 and 20% was recorded at a substitution level of 50% in the results for compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of normal and RAC, respectively, while the reductions were 10, 30, 22 and 30% at a level of 100% replacement.
- Adding steel fibres considerably enhanced the mechanical properties of normal and recycled aggregate concrete. Inclusion of steel fibres by 0.5, 1.0 and 1.5% showed increases of 1-5%, 11-55%, 16-53% and 4-15% in the results of cube compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of normal and RAC for replacement percentages of 50 and 100%, respectively.
- The compressive strength of cylindrical specimens increased by 5-25%; this is greater than that of cubes. The reason was thought to be due to the orientation of the fibres to the loading; i.e. parallel in the cube specimens; perpendicular in the cylindrical specimens.

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