Research Article

# Improving the impact resistance of recycled aggregate concretes with different types of fibers

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## ABSTRACT

In this study, the aim was to use different types of fibers to improve the impact resistance of recycled aggregate concrete (RAC) that normally shows poor performance against mechanical impacts compared to normal concrete (NC). For this purpose, 18 groups of concrete were cast using different parameters. The study examined different types of concrete mixtures where the proportion of RCA (recycled coarse aggregate) used was 30% and 50% respectively, and where steel fiber-reinforcement was used in proportions of 1% and 2%, and polypropylene fiber-reinforcement was used in proportions of 0.1%. While the material performance of RAC compared to NC is analyzed in existing published literature, there is no evidence on whether the use of RCA and hybrid fibers affect the impact properties of concrete. Drop weight impact testing was conducted on test specimens and the impact resistance of these specimens was studied at 28 days. It was observed that the increasing use of RCA reduced the impact resistance. The use of 30% RCA does not significantly influence the strength of concrete. According to the results, the performance of both the NC and RAC was increased with an increase in the volume fractions of steel fiber used. In addition, hybrid fiber-reinforced concretes showed the best results of all the concrete groups.



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## 1. Introduction

Recycled aggregates (RAs) obtained from demolished concrete structures are generally used as filler material in roads and in groundwork, and it can also be used in lean concrete and NC instead of, or with, natural aggregates. In the past, the reason why RAs were not widely used in concrete production was because they exhibited weaker mechanical properties than natural aggregates. But recently, diminishing natural resources and the importance of sustainability has meant that studies about the use of RAs in concrete have become popular (Khalaf and Devenny, 2004; Oikonomou, 2005; Ozturk, 2005).

Nowadays, concrete is the most preferred building material because of its high stress capacity It has recently been accepted that impact resistance is just as important as compressive strength in concrete and reinforced concrete structures. In developing countries, many structures, such as nuclear power plants, military structures, airports, railways, bridges and tunnels, are being built to more stringent lifecycle standards. Since these structures are exposed to impact effects during their lifetime, the impact resistance must be high in order not to cause any safety problems (Topcu and Guncan, 1995; Soe et al., 2013; Wan et al., 2016).

There are three types of factors that affect the concrete's impact resistance: the properties of the materials forming the concrete (aggregate type, maximum aggregate size and the water/cement ratio), the properties of the additives (mineral type and the proportions used in the mixture, the geometry, the slenderness of the fiber and the proportions used in the mixture) and the environmental conditions (concrete temperature and loading rate) (Oltulu and Altun, 2018).

One of the most effective methods to improve the mechanical properties and impact resistance of concrete is

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to add fibers. Studies in published literature report two main reasons for this improved performance when fiber is added: 1) the fiber absorbs impact energy, and 2) it prevents disaggregation by functioning as a bridge between cracks.

Different fiber types are employed in concrete production. These include steel fiber, polypropylene fiber, glass fiber, basalt fiber, polyamide fiber, polyvinyl alcohol fiber, ceramic fiber, polyethylene fiber, nylon fiber, kevlar fiber and natural fiber. Among these, the ones most frequently used are steel and polypropylene fiber, and as can be seen from Table 1, the steel fiber has the greatest effect on the impact resistance of concrete. Besides the choice of fiber type in the mixture, the geometry, slenderness ratio and fiber fraction also affect the impact resistance of the concrete. The studies in the literature illustrating these impacts are discussed below shortly. The ratio of fiber over concrete volume is presented as a percentage.

**Table 1.** An overview of existing studies on fiber-reinforced concrete under impact test.

| Researcher(s), (Year) | Fiber type and volume ratio (%) | Other variables | Variation vs. control specimen (%) |
|---|---|---|---|
| Swamy and Jojagha (1982) | Steel fiber (SF) (1.0) | Fiber geometry | %520 - 3505 |
| Mindess et al. (1986) | Polypropylene fiber (PF) (0.5) | Water/cement ratio | %19 -24 |
| Mindess and Vondran (1988) | PF (0.1-0.3-0.5) | | %12-40 |
| Mindess and Yan (1993) | PF (1.0), SF (1.0) | Loading rate | %(-22)-86 |
| Wang et al. (1996) | PF (0.25-0.5)<br>SF (0.25-0.5-0.75-1.0) | | %17-582 |
| Toutanji et al. (1998) | PF (0.1-0.3-0.5) | Silica fume ratio, fiber length | %40 -4100 |
| Banthia et al. (1998) | Carbon fiber (1.0)<br>macro and micro SF (1.0) | | %3.6 -210 |
| Nataraja et al. (1999) | SF (0.5) | | %80 |
| Marar et al. (2001) | SF (0.5-1.0-1.5-2.0) | Aspect ratio | %260-7360 |
| Song et al. (2005) | SF (1.0) | | %317 |
| Nataraja et al. (2005) | SF (0.5-1.0-1.5) | Water/cement ratio | %268 - 2450 |
| Ramakrishna and Sundararajan (2005) | Natural fiber (0.5-1.0-1.5-2.0) | | %40 -1713 |
| Badr et al. (2005) | PF (0.7) | | %40 |
| Yazıcı and Sezer (2008) | SF (1.0) | Maximum aggregate size | %682-800 |
| Zeynal (2008) | Micro SF (0.3)<br>SF (0.4-0.8-1.2) | Water/cement ratio | %210-4095 |
| Mohammadi et al. (2009) | SF (1.0-1.5-2.0) | | %41-67 |
| Xu et al. (2010) | PVA fiber (0.3-0.6-0.9-1.2) | | %23-91 |
| Nili and Afroughsabet (2010a) | SF (0.5-1.0) | Water/binder ratio | %232-2516 |
| Nili and Afroughsabet (2010b) | PF (0.2-0.3-0.5) | Water/cement ratio | %42- 845 |
| Erdem et al. (2011) | SF(1.0) , PF (1.0) | | %(-57)-414 |
| Caf (2012) | SF(0.5-1.0-1.5-2.0)<br>PF (gr) 300-600-900-1200 | | %1-1064 |
| Nia et al. (2012) | PF (0.2-0.3-0.5)<br>SF (0.5-1.0) | Water/binder ratio | %42-2516 |
| Su and Xu (2013) | Ceramic fiber (0.1-0.2-0.3) | | %(-28)-47 |
| Aliabdo et al. (2013) | PF(0.1-0.2) SF (1.0-2.0) | Agregate type | %13-81 |
| Gupta et al. (2015) | Rubber fiber ( 5-10-15-20-25) | Water/binder ratio,<br>Silica fume ratio | %46-472 |

Swamy and Jojagha (1982) reported that hooked and paddle-shaped fibers gave the best results against impact loads due to their longer lengths and higher slenderness ratios. Additionally, Marar et al. (2001) and Mohammedi et al. (2009) illustrated that with increasing fiber slenderness ratio and mixing proportions, there was an increase in the concrete's impact resistance.

This study aimed to investigate the optimum rate of reuse of RCAs in concrete, and to determine the influence on the mechanical properties of RACs when used with polypropylene and steel fibers separately and in combination (hybrid), because there is a limited number of studies about the use of hybrid fibers. Although the impact strength of concrete with hybrid fibers and with RAC was separately investigated, the impact strength of RAC with hybrid fibers was not considered. For this purpose, all concrete specimens were prepared with a water/binder ratio of 0.50, 5% silica fume and aggregates with a maximum size of 16 mm. The RCAs were used at proportions of 30% and 50% in place of the natural aggregates. Hooked-end steel fibers at a volume fractions of 1% and 2%, and polypropylene fibers at a volume fraction of 0.1%, were used separately and in combination. The mechanical properties (compressive strength, flexural strength and impact resistance) of all concrete specimens were assessed and compared to the control groups.

Using hybrid fibers in both NCs and RACs assured better performance under compressive and flexural strength tests. The hybridization of steel fiber and polypropylene fiber could enhance the mechanical properties of concrete by bridging macro-crack and delaying micro-cracks.

## 2. Experimental Program

### *2.1. Materials*

In this study, Type 1 42.5 R Portland cement and silica fume (SF) were used as the cementitious materials, and their chemical compositions are summarized in Table 2. The specific gravity of Portland cement and silica fume are 3.14 and 2.24, respectively.

**Table 2.** Chemical components of cement and silica fume.

| | Cement (%) | Silica Fume (%) |
|---|---|---|
| $SiO_2$ | 18.73 | 91.92 |
| $Al_2O_3$ | 4.56 | 0.42 |
| $Fe_2O_3$ | 3.07 | 0.20 |
| CaO | 63.91 | 2.06 |
| MgO | 2.08 | 3.69 |
| $SO_3$ | 2.90 | - |
| $K_2O$ | 0.62 | - |
| $Na_2O$ | 0.29 | - |
| Cl | 0.02 | - |
| $Cr_2O_3$ | - | 0.37 |
| C | - | 0.21 |
| S | - | 0.07 |

Both natural crushed limestone aggregates and RCAs with a maximum particle size of 16 mm were used as a coarse aggregate. Local river sand was used as a fine aggregate (NFA). The specific gravity and water absorption capacity of the aggregates were determined according to the EN 1097-6 Standard. The experiments conducted on the aggregate showed that the RCAs are about 16% weaker than the NCAs (natural coarse aggregates) because of their high porosity, and also that the water absorption of the RCAs is almost 3 times higher than that of the NCAs. Similar results were seen in published literature (Topçu and Şengel, 2004; Rao et al., 2007; Tam et al., 2008; Matias et al., 2013; Wagih et al., 2013). The physical properties of all aggregates are given in Table 3.

**Table 3.** Physical properties of natural aggregates and recycled coarse aggregates.

| | Specific gravity | Water absorption (%) | Surface moisture (%) | Bulk density (g/cm3) |
|---|---|---|---|---|
| 0-2 NFA | 2.45 | 2.09 | 0.20 | 2.40 |
| 2-4 NFA | 2.45 | 2.39 | 0.30 | 2.39 |
| 4-8 NCA | 2.54 | 1.51 | 0.25 | 2.50 |
| 4-8 RCA | 2.12 | 6.64 | 4.21 | 1.96 |
| 8-16 NCA | 2.64 | 1.95 | 0.45 | 2.59 |
| 8-16 RCA | 2.24 | 8.19 | 5.47 | 2.10 |

Polypropylene fibers of 9 mm in length and steel fibers of 35 mm in length with a 65 aspect ratio were used both separately and in combination. The pictures of the fibers are shown in Fig. 1, and the physical and mechanical properties of polypropylene and steel fibers are presented in Table 4.

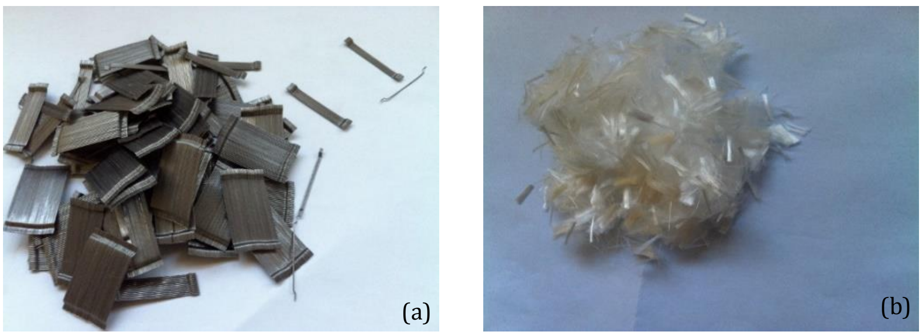


**Fig. 1.** (a) Polypropylene fibers; (b) steel fibers used for reinforced concrete.

**Table 4.** The physical and mechanical properties of polypropylene fibers and steel fibers.

| | Length (mm) | Diameter (mm) | Density (gr/cm³) | Tensile strength (N/mm²) | Modulus of elasticity (kN/mm²) |
|---|---|---|---|---|---|
| Polypropylene Fiber | 9 | 0.022 | 0.90 | 600 - 750 | 3.8 |
| Steel Fiber | 35 | 0.55 | 7.80 | 1338 - 1352 | 210 |

### *2.2. Mixing proportions*

A cement content of 350 kg/m³ and the same water-binder ratio (W/C+SF) of 0.50 were used in all batches. To improve the mechanical properties, silica fume was used at 5% of cement weight in all concrete specimens. Super plasticizer (SP)-based polycarboxylic ether was used at 2% of cement weight in all batches for better workability.

Hooked-end steel fibers at 1% and 2% volume fractions, and polypropylene fibers at a 0.1% volume fraction were used. The NCAs used in the production of NC were replaced with RCAs 30% and 50%. The mixing proportions are listed in Table 5.

**Table 5.** Concrete mix proportions for 1 m³.

| | W/(C+SF) | Water (kg/m³) | Cement (kg/m³) | Silica fume (kg/m³) | 8-16 mm (kg/m³) | | 4-8 mm (kg/m³) | | 2-4 mm NFA (kg/m³) | 0-2 mm NFA (kg/m³) | PF $V_f$ (%) | SF $V_f$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | NCA | RCA | NCA | RCA | | | | |
| N | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | - | - |
| NP | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | 0.1 | - |
| NS1 | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | - | 1 |
| NS2 | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | - | 2 |
| NPS1 | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | 0.1 | 1 |
| NPS2 | 0.50 | 175 | 333 | 17 | 687 | - | 283 | - | 244 | 531 | 0.1 | 2 |
| R30 | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | - | - |
| R30P | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | 0.1 | - |
| R30S1 | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | - | 1 |
| R30S2 | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | - | 2 |
| R30PS1 | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | 0.1 | 1 |
| R30PS2 | 0.50 | 175 | 333 | 17 | 481 | 175 | 198 | 71 | 244 | 531 | 0.1 | 2 |
| R50 | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | - | - |
| R50P | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | 0.1 | - |
| R50S1 | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | - | 1 |
| R50S2 | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | - | 2 |
| R50PS1 | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | 0.1 | 1 |
| R50PS2 | 0.50 | 175 | 333 | 17 | 343 | 291 | 142 | 118 | 244 | 531 | 0.1 | 2 |

Different codes have been used to identify the individual concrete groups to make the results easier to understand and interpret. The abbreviations are normal concrete (N), recycled aggregate concrete (R), polypropylene fiber (P), 1% steel fiber (S1) and 2% steel fiber (S2).

### *2.3. Mixing procedure*

All materials were mixed in a pan mixer. Firstly, the dry coarse and fine aggregates were mixed together for one minute in the mixer. Then cement and silica fume were added and mixed for another minute. Later, water equivalent to 70% of the water required for the mix was added. Then, a hyper plasticizer was mixed with the rest of the required water, and they were added to mix with the cementitious composite for another 2 minutes. In fibrous samples, the fibers were added last and mixed together with the mixture for another two minutes. The total mixing time in non-fiber samples was five minutes, while in fibrous samples it was six minutes.

### *2.4. Test methods*

All specimens were stored in molds for about 24 hours and were then cured in lime-saturated water at a temperature of 23 ± 2˚C, until the day of testing. Each value was determined by calculating the average of 3 different specimens. Compressive strength tests were performed at 28 days on 150x150x150 mm cubic specimens, and the flexural strength test was also performed at 28 days on 70x70x280 mm beam specimens. The compressive strength and flexural strength of specimens were determined in accordance with EN 12390-3 and EN 12390-5 Standarts, respectively.

The impact tests were conducted with the drop weight test machine as described at ACI Commitee 544, is shown in Fig. 2. The aparatus of the equipment are hammer, steel bowl and the test specimen. In this method briefly, 4.45 kg hammer is dropped sequentially from heights of up to 457 mm on the steel bowl with 64 mm diameter which placed on the concrete disc specimen 150 mm diameter by 64 mm thick. Then number of blows about first visible crack and ultimate crack were determined.

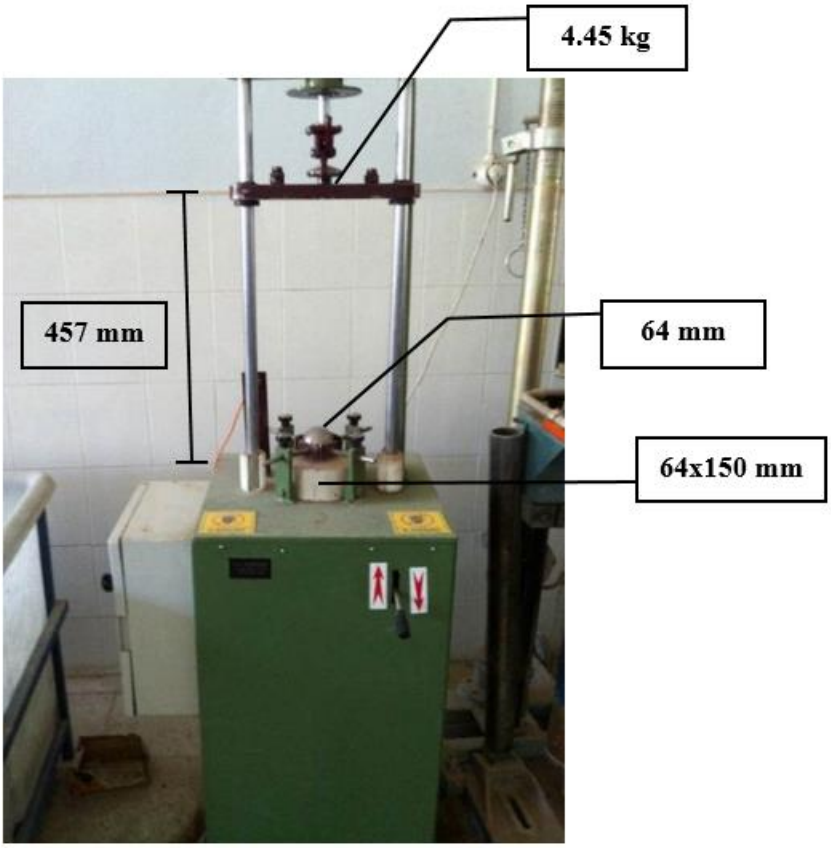


**Fig. 2.** Impact test machine.

The impact energy can be calculated with equations as follows:

$$H = gt^2/2 \quad (1)$$

$$V = gt \quad (2)$$

$$m = W/g \quad (3)$$

$$U = mV^2/2 \quad (4)$$

$$Impact\ energy = n \cdot U \quad (5)$$

$U$ = Energy occured with a blow (kNmm),
$W$ = Weight of hammer (kg),
$m$ = Mass of hammer (N),
$H$ = Drop height of hammer (mm),
$t$ = Drop time of hammer (s),
$g$ = Acceleration of gravity (mm/s$^2$),
$V$ = Velocity of hammer at the moment of blow (mm/s),
$n$ = Number of blows.

## 3. Results and Discussion

### *3.1. Compressive and flexural strengths*

The compressive and flexural tests were performed on NCs, RACs, fiber-reinforced concretes and fiber-reinforced RACs. The results of compressive and flexural tests are shown in Table 6 and Fig. 3.

It was found that in R30 and R50 concrete groups, the 28-day compressive strengths were lower than that of the control group by 7% and 24%, respectively. The reason due to the second RA-cement paste interface in addition to the interface of the aggregate-cement paste (Evangelista and Brito, 2007; Hoffman et al., 2012; Butler et al., 2013; Lima et al., 2013). For that reason the RAs can be used at a 30% ratio instead of normal aggregates in concretes, and they should not exceed that ratio.

It was found that the 28-day compressive strengths of R30S1 concrete groups were higher than the control groups by 1%. In the R30S1 groups, the negative effect of RA was countered why the steel fibers. A polypropylene and steel fiber mixture in a 1% ratio positively affected the 28-day compressive strength in both NCs and RACs. The NPS1 concrete group showed the maximum performance with a 21% increase in compressive strength compared to the control group (N), while R30PS1 had a 3% increase compared to the control group (N).

**Table 6.** The results of compressive and flexural tests.

| | Compressive strength (MPa) | Increase/decrease compared to NC (%) | Flexural strength (MPa) | Increase/decrease compared to NC (%) |
|---|---|---|---|---|
| N | 38.6 | --- | 5.24 | --- |
| NP | 40.9 | 6 | 5.49 | 5 |
| NS1 | 44.5 | 15 | 7.02 | 34 |
| NS2 | 28.8 | -25 | 7.83 | 49 |
| NPS1 | 46.7 | 21 | 7.51 | 43 |
| NPS2 | 29.8 | -23 | 7.98 | 52 |
| R30 | 36.0 | -7 | 4.79 | -9 |
| R30P | 37.2 | -4 | 4.93 | -6 |
| R30S1 | 39.0 | 1 | 6.07 | 16 |
| R30S2 | 28.8 | -25 | 7.05 | 35 |
| R30PS1 | 39.6 | 3 | 6.18 | 18 |
| R30PS2 | 29.3 | -24 | 7.32 | 40 |
| R50 | 29.2 | -24 | 4.00 | -24 |
| R50P | 29.9 | -23 | 4.10 | -22 |
| R50S1 | 30.8 | -20 | 5.29 | 1 |
| R50S2 | 26.5 | -31 | 6.81 | 30 |
| R50PS1 | 31.6 | -18 | 5.33 | 2 |
| R50PS2 | 27.9 | -28 | 6.85 | 31 |

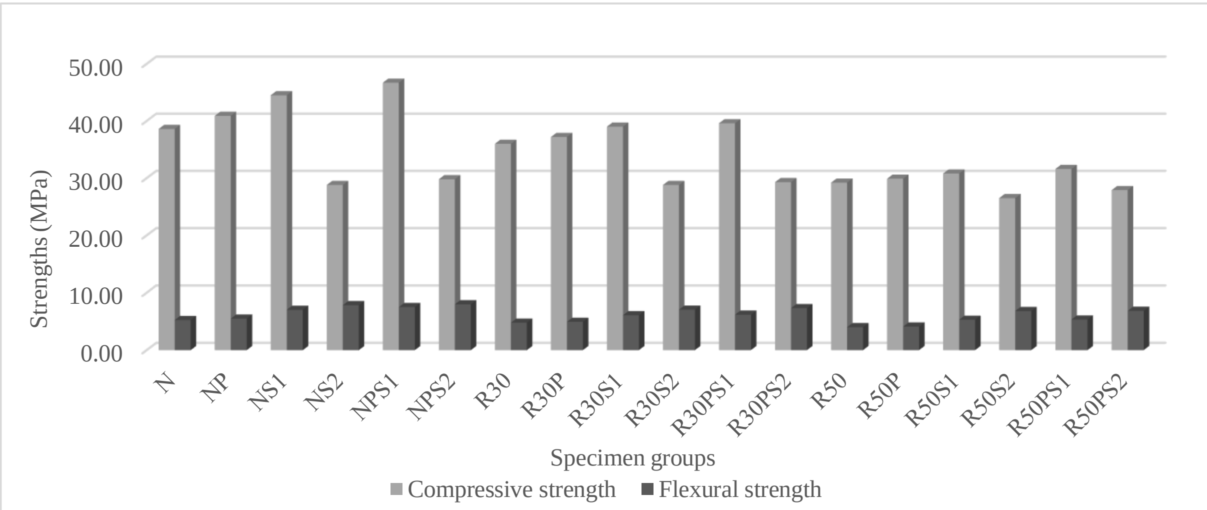


**Fig. 3.** Test results of compressive and flexural strengths.

The flexural strengths increased with the increase in steel fiber content. The amount of increase in the flexural strength in this study was 34% and 49% in 1% and 2% steel fiber-reinforced concretes, respectively. Fibers incorporated into concrete can hamper the growth of the cracks inside the concrete and improve the tensile strength and ductility of the concrete (Chenkui and Guafon, 1995; Eren and Celik, 1997; Abdul-Ahad and Aziz, 1999; Pajak and Ponikiewski, 2013; Khaloo et al., 2014).

In addition, 30% RACs, and 1% and 2% of steel fibers increased the flexural strength by 16% and 35%, respectively. Furthermore, adding 50% RACs, and 1% and 2% of steel fibers increased the flexural strength by 1% and 30%, respectively. According to these results, the addition of fiber gives more positive results in RACs. In this study the rates of increase were 18%, 40%, 2% and 31% for the R30PS1, R30PS2, R50PS1 and R50PS2 groups, respectively.

Using hybrid fiber in both NCs and RACs improved the performance of flexural strength and compressive strength in the specimens. The flexural strength of NPS1 and NPS2 specimens were 43% and 52% higher than the N concrete specimens. The increase in flexural strength is mainly due to the bridging effect of fibres, which restrains crack formation. Compared to the N concrete group, the flexural strength of the R30PS1 and R30PS2 concrete groups were higher by 18% and 40%, respectively. Also, compared to the N concrete group, the flexural strength of the R50PS1 and R50PS2 concrete groups were higher by 2% and 31%, respectively. According to the experimental results, the flexural strength of the hybrid fiber-reinforced concrete groups showed the best performance. The mechanical properties of RAC improved with the hybrid fiber content. This result implies that hybrid fibers should be used, especially in the RAC, depending on the fiber type and the amount.

### 3.2. Impact resistance

The results of impact tests, performed on recycled aggregate concretes, steel fiber concretes, polypropylene fiber concretes and hybrid fiber concretes, are presented in Table 7 and shown in Fig. 4.

**Table 7.** The results of impact test.

| | First crack (blows) | First crack impact energy (kNmm) | Failure crack (blows) | Failure crack impact energy (kNmm) |
|---|---|---|---|---|
| N | 142 | 2889 | 145 | 2950 |
| NP | 146 | 2963 | 151 | 3071 |
| NS1 | 617 | 12553 | 1140 | 23498 |
| NS2 | 1004 | 20426 | 1967 | 40019 |
| NPS1 | 676 | 13753 | 1155 | 23498 |
| NPS2 | 1057 | 21505 | 1994 | 40568 |
| R30 | 131 | 2665 | 132 | 2686 |
| R30P | 142 | 2889 | 149 | 3031 |
| R30S1 | 517 | 10518 | 889 | 18087 |
| R30S2 | 788 | 16032 | 1321 | 26876 |
| R30PS1 | 536 | 10905 | 899 | 18290 |
| R30PS2 | 797 | 16215 | 1342 | 27303 |
| R50 | 68 | 1383 | 69 | 1404 |
| R50P | 74 | 1506 | 79 | 1607 |
| R50S1 | 386 | 7853 | 675 | 13733 |
| R50S2 | 487 | 9908 | 1017 | 20699 |
| R50PS1 | 394 | 8016 | 688 | 13997 |
| R50PS2 | 498 | 10132 | 1031 | 20976 |

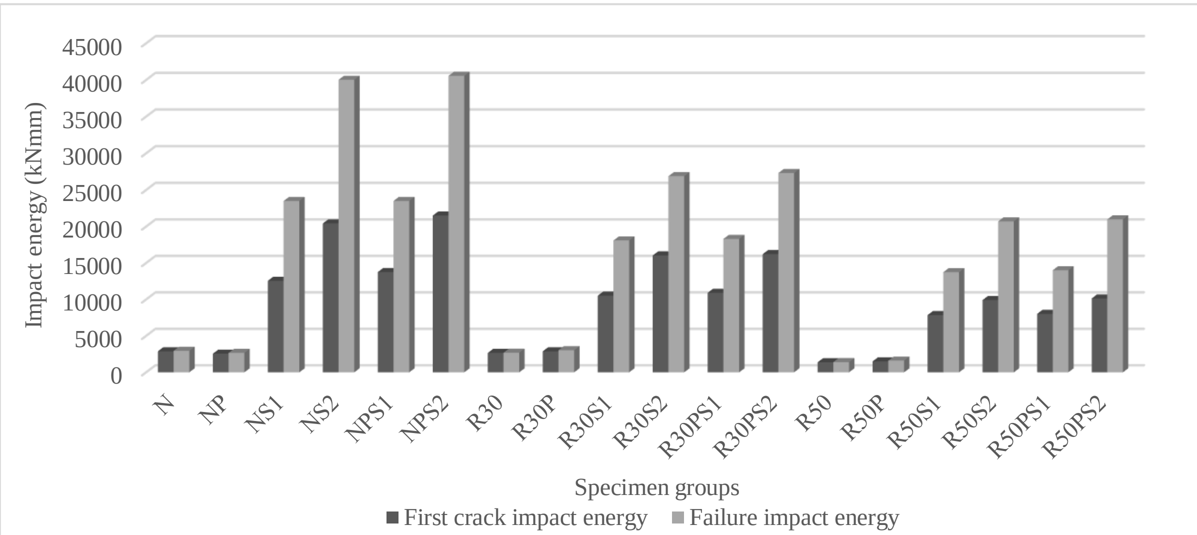


**Fig. 4.** Test results of impact resistance.

According to the values illustrated in Table 7, the energy at the first visible crack, and the failure energy of the R30 sample, were both lower than the control group at 8%. Also in the R50 sample, both the energy at the first visible crack and the failure energy were lower than the control group at 52% ratio. It appeared that the use of RCAs adversely affected the impact resistance of the concretes. The impact energy of concretes decreased with the increased proportion of RCA, likewise with the results for the compressive and flexural strength tests. The reason for this is the adherence between the cement paste and the RAs is weaker than the adherence between the cement paste and the natural aggregate (Erdem et al., 2011; Medina et al., 2014).

Using of 0.1% polypropylene fiber slightly increased the impact resistance in both NCs and RACs as confirmed by Badr et al. (2005), Nili and Afroughsabet (2010b), Mindess et al. (1986), Mindess and Vondran (1988), Mindess and Yan (1993), Wang et al. (1996), Toutanji et al. (1998) about the results of normal concretes.

Steel fibers increased the impact resistance of concretes too much due to their high energy absorption capacity, and the impact resistance increased with an increase in the steel fiber volume fraction (Marar et al., 2001; Mindess and Yan, 1993; Wang et al., 1996; Nataraja et al., 1999; Song et al., 2004; Nataraja et al., 2005; Mohammadi et al., 2009). In this study using 1% steel fiber increased the first crack energy and failure energy 4.5 times and 8.0 times respectively. As well as use of 2% steel fiber increased the first crack energy and failure energy 7.0 times and 13.5 times respectively.

Using steel fibers increased the impact resistance of RACs as it did for NCs. The use of 1% steel fiber in RACs with 30% RCA content increased the first crack energy and failure energy 3.5 times and 6.0 times, respectively. RACs with 50% RCA content and 1% steel fiber increased the first crack energy and failure energy about 3 times and 4.5 times respectively. RACs with 30% RCA content and 2% steel fiber increased the first crack energy and failure energy 5.5 times and 9 times, respectively, and 2% steel fiber in RACs with 50% RCA content increased the first crack energy and failure energy 3 times and 7 times respectively.

The compressive and flexural tests showed that hybrid fibers contributed to better impact resistance compared to other concrete groups. Compared to the NC, the impact resistance of NPS1, NPS2, R30PS1, R30PS2, R50PS1 and R50PS2 concrete groups were 5 to 8 times, 7 to 14 times, 4 to 6 times, 6 to 9 times, 3 to 5 times and 3.5 to 7 times higher, respectively. This result indicates that the mixed fibers have an important role in increasing the impact strength and should be taken into consideration in future work.

Using RCA decreased both the flexural strength and impact resistance, whereas using polypropylene fiber, steel fiber and hybrid fiber increased both the flexural strength and the impact resistance. The relationship between impact energy and flexural strength is shown in Fig. 5. It is understood from the correlation coefficient in the figure that there is a relationship between flexural strength and impact resistance.

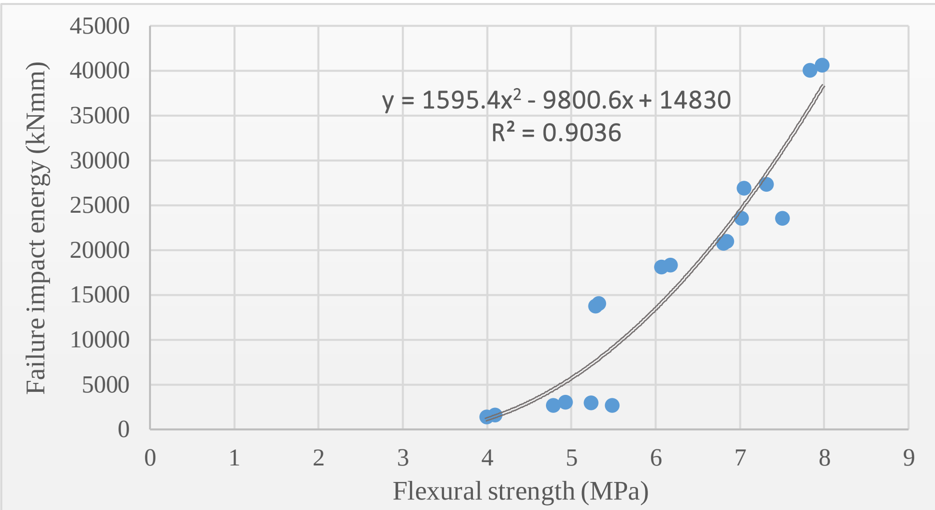


**Fig. 5.** Relationship between flexural strength and failure impact energy.

## 4. Conclusions

The main conclusions obtained from this study are as follows;

- The results of the compressive, flexural and impact tests showed that the use of RCA decreased the compressive strength, flexural strength and impact resistance of concrete. The addition up to 30% of RCA did not result in a significant difference between RAC and NC. These results have shown that up to 30% coarse RCA can be used without having any detrimental impact.
- In both NCs and RACs, using polypropylene fiber increased compressive strength and flexural strength by a small amount. While using steel fiber and hybrid fiber at a volume fraction of 1.0% increased the compressive strength, flexural strength and impact resistance, using a volume fraction of 2.0% just reduced the compressive strength because of its poor workability. By contrast, using steel fiber and hybrid fiber at 2.0% showed the best results.
- Polypropylene fibers made no significant contribution to impact resistance for any of the concrete

groups. Steel fibers increased the impact resistance of concretes too much due to their high energy absorption capacity. Hybrid fibers play an important role in increasing the impact strength and should be taken into consideration in future work on the effects on flexural strength and impact resistance.

- Considering environmental and economic impacts, it is expected that the use of RA will become more widespread and its contributions to the national economy will be increased. In addition, with these studies, it is considered that the number of facilities for the aggregate recovery and concrete recycling will increase throughout the country and thus there will be great progress in waste evaluation.
- Although many scientific studies were carried out about RACs, but there are no enough research about hybrid fiber reinforced recycled aggregate concretes. For future work, the various mechanical and durability properties of RACs should be investigated with using hybrid fibers at different ratios and using different parameters. Especially comparing studies about to different impact test methods should be examined. In addition, workability of fresh concrete, the compatibility of recycled aggregate-cement-plasticizer, should be investigated with the help of SEM, MIP analyses, XRD patterns.

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