The Impact of Recycled Concrete Aggregate on the Concrete's Properties: A Comparative Study

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Abstract

This research focuses on the mechanical and physical qualities of concrete made with aggregate from demolished concrete buildings rather than natural aggregate (NA). The use of recycled concrete aggregate (RCA) may help to preserve natural aggregate sources while also aiding in environmental conservation by minimizing the amount of demolition. RCA is produced by simple assembled equipment, and after crashing and storage, it may be blended with natural aggregate to produce fresh concrete. The aim of this study is to determine whether recycled concrete can serve as a substitute for natural aggregate. Additionally, the study investigates the impact of RCA on the mechanical properties of concrete made with recycled concrete, and other properties like durability, freezing-throwing resistance, structural performance, and workability. The treatment process may be employed to increase the quality of RCA, bringing its qualities closer to natural aggregates. It may be inferred that the treatment and pozzolanic material help to increase the strength. When compared to regular concrete with natural coarse aggregate, recycled concrete often has a strength difference of 10 to 25%.

Keywords: Recycled concrete aggregate, Natural aggregate, Compressive strength, Tensile strength, and durability

1. Introduction

Concrete is a widely used construction material. A concrete mixture consists mostly of aggregates, cement, water, and additives. The aggregate percentage accounts for 70 to 80% of the volume of the concrete mixture (Verian, K.P. et al., 2018).

It is expected that a huge amount of construction waste will be generated due to the demolition of old structures. While there is a need to increase concrete production due to the rapid growth of the construction industry, the consumption of natural aggregates will also increase, which will become an environmental problem. War, as well as earthquakes, cause the destruction of numerous structures (Ganiron, T., 2015). This generates massive amounts of construction and demolition trash, which is then disposed in landfills, polluting the natural environment and reducing valuable landfill space.

Concrete recycling is an environmentally responsible, sensible, and cost-effective technique to utilize aggregate left behind when buildings are destroyed or repaired. It may be turned into an environmentally friendly resource and utilized as an alternative to aggregate (Marinkovic, S. et al., 2010) and reduce the capacity of the final waste disposal facilities. The process includes breaking down existing concrete, screening and eliminating impurities, crushing, sorting, and producing a more sustainable alternative source that is becoming an increasingly popular option in various building projects as aggregates, road bases and subbases, and backfill materials. Marinkovic, S. et al. (2010) reported that the estimated recovery of coarse RCA from 1 m^3 of crushed concrete is 0.6 m3 (60%), implying that about 0.4 m^3 (40%) is wasted. According to Verian, K.P. et al. (2018) the aggregate characteristic influences the properties of new concrete. Recycled concrete from demolition activities is contaminated with hydrated cement paste, gypsum, and minor amounts of construction material, lowering the quality of RCA compared to NA; additionally, RCA comes from various demolished sites, and the strength of the concrete is unknown (Marinkovic, S. et al., 2010). During the crushing process, the aggregate particles are held together by gypsum and cement paste from the old concrete. This layer covering the particles changes the aggregate's quality, reducing its strength while increasing its water absorption as compared to NA. The water absorption rate of fine-grained RCA ranges from 5.5 to 13%, while coarse-grained RCA ranges from 3.5 to 9.2%, both of which are greater than that of NA (Marinkovic, S. et al., 2010); nevertheless, laboratory investigations have shown that

RCA may be successfully employed with coarse aggregates (Tabsh, S.W. and Abdelfatah, A. 2009). As the percentage of RCA in the mix rises, the quality and strength of the concrete reduce compared to normal concrete. Compressive strength drops by 10 to 25%, as do concrete bond strength, and splitting strength (Dimitriou, G. et al, 2017). The coated mortars on the surfaces of RCA particles after grinding lower their specific gravity and density compared to NA, making it more difficult to verify concrete quality (Dimitriou, G. et al, 2017, Verian, K.P. et al, 2018). Adding pozzolanic materials such as fly ash, silica fume, and metakaolin can improve the strength of recycled aggregate concrete to match or exceed natural aggregate concrete (Çakır, Ö., 2014).

Reusing decomposed concrete has several benefits, including cost savings, reduced truck traffic, less gravel mining, alternatives to non-renewable materials, and lower trucking expenses. Transporting concrete trash straight from the demolition site to the manufacturer is more cost-effective than using a landfill (Ganiron, T. 2015 and Mishra, G., 2021).

According to Ganiron T. (2015), RCA production and reuse are promoted in Europe, Canada, Japan, and Germany. According to the research (Akhtar A. and Sarmah A.K., 2018), the preceding nations, as well as other countries such as New Zealand, Australia, the United States, Brazil, China, India, and South Africa, are seeing an increase in concrete reuse throughout time. (Akhtar A. and Sarmah A.K., 2018) found that correctly controlling RCA manufacturing may save energy and boost the economy.

2. Improving the quality of recycled aggregate

2.1 Treatment method

RCA quality should be similar to NA quality. The damaged concrete's strength and quality affect the RCA's quality. Improving the properties of concrete using recycled aggregates are crucial for developing reliable and assessment methods. During RCA production, the crushed particles will be covered with a layer of mortar, and this process will result in the formation of microcracks, which in turn will enhance the porosity of the particles as illustrated in Fig. 1. The presence of mortar surrounding the aggregate affects the bond strength between the recycled aggregate and the new paste, as well as the concrete's strength (Behera, M. et al. 2014). These properties of RCA are weaker than those of NA, and failures are caused by the aggregates themselves

(Dimitriou, G et al., 2017). To boost bond strength, treatment is essential to improve the quality and characteristics of the aggregate while reducing the amount of mortar bonded. Low-quality aggregates can impact concrete hardenability, workability, and freezing-throwing resistance.

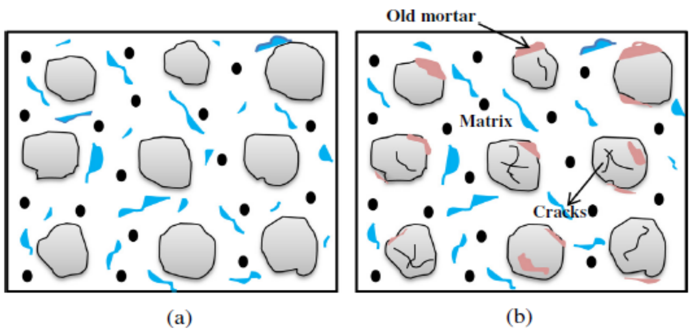

Fig.1 The difference between (a) natural aggregated and (b) recycled concrete aggregate (Behera, M. et al., 2014)

Mechanical grinding and pre-soaking are RCA treatment procedures to remove the adhering mortar. These are the treatment methods:

1. **Mechanical griding:**
   A. Mechanical griding

(Verma, A.et al., 2021) The RCA was treated by soaking it in (3% acetic acid) for 72 hours to weaken the bond between aggregate and compounds of adherent mortal, then mechanical grinding was used to loosen the mortar. while (Shi, C. et al., 2015) noted that the mortal can be cleaned using a traditional grinding machine with high-speed rotating eccentric gear in a grinding mill.

   B. Selective head grinding

This method involves heating the RCA using the microwave to loosen the bond between the RCA and the mortar attached to it, and then using a grinding machine to remove the mortar. (Shi, C. et al., 2015)

   C. Thermal griding

Shi, C. et al. (2015), Dimitriou, G. et al. (2017) stated in order to facilitate the grinding process, it was reported that RCA was heated to approximately 300°C to dehydrate the attached mortar to loosen the bond between the mortar and aggregate and then crushed with a grinder. | Furthermore, greater temperatures, approximately 500°C, have been shown to impair RCA characteristics.

2. **Pre-soaking:**

A. Simple treatment: This inexpensive method has been used to remove grout and mortar stuck to RCAs. This process can be accomplished by placing the RCA into the modified concrete mixture, adding water, and spinning at 10 rpm for 5 hours. Adding water continuously throughout the process to help remove impurities and grout, this method allowed the grout content to be reduced to 9%, and the RCA was sieved through a No. 4 (4.75 mm) sieve to improve aggregate quality (Dimitriou, G. et al, 2017, Verian, K.P. et al, 2018).

B. Soaking the RCA for 24 hours in '0.1M' hydrochloric acid (HCl) solution, this method eliminates around 0.76% and 0.54% of the total attached mortal surrounding RCA particles for the 10 and 20mm aggregates size, it has been noticed that water absorption of RCA decreased significantly after the treatment process, as reported (Verian, K.P. et al, 2018, and Shi, C. et al., 2015), but using this treatment method increases the production cost of RCA (Shi, C. et al., 2015).

C. Soaking the RCA in 2M sulphuric acid solution for 5 days. This method removes around 12 to 20% of the total attached mortal around RCA. To separate the aggregates from the mortar, the RCA was rinsed and sieved using a No. 4 sieve (4.75). (Verian, K.P. et al, 2018).

D. Self-healing of RCA: this mechanism enhances the hydration of the un-hydrated cement particles in the old mortar of attached RCA when it is immersed in water for 30 days (Verian, K.P. et al, 2018, Akhtar, A. and Sarmah, A.K., 2018).

E. Sodium silicate (SS) solution is also used to treat the RCA. The treatment process begins with soaking RCA in (Sodium silicate at 10% concentration) for 1 hour at approximately 20 °C. The RCA is then dried in an air conditioner at 20 °C for 4 hours until the particle surface reaches a dry and moist state. The RCA can then be coated using silica fume and dried in an air conditioner for about 4 hours. The purpose of using SS is to reduce water absorption, fill pores and cracks, and improve mechanical properties (Bui, N.K et al., 2017).

2.2 Using OPC replacements (pozzolanic material)

Pozzolanic materials can be used as partial replacements of cement to improve the long-term strength and quality of concrete, including:

1. **Fly ash**

The fly ash is usually used for increasing the reaction between cement and water and also improves the hydration of old attached mortar on the surface of RCA. The other benefits of fly ash are improving workability, reducing the permeability of concert, improving compressive strength at a later age, and reducing the shrinkage of concrete containing RCA (Verian, K.P. et al., 2018). Dimitriou, G. et al. (2017) reported a low early compressive strength was presented due to the delayed pozzolanic activity of fly ash.

2. **Silica fume (SF) and Metakaolin**

Adding silica fume and metakaolin improves the properties of self-compacting, increasing compressive strength and tensile strength, and lowering the maximum hydration temperature (Verian, K.P. et al., 2018, Akhtar, A. and Sarmah, A.K., 2018, Kisku, N. et al., 2017). Dimitriou, G. et al (2017) reported that the addition of fly ash and silica fume improved the durability properties of concrete containing RCA. Verian, K.P. et al. (2018) stated that the beneficial effects of SF were evident after 91 days, and the recorded compressive strength was between 70 and 85 MPa. This proves that SF increases the compressive strength. Çakır, Ö. (2014) and Kisku, N. et al. (2017) mentioned that SF raises the bond strength between cement paste and aggregate, and reduces the microcrack of RCA that developed during the crushing process.

3. Pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS)

Ann, K.Y. et al. (2008) studied the effect of 30% PFA and 65% GGBA substitution on the durability and compressive strength of concrete containing RCA. The use of PFA and GGBS will aid in closing the gaps between the cement paste and the aggregate, resulting in a decrease in permeability, increased durability, and decreased segregation, as well as a reduction in reinforcing corrosion as the permeability reduces. Because GGBA and PFA reduce cement hydration, this influences slower strength gain at early ages, but then improves strength in the long term.

2.3 Using saturated aggregate

An alternative method to enhance the quality of RCA in completely saturated conditions, which improve the concrete performance by helping to reduce water absorption, improve workability, increase the compressive strength, limit void effects, and promote internal hardening. Soak RCA for 24 hours to ensure complete saturation in water (Verian, K.P. et al., 2018, Çakır, Ö., 2014). Pickel, D. et al. (2017) studied the effect of humidity on the strength, the result of the experiment was better compressive strength was obtained when the concrete was fully saturated with RCA than when it was dry. RCA humidity does not have a significant effect on tensile strength (Dimitriou, G. et al, 2017).

3. Mechanical Properties

Concrete strength is determined by a variety of factors, including the water-cement ratio, temperature, humidity, curing time, and cement and aggregate type. When natural aggregates are replaced by RCA, the strength of the concrete is affected; this influence must be examined (Cavalline, T. et al., 2022).

3.1 Compressive strength

Comparative strength assesses the concrete's capacity to sustain loads before failing. Numerous studies investigated how RCA affects compressive strength. Various criteria were evaluated during the experiments while calculating compressive strength change. The characteristics that influence the compressive strength of RAC are:

3.1.1 Percentage of RCA

Researchers investigated the compressive strength of concrete using various percentages of RCA, and the results reveal that utilizing up to 25% RCA has no noticeable effect, but as the proportion increases, the compressive strength diminishes. When NA is substituted with 100% RCA, compressive strength drops by around 25% relative to natural aggregate concrete strength.

Figure 2 displays the findings from several investigations. Elhakam, A.A. et al. (2012) found that compressive strength fell from 33 MPa to 32.5 and 26.5 MPa when RCA substitution increased from 0% to 25% and 100%, respectively. Furthermore, when the 7-day and 28-day tests of (Hamad, B. S. and Dawi, A. H., 2017) were compared with the RCA 50%, the compressive strength increased from 19.5 to 31.4 MPA.

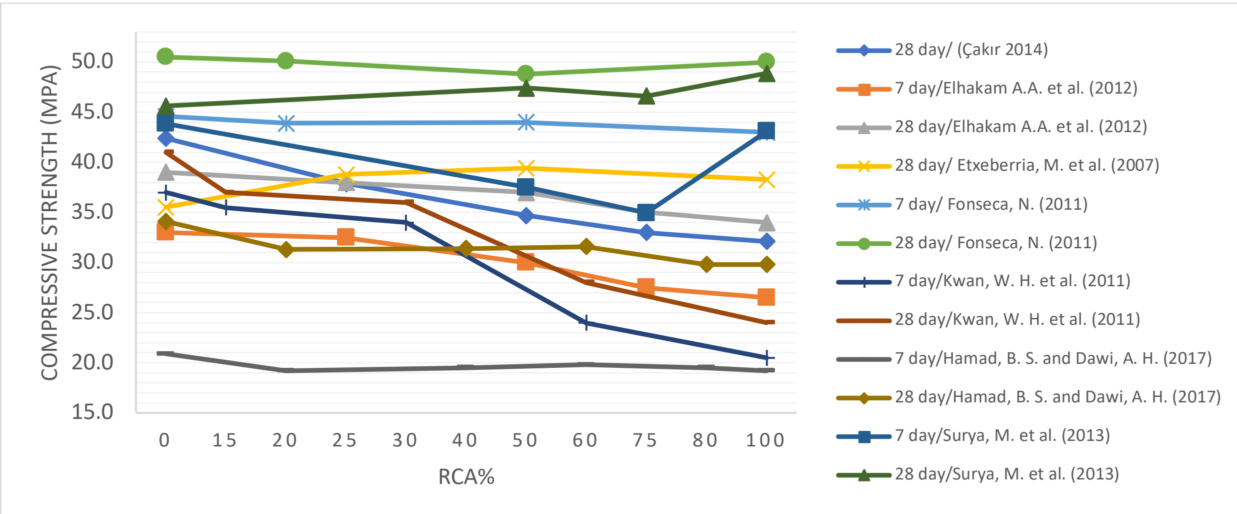

Fig. 2 Compressive Strength with RCA%

3.1.2 Water-to-cement ratio

Concrete with a lower w/c ratio has better compressive strength; nevertheless, compressive strength decreases as RCA increases. The researchers used several w/c ratios to examine concrete mixes, and the results of the studies are shown in Fig. 3. It has been discovered that compressive strength reduces by 50% when w/c increases from 0.35 to 0.55 (Zheng, C. et al. 2018). While (Elhakam, A.A. et al., 2012) demonstrate that reducing w/c from 0.6 to 0.4 increases strength by 35%. Furthermore, (Elhakam, A.A. et al., 2012) found that compressive strength improved from 27.5 to 35 MPa at w/c 0.45 and RCA 75% after 7 and 28 days.

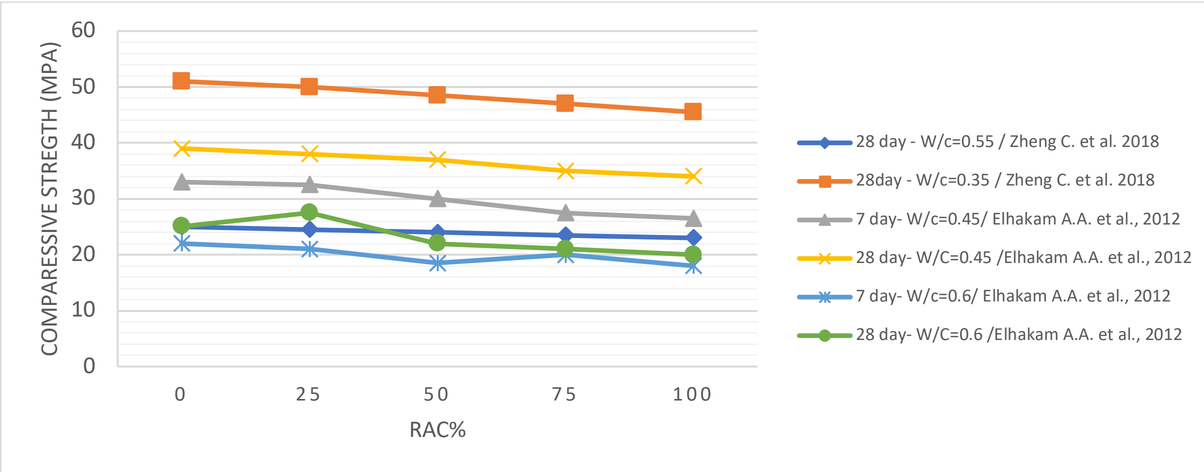

Fig. 3 Compressive Strength with RCA% and W/C

3.1.3 Treatment of RCA

Several studies support the usage of treated RCA in concrete. By compared it with concrete containing untreated RCA and NA. Dimitriou, G. et al. (2017) studied the impact of treating RCA and NA on compressive strength. A simple (low-cost) approach was used to clean the surface of NA and RCA of impurities and mortar.

Different amounts of superplasticizer were used to guarantee that each mix had the same level of slump. Figure 4 shows the test results, with RCA-T representing treated RCA and RCA-F representing untreated RCA. When 100% of treated RCA is present in concrete, compressive strength decreases by 13.8% compared to NA. When the amount of RCA is lowered by half, the strength improves, but it remains 11% lower than NA. Compressive strength improves by 10.6 MPa and 15.1 MPa when RCA is replaced at 50% and 100%, respectively, the results confirming the treatment's effectiveness (Dimitriou, G. et al. 2017).

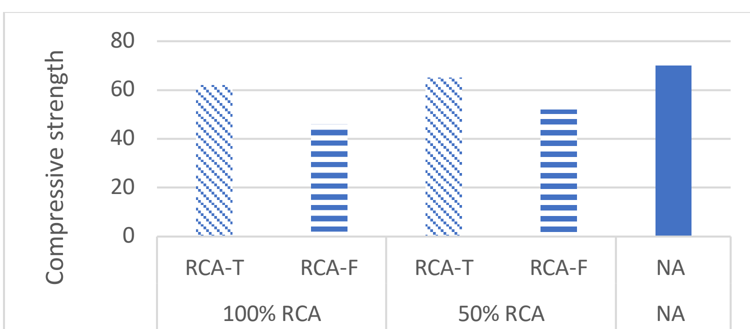

Fig. 4 Compressive strength at 28-day with RCA % and condition of treatment (Dimitriou, G. et al., 2017)

3.1.4 Pozzolanic material

Some researchers worked on the effect of pozzolanic material such as (fly ash (FA), silica fume (SF), and ground granulated blast furnace slag (GGBS)) with different percentages of RCA.

- The result of compressive strength using FA is shown in Fig. 5(a), it is clear that with an increase in the amount of FA, the compressive strength decreases which returns to the effect of the FA on the early strength of concrete. The test outcome of (Kurad, R. et al, 2017) demonstrates when the FA increased from 0% to 30% and 60% the strength was reduced from 52 to 39 and 23 MPa respectively using 100% RCA.
- Regarding SF, similarly to FA it improved the early strength of concrete containing RCA. In Fig 5(b) the test result by (Çakır, Ö. 2014) determined the increase in strength from 33 to 35.4 and 36 MPa when the FA was added by 5% and 10% when the replacement of RCA was 75%.
- GGBA is similar to FA, it decreases the early strength by 60% of GGBA the strength is reduced by 13% compared to 30% of GGBA with the same use of 50% RCA. The Fig 5 (c) illustrations the reduction of strength with the increase in GGBA% and RCA%.

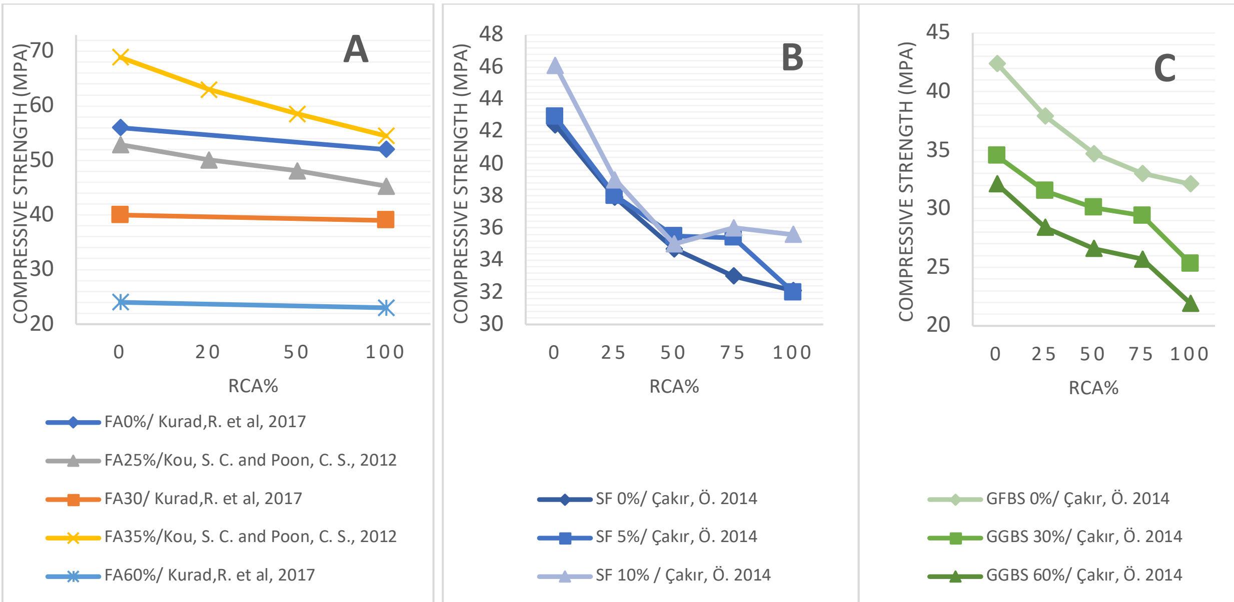

Fig.5 Effect of pozzolanic material and RCA% on the compressive strength at 28 days (A) fly ash, (B) silica fume, and (C) granulated blast furnace slag

3.2 Splitting tensile strength

The splitting tensile strength of the concrete containing the RCA is also a critical consideration; if the concrete strength is insufficient, it may fracture and collapse. As a result, understanding the tensile strength of concrete components is crucial for their safety and structural integrity. According to (Cavalline, T. et al, 2022), RCA concrete can have a greater splitting tensile strength, this might be due to increased angularity of the RCA particles, a stronger link between saturated RCA and the new paste, or possible chemical interactions between the RCA concrete and the paste. According to (Dimitriou, G. et al.2017) experiment, substituting 100% RCA reduced the splitting tensile strength by 5 to 25% when compared to conventional concrete. Furthermore, RCA treatment lowered splitting tensile strength, and the loss was attributed to the impact of RCA form and texture following treatment. Several investigations have found that increasing the RCA% in concrete decreases the spitting tensile strength, as indicated in Fig 6 When we compare the tensile strength of NAC with RAC (100% replacement) using the findings of (Elhakam, A.A. et al. 2012), the tensile strength was reduced by 45% and 39% for the 7- and 28-day tests, respectively. Tests by Çakır et al. (2014) and Surya et al. (2013) showed that 100%

RCA blends had greater split tensile strength. The rough texture and absorption capability of the adhering mortar in RA may increase the bonding and interlocking of cement mortar.

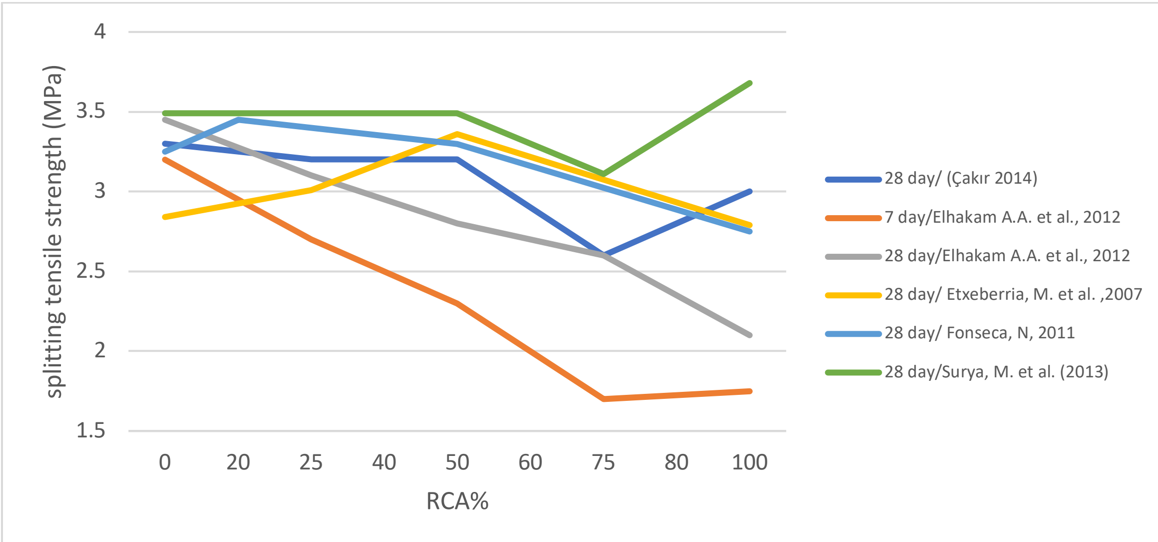

Fig.6 The effect of RCA% on the splitting tensile strength

3.3 Workability

Concrete including RCA has a lesser slump than normal concrete when the water/cement ratio is kept constant. The reduction in workability is due to the high water absorption rate of RCA. The shape and texture of the RCA also influence its performance. To attain the same workability as normal concrete, add 5-15% more water (Verian, K.P. et al., 2018). Using saturated RCA enhances workability when compared to dry RCA, provides for more control over the W/C ratio, and minimizes the quantity of admixture needed in mixing (Verian, K.P et al, 2018, Pickel, D., 2017, Dimitriou, G. et al, 2017). When the RCA is treated, fewer superplasticizers are used to get the desired slump (Dimitriou, G. et al., 2017).

3.4 Water absorption

The absorption of water in concrete is affected by the increasing amount of RCA the amount of coated mortar increases in mix and microcracks developed during the crushing process. The outcome of Table 1 comes from the experiment by (Çakır, Ö., 2014) which shows the percentage of water absorption raised up by 10.5% when 100% RCA was used, and 4.5% increased when RCA amount was reduced to 50%.

RCA%	0%	25%	50%	75%	100%
Water absorption%	5.1	7.2	9.6	12.4	15.6

Table 1 the effect of RCA% on water absorption (Çakır, Ö., 2014)

3.5 Durability

The ability of concrete to withstand impacts from the outside environment. The quantity of RCA, additive content, and RCA quality all have an impact on concrete durability. The permeability of concrete rises when the RCA percentage rises, then results in poor durability; however, it is feasible to improve permeability by incorporating pozzolanic material throughout the concrete production process (Kisku, N. et al., 2017).

3.6 Density

The density of RCA is 10% lower compared to that of NA (Marinkovic, S. et al., 2010). Concrete density falls as the RCA ratio increases, with a 5% reduction when concrete is prepared with 100% coarse RCA (Verian, K.P et al, 2018). The experiment by Çakır, Ö. (2014) in Table 2 shows that increasing the amount of RCA reduces the density of new concrete. When 100% of the replacement is included in concrete, the density is lowered by 20% compared to normal concrete (0% RCA).

RCA	0%	25%	50%	75%	100%
Density of new concrete kg/m3	**2513**	**2317**	**2254**	**2103**	**2008**

Table 2 Density of concrete with the RCA% (Çakır, Ö., 2014)

3.7 Freezing throwing resistance

The high porosity and water absorption properties of RCA reduce the freezing-throwing resistance of concrete containing the RCA, then it effects on reducing the mechanical properties of concrete and durability (Ann, K.Y. et al., 2008). Compressive strength is reduced by 5.8 MPa due to low resistance to freezing and throwing (Verian, K.P et al., 2018). Concrete resistance is determined by several elements, including replacement ratio, admixture, RCA quality, and air entraining. Reducing mortar content reduces water absorption, increasing resistance to freezing-throwing (Kisku, N. et al. 2017).

3.8 Permeability

Verian, K.P. et al, (2018) and Kisku, N. et al. (2017) concluded the investigation and said that the permeability of RCA-containing concrete is 2-5 times greater than regular concrete, which is compatible with the size and continuity of the pore in the hydrated cement paste. To minimize permeability, fly ash and silica fume may be used as a replacement for cement. (Cavalline, T. et al, 2022) said that lowering the water-cement ratio by 0.05 to 0.1 can boost strength while decreasing permeability.

3.9 Dry shrinkage

Due to its high water absorption, RCA-containing concrete has a higher paste content, which enhances drying shrinkage. Varian, K.P. et al. (2018) observed that the drying shrinkage of concrete with coarse RCA and fine NA was 20 to 50% larger than that of normal concrete, while the drying shrinkage of concrete with fine and coarse RCA was 70 to 100% higher. With an increase in mortar content and RCA, concrete exhibits substantial shrinkage. The effect of the percentage of RCA on dry shrinkage was studied by (Kou, S. C. and Poon, C. S., 2012), and the result of the experiment was that when RCA was increased by 20%, 50%, and 100%, the dry shrinkage increased by 10.4%, 17.5%, and 33.3%, respectively. In the same research, the impact of fly ash on the dry shrinkage was tested, and when 25% and 35% of FA was used for the concrete mix contained 25% RCA, the dry shrinkage reduced by 6.7% and 9.3 compared to the concrete free of FA.

Conclusion

- Concrete containing RA loses compressive strength with increased replacement amount. At 28 days, the strength of the 100% replacement fell by around 25%. As well as the splitting tensile strength decrease by 5% to 45%.
- To enhance concrete with RCA, use saturated RCA and mix in enough OPS replacements (FA, metakaolin, and SF). Other mixture-design adjustments include processing RCA before using it in concrete, lowering the quantity of old mortar and other contaminants in RCA particles, and integrating fiber into the RCA concrete mixture. The pozzolanic substance has an influence on the compressive strength; at the early age of concrete, compressive strength is reduced because it delays the hydration of cement; nevertheless, in the long run, compressive strength rises.

- The fundamental difference between RCA and NA particles is due to old mortars adhering to their surfaces. The mortar residue accounts for the difference in specific gravity, absorption rate, and density between RCA and NA.

  There are a couple strategies to reduce the loss of workability that happens when RCA is added to the concrete mixture: soak the aggregate before mixing, and use plasticizer or superplasticizer.

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