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Improving the mechanical properties of recycled concrete aggregate using chopped basalt fibers and acid treatment

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HIGHLIGHTS

- Surface treatment method and basalt fibers are used on recycled coarse aggregate (RCA).
- Using treated RCA and basalt fiber improved splitting tensile and flexural strength significantly.
- Using treated RCA and basalt fiber had little effect on enhancing compressive strength.
- Use of low concentration acid had significant effect on improving quality of RCA and mechanical properties.

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ABSTRACT

This paper presents the results of a study that investigated the improvement of the mechanical properties of recycled concrete aggregate (RCA) produced by adding chopped basalt fibers (BF) with contents of 0.1%, 0.3%, 0.5%, 1%, and 1.5% by total volume of the mix to treated and untreated recycled aggregates. The recycled aggregates were surface treated by pre-soaking them in a 0.1 M hydrochloric acid (HCl) solution for 24 h to remove the adhered mortars to improve the bond between the recycled aggregate and the cement. In addition, chopped BF was added to normal concrete (NA) mixes as a control for comparison. The results showed that using chopped BF minimally enhanced the compressive strength of the concrete mix but significantly improved its flexural and splitting tensile strength. Furthermore, the optimum BF content that produced the same splitting tensile and compressive strength as NA was 0.5% for untreated RCA and 0.3% for treated RCA, while the flexural strength was 0.3% for untreated RCA and 0.1% for treated RCA.

1. Introduction

Using concrete demolition and waste products to produce recycled concrete aggregate (RCA) for new concrete production was identified by researchers as having a positive impact on the environment, resource preservation, and the economy by reducing the use of non-renewable materials, such as natural aggregate (NA), while also reducing the areas of landfills [1].

However, the quality of RCA is usually lower than that of NA because RCA contains mortar particles and surface cracks that introduce higher water absorption, porosity, and weak portions which reduce mechanical strength and introduce workability and durability concerns [2,3]. Most of the RCA studies in the literature concluded that the mechanical strengths decreased as the percentage of RCA content increased [4–6]. Marie and Quiasrawi [7] reported that using RCA replacement ratio of 20% by weight of coarse NA reduced the workability, compressive, splitting tensile and flexural strength by 30%, 20%, 10%, and 12%, respectively. Wagih et al. [8] used RCA replacement ratio of 0%, 25%, 50%, 75%, and 100% by weight of coarse NA. The authors reported that replacing 25% had no significant adverse effects on mechanical properties, while the compressive strength reduced from 7% to 13% when the ratio was 50% and the reduction percentages increased when the ratio increased to 75% and 100%.

Many studies were conducted in the last few years that addressed the above drawbacks and how to enhance the performance of RCA. Shi et al. [9] provided a comprehensive literature review of surface enhancement treatment methods and suggested that carbonation treatment [10,11] was the most efficient method. Bru et al. [12] applied microwave and mechanical grinding to remove the remaining mortar. Dilbas et al. [13] concluded that 30% is the optimum replacement ratio for RCA and 5% silica fume is the most optimum content to improve the compressive strength.

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Song et al. [14] added polymer aluminum sulfate to enhance the volume stability of RCA; and their results indicated that the polymer was able to increase the micro-hardness and reduce the inhomogeneity of the interfacial transition zone (ITZ) in RCA. Spaeth and Tegguer [15] applied different polymer based treatments to improve the water absorption and fragmentation resistance of RCA. Cheng and Wang [16] used different concentrations of sodium silicate solutions to soak RCA. They reported that the optimum soaking time and concentration were 1 h and 5%, respectively.

One of the most efficient, environmentally-friendly, and feasible approaches for improving the mechanical strengths of RCA is pre-soaking in HCl, H_2SO_4, and H_3PO_4 acids. Tam et al. [17] reported that the mechanical strength and water absorption of RCA improved when the remaining mortar was removed by pre-soaking the aggregate in acid for 24 h. Ismail and Ramli [18,19] improved the mechanical strength of RCA by soaking the aggregate in HCl solution and impregnating them with calcium metasilicate. The authors concluded that the concentration of the used acidic solution should be low and the optimal concentration was 0.5 M.

Recently, basalt fiber (BF) has gained the attention of many researchers and several recommendations were reported in the literature for improving the mechanical properties of normal concrete using BF [20–23]. BF is produced from basalt volcanic rocks. BF is non-carcinogenic, non-toxic, and environmentally friendly. It is ideal for fire protection and insulation applications because of high temperature resistance. BF is known for high strength, high corrosion resistance, and resistance to acids and alkalis. Recently, Elshafie and Whittleston [24] provided a comprehensive literature review of the influence of using different chopped BF lengths and contents on the mechanical strength of normal concrete. They concluded that enhancement in the mechanical strength was achieved when the BF was between 12 and 24 mm in length and the content was between 0.1and 0.5% by total volume. Revade A. and Dharane [25] investigated the mechanical properties of grade 30 normal concrete using chopped BF 13 μm in diameter and 12 mm in length with a BF content of 0%, 1.0%, 1.5%, and 2.0% by the weight of the cement. They reported that the optimum BF content value for compressive strength was 1.0%. Irine [26] used chopped BF using three different contents, i.e., 1, 2, and 4 kg/m^3. The results showed that for the largest BF contents; the compressive, splitting tensile and flexural strength increased 14%, 62%, and 54%, respectively, compared with no BF.

Based on this study's extensive literature search, it became clear that there is a lack of information about BF's impacts on the mechanical strengths of concrete made with RCA mainly because most of the studies were conducted using normal concrete with NA. Therefore, the objective of the study of this paper was to evaluate the effects of using chopped BF in the following mixes: (1) normal concrete with NA (as control mixes), (2) untreated RCA, and (3) surface-treated RCA. The performance of RCA was improved through enhancement treatment methods. The RCA was pre-soaked in 0.1 M HCl for 24 h to remove the mortar attached to the original RCA aggregates. The following BF contents were adopted in this research: 0.1%, 0.3%, 0.5%, 1%, and 1.5% by the total volume of the mixes. According to the best author's knowledge, this is the first paper that studies the effect of using chopped BF on mechanical strengths of untreated and treated RCA.

2. Materials

2.1. Cement

The cement used in this study was Type I Ordinary Portland. The chemical composition of the cement is shown in Table 1. The specific gravity of the cement was 3.10 g/cm^3.

Table 1
Chemical composition of Ordinary Portland cement.

Chemical composition	% by mass
SiO_2	21.36
Al_2O_3	5.57
Fe_2O_3	3.35
CaO	62.5
Specific gravity (g/cm^3)	3.10

2.2. Aggregates

The coarse NA used in this study was crushed granite, and the coarse RCA was obtained by crushing old specimens of concrete beams, slabs, and cubes with a steel hammer and impact machine. Then, the concrete chunks were placed in a jaw crusher that broke them into the required sizes. The average cubic compressive strength of most of the concrete structural elements was 25–30 MPa at 28 days, while the age of the specimens ranged from two to three years. The source of the RCA was 100% concrete, and there were no bricks or stones in the specimens. Fig. 1 shows the process of crushing the old concrete beams. After completing the crushing process, the RCA was washed, dried, and sieved to obtain aggregates that were 20 mm or less in size.

The NA and RCA were graded separately. Table 2 shows the sieve analysis of the coarse aggregate used. The gradation of both aggregates was very similar and within the ASTM C33 [27] grading requirements, which ensured that the effects of the gradation changes on the mechanical strength of all the concrete mixes were kept to a minimum.

2.3. Basalt fiber (BF)

BF, which is produced by melting basalt rocks at 1450 °C, is known as a non-toxic, environmentally-friendly material that has high tensile strength and is resistant to alkalis, high temperatures, acids, and aggressive chemicals. BF is stronger and more stable than alternative mineral and glass fibers. BF can be considered as a green product compared to other materials because: (1) the row material used for production is natural rock; (2) only natural gas or electricity are used for melting; (3) does not need any chemical additives or hazardous materials in the melting process; (4) does not release any industrial waste during production; (5) does not produce any chemicals that may cause damage health; and (6) cannot penetrate the human respiration system.

Portal et al. [28] performed a life cycle assessment (LCA) on conventional steel (CS) and textile reinforced concrete (TRC) reinforced by glass, carbon, and BF. The authors studied the total energy demand and the environmental performance for a concrete section reinforced with CS and TRC. The results showed that concrete demand made up 70–95% of the total energy demand of concrete section. Furthermore, the concrete sections reinforced by BF exhibited lower total energy demand in comparison to the CS reinforced concrete section. This can be attributed to the decrease in the amount of concrete in the TRC section which compensated the increase in the energy consumption of BF. The authors reported that the total energy demand compared to CS section was reduced by 7% for carbon, 21% for BF and an increase of 10% for glass. In addition, the environmental impact of all specimens was evaluated. The categories were non-renewable energy consumption, global warming potential, respiratory inorganics, abiotic depletion, and acidification. The results showed that the concrete reinforced by BF was the most environmentally sound specimen.

Another LCA study was performed by the Flemish Institute for Technological Research (VITO) from Belgium and European