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Assessment of Mechanical Properties of Environmentally Friendly Concrete with Emphasis on Selection of Optimal Mix Designs in Terms of Resistance and Economy

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ABSTRACT: The main purpose of this study is to investigate the possibility of constructing environmentally friendly concrete. To achieve this purpose, the concrete waste was recycled and reused in constructing concrete. On the other hand, due to the high volume of environmental pollutants in the ordinary Portland cement (OPC) manufacturing process, OPC was replaced with ground granulated blast furnace slag (GGBFS). Therefore, this study was investigated the mixing designs by 0, 50 and 100% natural aggregates (NA) replaced with recycled concrete aggregates (RCA) and 0, 15, and 30% OPC with GGBFS. In addition, the mixing designs were reinforced with 0, 0.5, and 1% hooked-end steel fiber. In total, this study was investigated 27 different mix designs containing RCA, GGBFS, and steel fibers. Various tests such as slump, water absorption, UPV, compressive, splitting tensile, and flexural strength were performed on specimens. The results showed that using RCA and GGBFS had a negative effect on the workability and compressive strength of concrete. Finally, by economic analysis and optimization of mixing designs, it was concluded that it is justified in terms of resistance and economy to use RCA as a replacement for NA to 50% and the use of GGBFS as a replacement for OPC to 30%. Furthermore, the results showed that the weakness of using RCA and GGBFS can be compensated by adding steel fibers.

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1. INTRODUCTION

Given the increasing trend of using concrete, in the future, there will certainly be a shortage of mineral resources to produce natural aggregates (NA) for concrete production. Therefore, looking for a suitable replacement for NA is necessary [1-2]. On the other hand, since every structure has a limited service life, the destruction of the old structures and production of new ones are required. Due to the irreversibility of the concrete, waste disposal is done by burying or stacking. Both methods cause environmental and ecosystem changes in addition to transportation costs [3]. One of the ways to solve environmental problems caused by concrete waste is to recycle and reuse them [1]. The benefits of recycling concrete include reducing the use of NA, reducing the area of concrete disposal areas, reducing truck traffic, and reducing transportation costs [4]. On the other hand, cement production is associated with environmental pollution. About 7% of the annual CO_2 production comes from the cement production process, the reduction of which is a global concern [5]. Researchers are currently working to address this problem by using mineral slag as a replacement for ordinary Portland cement (OPC) used in concrete [6-7]. On the other hand, the use of mineral additives modifies some of the concrete properties including rheological and mechanical properties [8]. The by-product of the steel production process [ground granulated blast furnace slag (GGBFS)] has been used in civil engineering projects for decades. GGBFS is obtained by rapidly cooling iron slag in water [9]. Many studies have been conducted to investigate the effect of GGBFS on concrete mixtures. These studies have shown that slag concrete has higher mechanical properties than conventional concrete [10-11].

The purpose of this research was to investigate the effect of using recycled concrete aggregate (RCA) as a replacement for NA as well as the effect of using GGBFS as a replacement for the OPC. Moreover, the effect of hooked-end steel fibers on the behavior of recycled concrete was investigated. The results of this research can be effective in the more development of environmentally friendly concrete.

2. METHODOLOGY

2.1. Mix designs

27 different mix designs (See Table 1) were used to produce the specimens. The mix designs include replacement of 0, 50, and 100% NA with RCA, replacement of 0, 15, and 30% OPC with GGBFS, and the use of 0, 0.5, and 1% hooked-end steel fibers. Various tests were performed on specimens such as slump, ultrasonic pulse velocity (UPV), water absorption, compressive strength, splitting tensile strength, and flexural strength.

2.2. Test procedure

To investigate the effect of RCA, GGBFS, and steel fibers on concrete workability, the slump test was performed

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Table 1. Mix proportions

Mix ID	Binder (kg/m^3)		Coarse aggregates (kg/m^3)		Fine aggregates (kg/m^3)		Water (kg/m^3)	SP (kg/m^3)	Steel fiber (kg/m^3)
	Cement	GGBFS	Natural	Recycled	Natural	Recycled			
R0-G0-F0	456	0	973	0	717	0	182.4	0	0
R0-G0-F0.5	453.7	0	968.1	0	713.4	0	181.5	0	39.25
R0-G0-F1	451.4	0	963.2	0	709.8	0	180.6	0	78.5
R0-G15-F0	387.4	61.7	975.7	0	719.1	0	179.6	0	0
R0-G15-F0.5	385.5	61.4	970.8	0	715.5	0	178.8	0	39.25
R0-G15-F1	383.6	61.1	965.9	0	711.9	0	178	0	78.5
R0-G30-F0	319	123.5	979.9	0	721.6	0	177	0	0
R0-G30-F0.5	317.4	122.9	975	0	718	0	176.1	0	39.25
R0-G30-F1	315.8	122.3	970.1	0	714.4	0	175.2	0	78.5
R50-G0-F0	456	0	486.5	482.5	358.5	336.5	182.4	1.14	0
R50-G0-F0.5	453.7	0	484.1	480.1	356.7	334.8	181.5	1.13	39.25
R50-G0-F1	451.4	0	481.6	477.7	354.9	333.1	180.6	1.13	78.5
R50-G15-F0	387.4	61.7	487.9	484	359.6	337.5	179.6	1.12	0
R50-G15-F0.5	385.5	61.4	485.4	481.6	357.8	335.8	178.8	1.12	39.25
R50-G15-F1	383.6	61.1	483	479.2	356	334.1	178	1.11	78.5
R50-G30-F0	319	123.5	490	486.1	360.8	339	177	1.11	0
R50-G30-F0.5	317.4	122.9	487.5	483.7	359	337.3	176.1	1.10	39.25
R50-G30-F1	315.8	122.3	485.1	481.3	357.2	335.6	175.2	1.10	78.5
R100-G0-F0	456	0	0	965	0	672.9	182.4	2.28	0
R100-G0-F0.5	453.7	0	0	960.2	0	669.5	181.5	2.27	39.25
R100-G0-F1	451.4	0	0	955.4	0	666.1	180.6	2.26	78.5
R100-G15-F0	387.4	61.7	0	967.9	0	674.9	179.6	2.25	0
R100-G15-F0.5	385.5	61.4	0	963.1	0	671.5	178.8	2.24	39.25
R100-G15-F1	383.6	61.1	0	958.3	0	668.1	178	2.22	78.5
R100-G30-F0	319	123.5	0	972.2	0	677.9	177	2.21	0
R100-G30-F0.5	317.4	122.9	0	967.4	0	674.5	176.1	2.20	39.25
R100-G30-F1	315.8	122.3	0	962.6	0	671.1	175.2	2.19	78.5

under ASTM C143 [12]. The UPV test was carried out by direct method (i.e., placing the converter on both sides of the specimen) on cubic specimens with 100 mm sides. Using Eq. (1), the pulse velocity has been calculated.

$$V = \frac{L}{t} \tag{1}$$

Where V denotes the pulse velocity in terms of km/sec, L is the length or the space between the two transducers in mm, and T is the pulse transit time in µsec. The water absorption test was performed on cubic specimens with 100 mm sides in accordance with ASTM C642 [13]. The test was performed in half-hour (primary) and 72-hour (ultimate) water absorption. Based on ASTM C39 [14], the compressive strength test was performed on cubic specimens, with the loading rate being 0.3 MPa/s. The test used a digital compression testing machine with a capacity of 1000 kN. The test managed to determine the maximum compressive force tolerated by the specimen. For the calculation of compressive strength, Eq. (2) was used.

$$\sigma_c = \frac{P}{A} \tag{2}$$

Where, σ_c, P, and A are the compressive strength, the maximum compressive force tolerated by the specimen, and the cross-sectional area of the specimen (100 × 100 mm), respectively. Based on ASTM C496 [15], a splitting tensile strength test was conducted on cylindrical specimens having a diameter of 100 mm and a height of 200 mm at a loading rate of 0.05 MPa/s. Splitting tensile strength computations were based on Eq. (3).

$$\sigma_t = \frac{2P}{\pi . L . D} \tag{3}$$

Where σ_t, P, D, and L are the splitting tensile strength, applied force, the cylindrical specimen diameter (100 mm), and the cylindrical specimen length (200 mm), respectively. Based on ASTM C1609 [16], the TPB (three-point bending) test was conducted. A load cell with a 100 kN capacity was used to measure the applied force. For the computation of flexural strength of beams Eq. (4) was used.

$$\sigma_f = \frac{3FL}{2b.d^2} \tag{4}$$

Where σ_f, F, L, and b are the flexural strength, the applied force, the span length, the beam width and the beam height, respectively.

3. RESULTS AND DISCUSSION

By the increasing amount of replacement of NA with RCA, increasing water absorption and decreasing concrete workability were observed. Adding steel fibers to concrete also increased water absorption and decreased workability. Replacing the OPC with the GGBFS also reduced concrete workability. In addition, the results of the UPV test showed a negative effect of RCA and steel fibers on concrete quality, but the GGBFS reduced the water absorption due to its filling structure and increased the UPV in the concrete.

The results of the compressive strength test showed the negative effect of the RCA and GGBFS on the compressive strength of concrete. The addition of 0.5% and 1% steel fibers increased and decreased the compressive strength, respectively. Therefore, the compressive strength of specimens containing 0.5% steel fibers increased, and compressive strength containing 1% steel fibers decreased compared to the control specimen.

The combination of the NA and RCA increased the splitting tensile strength of concrete. The most desirable result was obtained in the splitting tensile strength test of specimens containing an equal combination of the NA and RCA. The splitting tensile strength of the specimens containing the GGBFS was approximately equal to that of the OPC. The addition of steel fibers also significantly increased splitting tensile strength by bridging the splitting tensile cracks.

The results of the flexural strength test showed that using the combination of the NA and RCA was more useful than using them alone. Specimens containing 50% NA and 50% RCA showed the best flexural strength. The use of GGBFS also reduced flexural strength. The decrease in flexural strength created in exchange for replacing OPC with GGBFS was more significant in the mix designs containing RCA than in the mix designs containing NA. The specimens without fiber, including the specimens containing NA, RCA, and their combination are exhibited low flexural strength. The addition of steel fibers greatly increased the flexural strength of these specimens.

4. CONCLUSION

The results showed that using the RCA and GGBFS had insignificant negative effects on some concrete properties such as workability and compressive strength. On the other hand, the reuse of concrete waste and GGBFS can help conserve natural resources and prevent the accumulation of concrete waste and the production of environmental pollution. Moreover, the optimization procedure revealed that using the RCA as a replacement for NA by up to 50% and using the GGBFS as a replacement for OPC by up to 30% is justified, in terms of high mechanical properties, as well as low cost. In addition, the results of this study showed that the weakness related to the use of RCA and GGBFS can be compensated by the addition of steel fibers**.**

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