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Replacement of OPC with RCP in Concrete Containing RCA (Investigation of Mechanical, Economic and Environmental Characteristics)

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ABSTRACT: This paper presents the results of an experimental study on the properties of environmentally friendly concrete. In the making of specimens, 0%, 15%, and 30% of ordinary Portland cement (OPC) were replaced by recycled concrete powder (RCP) and silica fume (SF). In addition, 0%, 50%, and 100% of natural aggregates (NA) were replaced by recycled concrete aggregates (RCA). In the production of RCA, 3 types of concrete waste with an initial strength of 20, 40, and 80 MPa were used. In this study, rheological, mechanical (compressive, splitting tensile and flexural strengths), economic and environmental (GWP) properties of 28 mix designs were investigated. The results showed that the use of RCA and RCP has a negative effect on rheological and mechanical properties. However, the results showed that the use of RCA and RCP has a positive effect on environmental and economic properties. Moreover, the results indicated that the negative effect of RCA can be prevented by increasing the initial strength of RCA, and the negative effect of RCP can be prevented by using SF. Finally, by optimization of mixing designs, it was concluded that it is justified to use 50% of RCA with an initial strength of 40 and 80 MPa and 30% of RCP and SF, in terms of rheological, mechanical, economic, and environmental properties.

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1. INTRODUCTION

Cement is one of the most basic components of concrete, therefore a large amount of this material is produced annually in the world [1]. According to the US Geological Survey, approximately 3,300 million tons of cement were produced worldwide in 2010 [2]. However, the production of cement causes many environmental problems. Cement factories produce the most greenhouse gas after power plants. About 7% of the annual carbon dioxide (CO^2) production is related to the cement production process, so its reduction is a global issue. To overcome this problem, several studies have been done on the use of cement substitutes [1]. In recent years, researchers have sought to replace ordinary Portland cement (OPC) with recycled concrete powder (RCP). To produce higher-quality RCA, mortar attaching to the surface of these aggregates should be separated. RCP constitutes about 10 to 30% of the total recycled resources [3]. Several studies have been conducted to replace OPC with RCP in concrete production [4-7].

In Tehran, more than 42,000 tons of construction waste is produced daily. This volume of construction wastes will have adverse environmental consequences. One of the solutions to manage such wastes is to recycle and reuse them [8]. Since a significant part of natural resources is destroyed annually to produce aggregates used in concrete construction, recycling and reuse of construction wastes not only reducing environmental pollution but also helps preserve natural resources [9]. In previous research, both increasing and decreasing effects on concrete strength due to the use of recycled concrete aggregates (RCA) as a substitute for natural aggregates (NA) have been reported [10]. Chan et al. [11] reported the adverse effects and Moghadam et al. [12] reported the favorable effects of using RCA. One of the reasons for the variable behavior of concretes containing RCA in previous research could be the initial strength of concrete wastes used in the production of RCA.

In this study, the properties of concretes made with recycled concrete aggregates (RCA) have been investigated. Three types of parent concrete with strength grades of 20, 40, and 80 MPa were considered for RCA production. Moreover, recycled concrete powder (RCP), as well as combination of this powder with micro silica (SF), were used as a substitute for ordinary Portland cement (OPC). Experimental specimens of this paper were made from 28 different mixing designs including replacement of 0, 50, and 100 vol.% NA with RCA produced from concrete wastes with an initial strength of 20, 40, and 80 MPa as well as replacement of 0, 15, and 30 vol.% OPC with RCP and SF. In this study, the flowability and mechanical properties, as well as economic and environmental characteristics of concrete containing recycled materials, were investigated. Finally, optimal mixing

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design using multivariate optimization was introduced.

2. METHODOLOGY

RCA production: Parent concretes with three strength grades of 20, 40, and 80 MPa were used to produce RCA. First, a compressive strength test was performed on three standard cylindrical specimens made from each parent concretes, under ASTM C39 [13]. The results of the compressive strength test show good compliance between the compressive strength of the specimen and the considered strength grades for parent concretes. After ensuring the compressive strength of the considered mix designs, the parent concretes were made. After 90 days, parent concretes were demolished and recycled.

Material: In this study, OPC based on ASTM C150 [14] was used. In some of the mixing designs of this study, part of OPC was replaced with RCP, SF, and a combination of them. RCP was obtained from the recycling of concrete wastes. To produce specimens, 4 types of aggregate including 1 type of NA and 3 types of RCA with an initial strength of 20, 40, and 80 MPa were used.

Mix proportions: There are 28 mixing designs in this study, which are presented in Table 1. The variables of these mix designs include the percentage of NA replacement with RCA by 0, 50, and 100 vol.%, the initial strength of RCA 20, 40, and 80 MPa, and the percentage of OPC replacement with RCP and SF by 0, 15, and 30 vol.%. The specimens are named in such a way that the number opposite the letter R indicates the percentage of replacement of NA with RCA, the number opposite the letter C indicates the initial strength of RCA, and the numbers opposite the letters RCP and SF represent the percentage of replacement of OPC with RCP and SF, respectively. From each of the 28 mix designs used, three specimens were made for each test. All specimens were stored for 24 hours at 25 °C temperature and 85% relative humidity. The specimens were then cured in water tanks at 20 °C for 28 days.

Test procedure: To investigate the effect of RCA, OPC, and SF on concrete workability, the slump test was performed under ASTM C143 [15].

Based on ASTM C39 [13], 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. (1) was used.

$$\sigma_c = \frac{P}{A} \tag{1}$$

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 [16], 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. (2).

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

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 C78 [17], 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. (3) was used.

$$\sigma_f = \frac{3\text{F}L}{2b.d^2} \tag{3}$$

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

RCA had lower density, abrasion resistance, and higher water absorption, in comparison with NA. Increasing the initial strength of RCA increased the density and abrasion resistance and decreased the water absorption of these aggregates.

Replacing 30 vol. % OPC with RCP reduced the concrete workability by 13% and replacing 100 vol. % NA with RCA with initial strengths of 20, 40, and 80 MPa reduced the concrete workability by 38, 36, and 38%, respectively.

Mechanical properties of concrete were reduced due to the use of RCP. Using 15 vol. % of RCP caused a slight reduction and using 30 vol. % significantly reduced mechanical properties. Using 15 and 30 vol. % RCP reduced the compressive strength by 13 and 29%, the splitting tensile strength by 10 and 29%, and the flexural strength by 10 and 26%, respectively.

Using SF compensated the weakness of concrete containing RCP. The mechanical properties of concrete containing 30 vol. % of the combination of RCP and SF were approximately the same as the mechanical properties of concrete containing 100 vol. % of OPC. Using 30 vol. % combination of RCP and SF reduced 1, 5, and 2% in compressive, splitting tensile and flexural strengths, respectively.

Using RCA as an alternative to NA reduced the mechanical properties. Increasing the initial strength of the RCA partially compensated for this weakness. Using 100 vol. % RCA with initial strengths of 20, 40, and 80 MPa reduced the compressive strength by 27, 16, and 9%, splitting tensile strength by 24, 15, and 5%, and flexural strength by 27, 17, and 10%, respectively.

Economic analysis showed that using RCP as an alternative to OPC reduces the cost of mix designs and using RCA as an alternative to NA increases it. The lowest cost was related to the mix design containing 100 vol.% NA and 30 vol.% RCP

Table 1. Mix proportions.

Mix id	Binder (kg/m^3)			Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)				Water (kg/m^3)
					NA	RCA			
	OPC	RCP	SF			20MPa	40MPa	80MPa	
R0	488	0	0	652	1024	0	0	0	205
R0-RCP15	414.8	60.2	0	652	1024	0	0	0	205
R0-RCP30	341.6	120.4	0	652	1024	0	0	0	205
R0-RCP15-SF15	341.6	60.2	52.2	652	1024	0	0	0	205
R50-C20	488	0	0	652	512	480	0	0	205
R50-C20-RCP15	414.8	60.2	0	652	512	480	0	0	205
R50-C20-RCP30	341.6	120.4	0	652	512	480	0	0	205
R50-C20-RCP15-SF15	341.6	60.2	52.2	652	512	480	0	0	205
R100-C20	488	0	0	652	0	960	0	0	205
R100-C20-RCP15	414.8	60.2	0	652	0	960	0	0	205
R100-C20-RCP30	341.6	120.4	0	652	0	960	0	0	205
R100-C20-RCP15-SF15	341.6	60.2	52.2	652	0	960	0	0	205
R50-C40	488	0	0	652	512	0	485	0	205
R50-C40-RCP15	414.8	60.2	0	652	512	0	485	0	205
R50-C40-RCP30	341.6	120.4	0	652	512	0	485	0	205
R50-C40-RCP15-SF15	341.6	60.2	52.2	652	512	0	485	0	205
R100-C40	488	0	0	652	0	0	970	0	205
R100-C40-RCP15	414.8	60.2	0	652	0	0	970	0	205
R100-C40-RCP30	341.6	120.4	0	652	0	0	970	0	205
R100-C40-RCP15-SF15	341.6	60.2	52.2	652	0	0	970	0	205
R50-C80	488	0	0	652	512	0	0	497	205
R50-C80-RCP15	414.8	60.2	0	652	512	0	0	497	205
R50-C80-RCP30	341.6	120.4	0	652	512	0	0	497	205
R50-C80-RCP15-SF15	341.6	60.2	52.2	652	512	0	0	497	205
R100-C80	488	0	0	652	0	0	0	994	205
R100-C80-RCP15	414.8	60.2	0	652	0	0	0	994	205
R100-C80-RCP30	341.6	120.4	0	652	0	0	0	994	205
R100-C80-RCP15-SF15	341.6	60.2	52.2	652	0	0	0	994	205

and the highest cost was related to the mix design containing 100 vol.% RCA, 15 vol.% RCP, and 15 vol.% SF. The difference between the most expensive and cheapest mix designs was 59%.

The results of the GWP calculation showed that this parameter is only affected by the binder used and the change in the type of aggregate causes a slight change in it. Replacing OPC with RCP was very effective in reducing GWP. Replacing 15 and 30 vol. % of OPC with RCP reduced GWP by 15 and 30%, respectively.

4. CONCLUSIONS

Multivariate optimization showed that the use of 15 and 30 vol. % RCP and SF and 50 vol. % RCA with initial strengths of 40 and 80 MPa is justifiable in terms of workability, mechanical properties, economic and environmental characteristics.

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