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Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives

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HIGHLIGHTS

- At 100% RCA content, the concrete strength decreases about 24%.
- Tensile splitting strength/compressive strength of RCA concretes are 7.7–11.4%.
- Inverse relation between density–water absorption at higher RCA content observed.

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ABSTRACT

Nowadays, researches on the usability of recycled aggregate (RA) in concrete is gaining popularity in all over the World due to the preservation of the environment and sustainable development. RA can be obtained after crushing and screening of the construction rubble obtained from demolished structures. The recycled coarse aggregate (RCA) used in this work is obtained from İSTAÇ (The İstanbul Environmental Protection and Waste Processing Corporation) to replace the natural coarse aggregates (NCA) in different proportions. Mineral additives used in this experimental work are silica fume (SF) and ground granulated blast furnace slag (GGBFS) at various ratios. The influence of SF and GGBFS with RCA of hardened concrete, such as compressive strength, tensile splitting strength, density and water absorption of are experimentally investigated. The test results obtained showed that at 100% of the replacement level of RCA, the compressive strength decreases about 24% and the strength reduction is more significant at over 50% RCA content. Increasing the RCA content significantly improves the tensile splitting strength of the concrete according to the compressive strength. The ratios between the tensile splitting strength to the compressive strength are greater in the RCA concretes incorporating GGBFS than the RCA concretes incorporating SF. An inverse relationship between the density and the water absorption ratio is observed in RCA concretes and this relation is more significant in higher amounts of RCA contents.

1. Introduction

Concrete is the most common and useful material in the construction industry and has contributed to the advancement of civilizations throughout last century. However, construction activities demand a significant amount of natural materials in order to produce cement and aggregate. Procurement of these natural materials significantly modifies the natural sources and creates major environmental problems [1]. Furthermore, sustainable waste management is another major issue faced by countries all over the world. In order to minimize the environmental impact and energy consistency of concrete used for construction facilities, reuse of construction and demolition (C&D) wastes can be a beneficial way which leads sustainable engineering approaches to concrete mix design [2].

As many developing countries all over the world, Turkey has also been generating a huge amount of C&D waste which generates serious environmental problems to deal with. Due to the Urban Renewal Law, it is estimated that demolition and maintenance of the structures at the end of their design span result 4–5 million ton/year of C&D waste [3]. In March 2006, the Istanbul Metropolitan Municipality and the Istanbul Environmental Management in Industry and Trade Inc. (İSTAÇ) prepared a plan, called Construction and Demolition Waste Management Plan. According to the plan, it was decided that import centers would be established at each municipality to collect local wastes [4].

On the other hand, the cement industry, in particular, already uses by-products from the production of silicium (silica fume) and steel (blast furnace slag). As recycling and reuse are

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alternatives to minimize the impact of energy and raw material consumption on the environment, another waste that can be potentially used for concrete production is recycled aggregate (RA) obtained via C&D waste [5,6].

RA mainly differs from natural aggregate (NA) as it is composed by two different materials: NA and residue old cement mortar attached. Old cement mortar is the origin of the worse properties of RA: lower density, higher absorption, and higher Los Angeles abrasion [7,8]. RA is also highly heterogeneous and porous, as well as a high content of impurities. The heterogeneity influences the characteristics of RA and these aggregate properties have a negative influence on recycled aggregate concrete (RAC) quality such as reduction of the compressive strength, tensile strength due to the increased concrete porosity and a weak aggregate–matrix interfacial bond [9–11]. Although concrete strength decreases when RA is used and the strength reduction could be as low as 40% [12–14]. It is reported in an experimental study carried out by Corinaldesi and Moriconi [15] that the compressive strength of RAC can be improved to equal or exceed that of natural aggregate concrete (NAC) by adding mineral admixtures. Moreover, common cement replacements used as mineral admixtures are fly ash, silica fume (SF) and ground granulated blast furnace slag (GGBFS) [16,17].

Furthermore, poor performance of the RAC is associated with the cracks and fissures, which is formed in RA during processing, thereby rendering the aggregate having weaker and more susceptible to permeation, diffusion and absorption of fluids [18]. Additionally, the permeability of concrete made with RA tends to increase with increasing RA content [19]. Some authors have reported differences between NAC and RAC regarding carbonation rates [20–22], while others [23] found that the carbonation depth decreases in concrete with high percentages of RA. Thomas et al. [24] reported that there is no significant increase in the rate of carbonation with the RA incorporation. Pereira et al. [25] used two types of superplasticizers (SP) in RAC with fine recycled aggregate. They found that the performance of RAC with incorporation of RA was poorer than the performance of NAC. However, the mechanical performance of RAC was generally increased when SP was utilized in the mixture. Sheen et al. [26] produced RAC using concrete wastes from the earthquake of Chi-Chi in Taiwan. They observed that the compressive strength of RAC was affected by RA; because fine ingredients decreased the compressive strength. Also, it was observed that high water absorption had a negative effect on the strength of RAC. Sagoe-Crenstil et al. [27] analyzed the mechanical and workability properties of RAC. They found that RA, produced in a plant, had smoother and spherical particles, which made the workability of RAC easy. Meftef et al. [28] examined the moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. The experimental results of their study concluded that the RCA used in pre-wetting and surface-saturated-dry conditions improve the concrete workability.

Moreover there are number of previous studies concluding that mineral additives can be successfully used as partial replacement of cement in order to mitigate the poor performance of the RAC [4,5,17,29–32] Kou et al. [32] prepared some mixtures containing NA, RA, and mineral additions such as fly ash, SF, metakaolin and GGBFS. The study concluded that mineral additions increased the performance of RAC. For example, SF and metakaolin improved both the mechanical and the durability properties however fly ash and GGBFS improved essentially durability performance. Dilbas et al. [33] used SF in RAC and twelve groups of concrete mixtures were produced with $w/b = 0.5$ and the quantity of cement 350 kg/m^3. They found that the SF addition is an alternative way to increase the compressive strength of RAC to use concrete in structural industry. Furthermore, they also concluded that the addition of the 5% SF content in RAC increases the ratio of the tensile splitting strength to the compressive strength.

In spite of concretes made with slag cement tend to exhibit slower strength gains and higher later strengths due to the pozzolanic reaction to form extra C–S–H gel in the paste [34–36], the permeability of concretes made with slag cement significantly decreased with increasing slag cement content [37]. On the other hand, it is well-known that SF's effects (the pozzolanic effect and the filler effect) improve all the mechanical and physical properties of the concrete but, particularly, its compressive strength [15,38–40]. RA is more porous than that of NA and some part of the cement blended with SF would be able to penetrate into the aggregate, which subsequently would increase the bond strength between the aggregates and cementitious matrix. Furthermore, the cracks in the RA is reduced due to the healing effect after longer curing of SF blended cement pastes. Therefore, the concrete made with RA, and the quality of the interfacial transition zone, is better than that of the old paste and NAC. The bond between the new cement paste and RA was enhanced [38,41].

The objective of this study is to investigate the mechanical and the physical properties of concretes containing SF (0–5–10%) and GGBFS (0–30–60%) at various ratios and replacing (0–25–50–75–100%) the natural coarse aggregate (NCA) with the recycled coarse aggregate (RCA). In this study, the RCA obtained from İSTAÇ (The İstanbul Environmental Protection and Waste Processing Corporation) was used. For this purpose, 25 concrete mixtures in five groups are produced, and the mechanical properties such as the compressive strength, the tensile splitting strength, physical properties such as density and water absorption of RAC are investigated at 28 days. Each group has five concrete mixtures. The conventional concrete mixture with NCA, also named as natural aggregate concrete (NA), is included in the first group. The groups, mixture names and notations are listed in the tables. The regression analysis between the tensile splitting strength and the compressive strength, the density and the water absorption are examined. The ratios of the tensile splitting strength to the compressive strength are also investigated.

2. Experimental studies

2.1. Materials

2.1.1. Cement, SF and GGBFS

Type I general use Portland cement (CEM I 42.5R) compatible with Turkish Standard "Cement-Part 1: Composition, specifications and conformity criteria for common cements" (TS EN 197-1 (2012)), SF suitable with American Society for Testing and Materials "Standard Specification for Silica Fume Used in Cementitious Mixtures" (ASTM C 1240-12) and GGBFS suitable with Turkish Standard "Ground granulated blast furnace slag for use in concrete, mortar and grout" (TS EN 15167-1 (2006)) are used in the concrete mixtures. The chemical and physical properties of cement, SF and GGBFS are given in Table 1.

2.1.2. Aggregates

NCA and RCA are used as aggregate in the concrete mixtures. In this analysis, crushed lime stone aggregate was used as the NCA and the RCA was obtained from İSTAÇ (The İstanbul Environmental Protection and Waste Processing Corporation).

Table 1
Properties of cement, SF and GGBFS.

Contents	Cement	SF	GGBFS
SiO_2 (%)	20.1	>85	35.6
CaO (%)	63.5	0.2	35.1
SO_3 (%)	2.9	–	0.02
Al_2O_3 (%)	4.9	0.7	14.7
Fe_2O_3 (%)	3.6	1.2	0.44
MgO (%)	1.2	0.1	9.7
Structure of material	–	Condensed microsilica	–
Density (g/cm^3)	3.16	2.20	2.85
Chlorine ratio (%)	–	<1	<1
Specific surface area (m^2/kg)	3942	15,000	4000
Activity index (%)	–	>95	–
Particle ratio (<0.045 mm) (%)	–	<40	–
Loss on ignition (%)	1.7	–	1.0