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Combined Use of Natural and Artificial Slag Aggregates in Producing Self-Consolidating Concrete

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This study addresses properties of self-consolidating concrete (SCC), in which natural coarse aggregates had been substituted by artificial slag aggregates (ASAs). For this, 90% ground-granulated blast-furnace slag and 10% portland cement by weight were pelletized in a tilted pan through cold-bonded agglomeration process. Then, the hardened coarse aggregates (ASA) were tested for specific gravity, water absorption, and crushing strength. Thereafter, they were partially used in producing SCCs in which ASA replaced the natural coarse aggregates at 0, 20, 40, 60, 80, and 100% by volume. Therefore, six SCCs with 0.32 water-binder ratio (w/b) were designed and cast using both natural and/or ASA. Hardened concrete properties were tested for compressive and splitting tensile strengths, modulus of elasticity, drying shrinkage, freezing-and-thawing resistance, chloride ion permeability, gas permeability, and sorptivity. Test results indicated that SCCs with ASA displayed better performance than the control mixture in terms of durability-related properties. Incorporating ASA in SCCs increased the compressive strength and elastic modulus (up to 60%) but decreased the splitting tensile strength. However, ASA provided gradual reduction in sorptivity coefficient, chloride ion, and gas permeability especially at 60% replacement level and 56 days.

Keywords: artificial aggregate; cold bonding process; ground-granulated blast-furnace slag; self-consolidating concrete; transport properties.

INTRODUCTION

Industrialized countries such as Turkey produces large amounts of waste materials such as fly ash (FA) and ground-granulated blast-furnace slag (GGBFS). Although almost 15 million tons (14.7 million tonnes) of FA and 600,000 tons (590,523.9 tonnes) of GGBFS are generated annually in Turkey; limited amounts of them are used in the construction industry.[1,2] Because self-consolidating concrete (SCC) requires 500 to 600 kg/m^3 (31.20 to 37.20 lb/ft^3) of the materials finer than 0.1 mm (0.039 in.) to prevent segregation and bleeding during transportation and placing, the formulators have employed either a high portland cement (PC) content and viscosity-modifying admixtures or use of mineral admixtures such as fly ash, blast furnace slag, and/or limestone filler.[3,4] The cost of such concrete is remarkably higher associated with the use of a high volume of PC and chemical admixtures.[5-7]

Because aggregates are the main volumetric component of concrete, occupying 65 to 75% of total concrete volume, producing artificial aggregates to be used in making concrete may be considered as an effective way to recycle such mineral admixtures. Moreover, the natural and/or scarce materials of aggregates may be conserved and damaging activities of aggregate mining may be prevented as artificial aggregates replace the natural ones, especially in SCCs.[8] For this purpose, a number of the studies have been reported in literature focusing on the artificial lightweight aggregates made with fly ash.[9-12] Mayfield[13] however, carried out an investigation on the use of pelletized blast-furnace slag as a lightweight aggregate in structural concrete. In the study by Robinson,[14] the fundamental reactions occurring during the heat treatment of cold bonded pellets comprised of iron and steel making by-products were studied.

Cold bonding, autoclaving, or sintering procedures are the most commonly applied techniques for manufacturing artificial aggregates.[15,16] Although the general inclination of these studies highlights the production of artificial aggregates by sintering up to 1200°C (2162°F), the energy saving concern has led the researchers to use cold-bonding process, which requires minimum energy consumption for making the pellets. Gesoğlu et al.[17] produced artificial slag aggregates through cold bonding process under a water spray acting as a coagulant.

SCC with excellent segregation resistance and flowability in fresh state is capable of filling up any given structure form only by its self-weight and encapsulates even the most congested reinforcement. Use of SCCs can lead to a reduction in construction time, labor cost, and noise level on the construction site.[18] To achieve the self-compacting property, concrete contains large amounts of quartzite fillers, which is optimum economically such as GGBFS, FA, and lime powder to avoid segregation of larger particles in fresh mixture. Also, the content of coarse aggregate and the water-binder ratio (*w*/*b*) are lower than those in conventional concrete.[19] A number of studies have been reported in the literature concerning the use of mineral admixtures to enhance the self-compactibility characteristics while reducing the material cost of the SCCs.[3,20,21] It has been reported that economically competitive SCCs can be produced by replacing up to 50% of PC with mineral admixtures. Because aggregates occupy the major volume fraction in SCCs, they significantly affect self-compatibility characteristics as well as mechanical and durability properties.[22] The work of Wang[23] showed that the SCCs made with artificial aggregate with a lower *w*/*b* had lower chloride penetration, smaller number of cracks, and less weight loss. Wu et al.[24] conducted a study on SCC in which expanded

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shale was incorporated to enhance the workability. It was found that fresh SCC with such lightweight aggregates had good fluidity, deformability, filling ability, uniform aggregate distribution, and minimum resistance to segregation. Madandoust et al.[25] used expanded polystyrene (EPS) at varying amounts to investigate the fresh properties of SCCs. The results indicated that mixtures with density higher than 1900 kg/m^3 (117.8 lb/ft^3) (up to 22.5% of EPS) generally satisfied the self-compactibility criteria of SCCs containing EPS. To the knowledge of the authors, however, there is a lack of information in the literature on the properties of SCCs incorporating cold-bonded slag aggregates.

The aim of this study was to investigate the hardened properties of SCCs with artificial slag aggregate (ASA). For this purpose, a powder mixture of 90% GGBFS and 10% PC by weight were pelletized through cold-bonding process to produce ASA. Thereafter, they partially replaced the natural coarse aggregates in producing SCCs. Therefore, a total of six mixtures were designed and cast using both natural and/or ASA coarse aggregates. Hardened properties of SCCs were tested for compressive strength, splitting tensile strength, modulus of elasticity, drying shrinkage, resistance to freezing and thawing, chloride ion permeability, gas permeability, and sorptivity.

RESEARCH SIGNIFICANCE

Environmental impacts and economic considerations have had a great role in the use of waste material. As a result of the industrial revolution in various fields including the field of construction, the ideas has arisen from the possibility of taking advantage of waste materials such as GGBFS through recycling in the manufacture of artificial aggregate. Because aggregates occupy a large volume of SCCs, using such mineral for making artificial aggregate through cold bonding process and using it in production of SCCs may be an effective way to increase interest about recycling of waste products.

EXPERIMENTAL STUDY

Materials

An ordinary portland cement CEM I 42.5 R conforming to TS EN197-1 was used for producing both artificial slag aggregate (ASA) and concrete. Industrial waste minerals used in the study were Class F FA as mineral admixture in SCCs and GGBFS as the main material in making ASA. The chemical composition of cement, FA, and GGBFS are given in Table 1. Polycarboxylic ether-based high-range water-reducing admixture (HRWRA) with a specific gravity of 1.07 g/cm^3 (66.8 lb/ft^3) was used to achieve the target slump flow of SCCs. Fine aggregate was a fine sand mixture of 5 mm (0.196 in.) crushed and natural river sands with specific gravities of 2.45 and 2.66, respectively. Natural river coarse aggregate with a maximum size of 16 mm (0.6299 in.), with a fineness modulus of 5.68 and with a specific gravity of 2.72, was also used. Similarly, ASAs used in the study had a maximum particle size of 16 mm (0.6299 in.), fineness modulus of 5.53, and a specific gravity of 2.14. Sieve analysis and physical properties of both natural and artificial slag aggregates are shown in Table 2.

Table 1—Physical and chemical properties of cement, ground-granulated blast-furnace slag, and fly ash

Chemical analysis, %	Cement	GGBFS	FA
CaO	62.12	34.12	4.24
SiO_2	19.69	36.41	56.2
Al_2O_3	5.16	10.39	20.17
Fe_2O_3	2.88	0.69	6.69
MgO	1.17	10.26	1.92
SO_3	2.63	—	0.49
K_2O	—	0.97	1.89
Na_2O	0.17	0.35	0.58
Cr_2O_3	0.88	—	—
Loss on ignition	0.87	1.64	1.78
Specific gravity	3.15	2.79	2.25
Blaine fineness, m^2/kg	394	418	287

Note: 1 cm^2/g = 0.48843 ft^2/lb

Table 2—Sieve analysis and physical properties of natural and artificial aggregates

Sieve size, mm	Fine aggregate, %		Natural coarse aggregate, %	Artificial slag aggregate, %
	River sand	Crushed sand		
31.5	100	100	100	100
16	100	100	100	100
8	99.7	100	31.5	45.1
4	94.5	99.2	0.4	2
2	58.7	62.9	0	0
1	38.2	43.7	0	0
0.5	24.9	33.9	0	0
0.25	5.4	22.6	0	0
Fineness modulus	2.79	2.38	5.68	5.53
Specific gravity, g/cm^3	2.66	2.45	2.72	2.14
Water absorption, %	0.55	0.92	0.45	4.7

Notes: 1g/cm^3 = 0.036127 lb/in.^{3}; 1 mm = 0.0394 in.

Production of ASA

ASA was produced through cold bonding process, in which a dry powder mixture of cement plus GGBFS in particular magnitude (90% of GGBFS and 10% of PC) were pelletized through moisturizing in a rotating inclined pan at ambient temperature. The pelletizer used had a pan diameter of 80 cm (31.5 in.) and a depth of 35 cm (13.78 in.), as shown in Fig. 1. After the dry powder mixture was fed into the pan, the disc was rotated at a constant speed followed by water spraying to form ball-shaped fresh pellets. The amount of water used during the pelletization process has been determined as the coagulant to form spherical pellets with the motion of rolling disc. The pellets formed approximately in 10 minutes while an additional 10 minutes were devoted to further stiffening of the fresh pellets so