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Permeation characteristics of self compacting concrete made with partially substitution of natural aggregates with rounded lightweight aggregates

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HIGHLIGHTS

- Lightweight aggregates (LWAs) were manufactured via pelletization technique.
- Fine and coarse LWAs were replaced with natural ones at different volume fractions up to 100%.
- SCCs (self compacting concretes) were produced at fixed slump flow diameter.
- The mechanical and transport properties reduced regardless of size of LWA.
- SCCs including LWFA exhibited better performance in the terms of durability aspects with respect to the SCCs with LWCA.

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ABSTRACT

This study presents transport properties of self-compacting concretes (SCCs) in which natural aggregates had been partially replaced with lightweight fine (LWFA) and coarse aggregate (LWCA). Lightweight aggregates were manufactured through the cold bonding pelletization of 90% fly ash and 10% portland cement in a tilted pan at room temperature. A total of 17 SCCs with a water/binder ratio of 0.32 were produced at a fixed slump flow of 720 ± 20 mm by adjusting the amount of High-Range-Water-Reducing-Admixture (HRWRA) used. The transport properties were investigated via water sorptivity, water permeability, rapid chloride ion permeability, and gas permeability. Mechanical properties of SCCs were determined in terms of compressive strength, splitting tensile strength, and structural efficiency. It was found that with increasing volume of LWFA and/or LWCA, the hardened properties reduced regardless of testing age. Moreover, in spite of lower compressive strength, SCCs with LWFA had better performance in the case of durability related properties compared to the SCCs with LWCA.

1. Introduction

Due to occupation of 60–70% of the concrete volume, the aggregates play a main role in affecting the workability, strength, dimensional stability, and durability as well as the cost of concrete [1,2]. There is a tremendous interest in using alternative aggregates in construction sector since the critical shortage of natural aggregates [3]. As in most of the industrialized countries, a large quantity of waste materials is emerged in Turkey. Even though almost 15 million tons of fly ash (FA) annually is generated from thermal coal-fired power plants in Turkey, a very small amount of it is utilized in the construction industry [4]. In recent years, the artificial lightweight aggregates (LWA) produced from waste materials have been used in the production of concrete. Cold bonding, autoclaving or sintering procedures are the most commonly applied techniques for manufacturing artificial aggregates [5–11]. Pelletization method requires minimum energy consumption for making pellets, a ball like shape of material, by agglomeration of moisturized fines with water acting as a coagulant in a rotating disc [7–9]. Production of LWA with spherical shape by cold bonding is achieved after hardening of the pellets at ambient temperature through pozzolanic reaction between fly ash and a cementitious material and it is an effective way to use such waste materials as aggregate in concrete. Thus, the depletion of natural resources and the damage to environment by aggregate mining can be prevented. Also, the aggregates obtained from the waste materials are mostly lighter in comparison with natural aggregates, leading to the production of lightweight concrete (LWC) [12].

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Self-compacting concrete (SCC) is a highly flowing concrete that easily spreads through congested reinforcement, fills restricted areas without segregation and bleeding, and is consolidated under its own weight [1,2]. In spite of its favorable properties, the usage of SCC can be limited in some structures due to its high unit weight [13,14]. Using LWA in the production of SCC in the other hand, can reduce the self weight of the structures which can result in smaller size structural members. SCC incorporated with LWA will have higher quality compared to normal weight concrete due to reduced risk of segregation of LWA [13–16]. SCC is very sensitive to aggregate characteristics such as shape, texture, maximum size and grading. Owing to the wide diversity of LWA resources and manufacturing processes, the characteristics of LWA should be taken into consideration for the performance required in fresh and hardened state of SCC [2]. Spherical shape aggregates with smooth surface are preferred because they more readily flow past each other as the reduced specific surface area requires less cement and water in the design of SCCs [17–22]. Many researchers have examined the effect of LWA properties on SCC in hardened state. Choi et al. showed that compressive strength of SCC with artificial lightweight aggregate at 28 days has come out to more than 40 MPa in all mixes expect at 100% replacement level of artificial lightweight coarse aggregate [23]. Bogas et al. conducted a study on the SCC in which expanded clay was incorporated to enhance the workability. It was found that SCC with expanded clay can perform better than normal vibrated LWC [18]. Additionally, it was indicated that a good quality SCC with LWA could be designed to achieve hardened properties similar to those of normal density concrete [13]. Moreover, the work of Wang showed that the SCCs made with dredged silt with a lower water/binder ratio had lower chloride penetration, smaller number of cracks, and less weight loss [16]. To the knowledge of authors, however, there is a dearth of research in the literature related to the use of the cold-bonded fly ash lightweight aggregate in the production of SCCs, especially from the durability point of view.

The aim of this study is to investigate the hardened properties of SCCs made with combined use of natural normal aggregates and cold-bonded fly ash lightweight aggregates. Following the production and curing, artificial cold-bonded fly ash aggregates were sieved to proper fractions of 0.25–4 mm and 4–16 mm sizes. The hardened fine and/or coarse LWAs replaced partially with natural coarse and fine aggregate at five volume fractions from 0% to 100% at 20% increments. Thus, a total of 17 different SCLC mixtures were designed having constant water-binder ratio of 0.32 and total binder content of 550 kg/m^3. Hardened properties of SCCs were tested in terms of compressive strength, splitting tensile strength, water sorptivity, water permeability, chloride ion permeability, and gas permeability at 28 and 90 days.

2. Experimental study

2.1. Materials

The portland cement with density of 3.15 g/cm^3 and blaine fineness of 326 m^2/kg was used in the production of both artificial lightweight aggregates and fresh concrete mixes. Type F fly ash (FA) provided from Çatalağzı Thermal Power Plant, located in Turkey, was added to the concrete mixtures as a secondary binder replacing 20% by weight of cement and was also utilized for producing of LWA. Table 1 presents the physical and chemical properties of the cement and FA. To achieve the target slump flow for SCCs, a polycarbonate-based high-range water reducer (HRWRA) having a density of 1.07 g/cm^3 was used.

2.2. Aggregates

2.2.1. Lightweight aggregates (LWAs)

LWAs were manufactured through cold bonding process in a tilted pan at room temperature. A dry mixture of 10% Portland cement and 90% fly ash (FA) by weight was first fed into the 45° inclined pan rotating at 42 rpm. Water was then sprayed on the mixture adding up to 22% of the powder material by weight for about 10 min. Additional 10 min was allocated for stiffening to form the spherical pellets (Fig. 1). As soon as pelletization process was completed, the fresh pellets were kept in sealed plastic bags at a temperature of 20 °C and a relative humidity of 70% for 28 days for self-curing. Thereafter, the hardened fly ash aggregates were sieved into size fractions of 0.25–4 mm as fine aggregate (LWFA) and 4–16 mm as coarse aggregate (LWCA) as seen in Fig. 2. Physical properties of LWAs were evaluated in terms of specific gravity and water absorption as per ASTM C127 [24]. Absorptions rates of LWCA and LWFA after 24 h in water were found to be 17% and 21%, respectively. Moreover, specific gravity of both LWCA and LWFA were about 1.76 g/cm^3 on the basis of saturated surface dry condition.

Table 1
Chemical compositions and physical properties of Portland cement and fly ash.

Analysis report (%)	Cement	Fly ash
CaO	62.58	2.24
SiO_2	20.25	57.2
Al_2O_3	5.31	24.4
Fe_2O_3	4.04	7.1
MgO	2.82	2.4
SO_3	2.73	0.29
K_2O	0.92	3.37
Na_2O	0.22	0.38
Loss on ignition	2.96	1.52
Specific gravity	3.15	2.04
Blaine fineness (m^2/kg)	326	379

2.2.2. Natural aggregates (NWAs)

Natural fine and coarse aggregates were replaced with fine and/or coarse LWA, respectively to manufacture 17 different SCC mixtures. Natural fine aggregate including a mixture of crushed and natural river sand with specific gravities of 2.45 g/cm^{3}and 2.66 g/cm^3, respectively, was used with a maximum size of 4 mm. Natural river coarse aggregate with a specific gravity of 2.72 g/cm^3 was also used with a maximum size of 16 mm. Table 2 gives the sieve analysis and physical properties of both natural and lightweight aggregates.

2.3. Concrete mixture proportioning and casting

The same procedure for batching and mixing was followed in the production of SCCs in accordance with ASTM C192 [25]. Before mixing, considering the high water absorption of LWAs, they were immersed in water for 30 min to ensure sufficient saturation and kept in air for another 30 min to have saturated surface dry condition [7–11]. Totally, 17 concrete mixes were designed in which the natural aggregates were replaced by LWFA and/or LWCA at different volume fractions, as seen in Table 3. To investigate the effectiveness of LWFA and/or LWCA on the mechanical and durability properties of SCCs, three group mixes were designed with a constant water/binder ratio (w/b) of 0.32 and total binder content of 550 kg/m^3. The process of replacement was conducted in volume fractions from 0% to 100% at 20% increments by volume of LWCA, LWFA, and both (at equal proportions). The control mixture (CM) included 100% natural aggregates. Furthermore, MC mixes were designed such that LWCA replaced coarse normal weight aggregate to produce the mixes, namely MC10 to MC50; then the MF mixes were designed in which LWFA replaced natural fine aggregate resulting in MF10, MF20, MF30, MF40 and MF50 mixes. In the case of MCF mixes, however, the natural fine and coarse aggregates were substituted with fine and coarse lightweight aggregates in equal proportions so as to produce MCF10, MCF20, MCF30, MCF40, and MCF50 mixes. Moreover, MCF100 mix was designed to have full replacement of natural aggregates by lightweight aggregates. All of the concretes were designed to have a slump flow diameter of 720 ± 20 mm to fulfill EFNARC limitation [21]. For this, trial batches were produced for each mixture by adjusting HRWRA used until the desired slump flow was obtained. Proportioning of the 0.25–4 mm and 4–16 mm aggregate size fractions conformed to the grading curve specified in TS 706 [26].

2.4. Test methods

Compressive strength was measured on three 150 mm cubes by means of a 3000 kN capacity testing machine [27]. Similarly, splitting tensile strength was tested on three Ø100 × 200 mm cylinders as per ASTM C496 [28]. Both strength tests were performed at 28 and 90 days.

Sorptivity test measures the rate at which water is drawn into the capillary pores of concrete. The test was performed on the four disc specimens of 100 mm diameter and 50 mm height cut from the Ø100 × 200 mm cylinders. Before the test, the specimens were dried in an oven at 100 ± 5 °C till they reached the constant mass. The test was conducted on the surface of concrete which was in contact with water while the sides of the specimens were coated by paraffin so that capillary suction was considered the dominant invasion mechanism. The specimens were removed from the tray and weighed at different time intervals up to 1 h to evaluate