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Shear thickening intensity of self-compacting concretes containing rounded lightweight aggregates

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HIGHLIGHTS

- Recycling of fly ash as lightweight aggregate (LWA) were achieved by pelletization.
- Natural aggregates were replaced with LWAs in making self-compacting concrete (SCC).
- Seventeen SCCs were produced to have a fixed slump flow diameter.
- The High-Range-Water-Reducing Admixture decreased with the increasing level of LWA.
- Increasing amount of LWA made SCCs less susceptible to shear thickening.

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ABSTRACT

This paper investigates the rheological behavior of self compacting concrete (SCC) made by replacing normal-weight aggregates (NWAs) with cold bonded lightweight fly ash aggregates (LWAs). Dry powder mixture of 90% fly ash and 10% Portland cement by weight was pelletized through moistening in a revolving tilted pan at ambient temperature to produce lightweight fly ash aggregates which were then cured for 28 days. Seventeen concrete mixtures were produced to have a fixed slump flow by using varying amounts of High-Range-Water-Reducing-Admixture (HRWRA). Increasing replacement level for fine and/or coarse LWA simultaneously decreased density and plastic viscosity which made the concretes less susceptible to shear thickening. Meanwhile, the increasing percentage of LWA used reduced the HRWRA needed for gaining constant workability. With full replacement by lightweight fly ash aggregates, 25% reduction was achieved in the fresh density of self-compacting concrete produced.

1. Introduction

Certain materials like special cements, artificial aggregates, micro-fines, fiber reinforcement, new age chemical admixtures, etc. when used in conventional concretes (CC) can have some unexpected consequences on the fresh properties. Even though, the workability of these new generation concretes such as self-compacting concrete (SCC) can be measured by slump test, slump flow test, J-ring test, V-funnel test, U-box filling test, L-box test or column test, those tests are not sufficient alone to determine the fresh properties of SCCs [1–4]. Therefore, the workability of self-compacting concrete that flows readily under its own weight through the incorporation of special chemical admixtures as well as the utilization of enhanced particle size distributions must be determined and monitored carefully by using the concrete rheometer [5]. The theoretical model of the concrete rheometer was expressed by Tattersall and Banfill [6]. The rheological behavior of concrete can be simulated by the Bingham model as given in Eq. (1)

$$\tau = \tau_0 + \mu\gamma' \tag{1}$$

where, τ: shear stress (Pa), τ_o: yield stress (Pa), μ: plastic viscosity (Pa.s), γ' shear rate (1/s). Due to the thixotropy and loss of workability of the fresh concrete, the parameters in the Bingham equation, particularly yield stress also viscosity are not constant in time [7–9]. Moreover, the apparent viscosity increases by increasing shear rate. This decrease in viscosity is due to the preferential orientation of the particles which results in the shear stress increasing less rapidly than the shear rate [9,10].

Because it is designed to flow under its own weight, resist segregation and meet other requirements, SCC, compared to CC, needs

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to have lower yield stress and comparable viscosity to impart high fluidity and retain kinetic energy for flowing concrete. The kinetic energy possessed by the concrete, because of its motion, provides the initial flowing of SCCs by the action of gravity. Yield stress for CC ranges from about 500 Pa to a many thousand Pa and that for SCC varies from zero to about 60 Pa, whereas the viscosity of CC and SCC vary similarly from 20 Pa.s to over 100 Pa.s [11–14].

Rheology is significantly used as a tool to accurately describe the workability of SCC, and it can also aid in the design of future SCC mixtures. A design methodology for SCC was proposed by Saak et al. [15] based on the assumption that reduced viscosity with minimized yield stress are required for restraining segregation. Schwartzentruber et al. [16] studied the rheological response of fresh cement pastes designed for SCC. They used the vane method to measure the evolution of torque at an extremely low speed over a constant duration to determine the highest value of the shear stress corresponding to the yield stress.

Disposal material like fly ash can be used for enhancing the properties of fresh SCC. The use of fly ash as a binder is also advantageous for reducing the need for large quantities of cement whose production is a major contributor to greenhouse gases such as CO_2. Moreover, the use of fly ash for producing lightweight aggregate (LWA) is going to save the nature from the scarring and damaging activities of aggregate mining [17]. Also, this leads to a new type of concrete called self-compacting lightweight aggregate concrete (SCLC) with characteristics different from both lightweight aggregate concrete (LWC) and SCC. SCLC combines the favorable properties of LWC and SCC, in transporting and placing of the fresh concrete. Additionally, the unit weight of SCC can be reduced by using LWA which results in reducing the total mass of the structure or building [18]. Furthermore, skipping the process of vibration helps to prevent the segregation of LWA in placing the SCC.

Aggregate shape and texture are strongly effective on the rheological parameters of SCLCs. In concentrated suspensions, any deviation from a spherical shape results in an increased viscosity [19]. In order to ensure a high flowing ability as well as a good de-airing of the SCC, a low yield stress and moderate viscosity are required. At the same time, both characteristics have to be chosen high enough to prevent the lightweight aggregates from buoying upwards or blocking [20]. Lightweight fly ash aggregate is suitable for use in SCLC due to its spherical shape so as to improve the rheological properties of the fresh concrete mixture. The spherical shape of the LWA particles yield a “ball bearing” effect that permits coarser particles to flow more readily and decrease the surface area that should be wetted for enhanced workability [5]. Additionally, EFNARC [4] specifies that the more the spherical aggregate particles the less the likelihood of blocking and the greater the flow of the fresh mixture because of the reduced internal friction. Sakai et al. [21] investigated that the spherical particles achieved higher packing densities than crushed particles. Likewise, Ferraris et al. [22] hypothesized that the increase in workability provided a reduction in water required and a reduction in inter particle friction due to the spherical shape of the particles. Moreover, Quiroga [23] found that aggregates with spherical, cubical, or rounded shapes, and smooth textures needed less cement and water to obtain the same slump as aggregates with flat, elongated, or angular shapes and rough textures. Similarly, Tattersall [24] reported that spherical shape particles were preferred because they more readily flowed past each other and decreased specific surface area. On the other hand, despite its various favorable properties, there is a dearth of research related to the effect of the cold-bonded fly ash lightweight aggregate on the rheological properties of SCC.

The main purpose of this study is to ascertain the rheology of the fresh concrete as artificial lightweight aggregates substitute natural aggregates in SCCs. The workability and the aggregate volume content were kept constant so that LWA can easily replace NWA and the parameters defining the rheological behavior can successfully be determined. As a result, this paper aims to obtain and investigate the rheological behavior of a new kind of material called self-compacting lightweight concrete.

2. Experimental study

2.1. Cement, fly ash, and superplasticizer

In this study, ordinary Portland cement CEM I 42.5 R was utilized for producing both artificial lightweight aggregates and fresh concrete mixes. Type F fly ash as per ASTM C618 [25], supplied from Çatalağzı Thermal Power Plant, Zonguldak, Turkey, was utilized both as a secondary binder material at a 20% replacement level by weight of cement and as for producing LWA. Physical and chemical characteristics of cement and fly ash are given in Table 1. A polycarboxylic ether-based High Range Water Reducing Admixture (HRWRA) with a specific gravity of 1.07 was used to achieve the target workability.

2.2. Lightweight aggregates (LWAs)

Cold bonding process was utilized for producing the lightweight aggregates. Dry mixture of fly ash and Portland cement at 90% and 10% weight proportions, respectively, was pelletized by moistening in an inclined rotating pan with a diameter of 80 cm and a depth of 35 cm. Pelletization was completed at about 20 min. The initial water spraying on the dry mixture at about 18–20% by weight of the total binder mixture took about 10 min. The remaining time was spared for growing up and stiffening of the freshly formed pellets. The last step in the production of the lightweight aggregates was the cold bonding of the fly ash pellets which were self-cured in sealed plastic bags that were stored in a curing room at a temperature of 20 °C and a relative humidity of 70% for 28 days [26–28]. Thereafter, the hardened fly ash aggregates were sieved to group into size fractions of 0.25–4 mm as fine aggregate and 4–16 mm as coarse aggregate. Fig. 1(a–c) shows the pelletization disc, fresh artificial lightweight aggregates in the inclined pan, and self-curing process of the agglomerates, respectively.

Specific gravity and water absorption of the LWA were determined as per ASTM C127 [29]. It was found that water absorption of the coarse aggregate after 24 h of soaking in water was about 17.1% while the specific gravity of the coarse LWA for bulk; apparent and saturated surface dry conditions were 1.5, 2.0, and 1.76 g/cm^3, respectively. Water absorption of the fine aggregate was about 21.2%, while the specific gravity of the fine LWA for bulk, apparent and saturated surface dry conditions were 1.46, 2.1, and 1.76 g/cm^3, respectively.

Moreover, crushing strength of LWAs was determined according to BS 812 [30] (part 110). Practically, individual pellets were placed between two parallel plates and loaded diametrically until

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	3.02	1.52
Specific gravity	3.15	2.04
Blaine fineness (m^2/kg)	326	379