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Original Research Article

Evaluation of the rheological behavior of fresh self-compacting rubberized concrete by using the Herschel–Bulkley and modified Bingham models

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ABSTRACT

The study herein presents the use of the Herschel–Bulkley and modified Bingham models to monitor the rheological behavior related to workability of the fresh self-compacting concrete containing waste rubber. Therefore, the self-compacting rubberized concretes were produced at a constant water-to-binder ratio of 0.35 and binder content of 520 kg/m^3. Class F fly ash was incorporated as 30% of total binder content by weight. Two types of waste scrap tire rubber, crumb rubber and tire chips, were utilized instead of natural fine and coarse aggregate at various level, respectively. The tire chips and three different graded crumb rubbers (No.18, No.5, and mixed crumb rubber) and five designated rubber contents of 5%, 10%, 15%, 20%, and 25% were considered as experimental parameters. The rheological behavior related to workability of the fresh concretes was investigated by using the ICAR rheometer. The torque–speed relationship obtained from rheometer was used to characterize the rheological behavior of fresh self-compacting rubberized concrete by applying the Herschel–Bulkley and modified Bingham models to experimental data. The results revealed that the self-compacting concretes produced in this study exhibited shear thickening behavior and increasing the rubber content resulted in higher exponent 'n' values for the Herschel–Bulkley and c/μ coefficients for the modified Bingham models.

1. Introduction

Concrete, which is described by rheologists as one of the most difficult materials to study, is thixotropic material according to extensively studies in the literature [1,2]. The thixotropic materials have a yield stress and a plastic viscosity which is the result of hydration in concrete [1,3,4]. However, the utilization of certain materials such as special cements, artificial aggregates, micro-fines, fibers, chemical admixtures, and waste products in the concrete production changes both the workability and hardened properties of concrete. The certain test methods measuring the workability are not enough to identify the workability of new generation concretes [5]. For instance, self-compacting concrete (SCC), which is more liquid than conventional concrete, is one type of these

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new generation concretes. In order to better understand the fresh behavior of self-compacting concrete, the rheological behaviors must be also investigated. The Bingham model (Eq. (1)), which is the most applied rheological model on the fresh concrete to simulate its rheological behavior, was expressed by Tattersall and Banfill [1]:

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

where τ, τ_0, μ, and $\dot{\gamma}$ are shear stress (Pa), yield stress (Pa), plastic viscosity (Pa s), and shear rate (1/s), respectively. However, the Bingham model considers that the yield stress and plastic viscosity are constant in time. Namely, thixotropy and loss of workability are not incorporated in this model [1,3].

The workability of SCC can be described accurately by using the rheology and it can also be used in the design of the SCC mixtures. For example, Saak et al. [6] studied on the effect of wall slip between the fresh concrete and rheometer on the yield stress and viscoelastic measurements of cement paste and their assumption on a design methodology for SCC was that reduced viscosity with minimized yield stress are required for restraining segregation. The research of Feys et al. [4] was on the rheological behavior of fresh SCC and their study revealed that the fresh SCC had shear thickening behavior. Changing the mix proportions of concrete influences the rheological properties, particularly yield stress and viscosity, has been evaluated in more detail [4]. Furthermore, mineral and chemical admixtures are generally used in the production of SCC [7]. Güneyisi [7] focus on the influences of fly ash incorporation on the fresh state behavior of SCC and the results of this study found out that fly ash significantly improved the fresh state properties of SCC. The same findings on the effect of fly ash on the fresh properties of SCC were observed in the studies of Gesoğlu and Özbay [9] and Madandoust and Mousavi [10]. Flatt [8] studied on the effects of superplasticizer on the rheological behavior of the concrete and it was revealed by this research that the utilization superplasticizer, one of these chemical admixtures, caused decreasing of yield stress. Moreover, the viscosity of the SCC can be increased by many ways, such as adding more fine materials, and adding a viscosity modifying agent, to maintain the stability of the SCC (flowing under its own weight, resisting to segregation, and meeting other requirements) [4,11].

All around the world, there have been huge amount of waste materials and their disposal is one of the most serious environmental problems. Waste tire is one of these disposal waste materials. Using the waste tires as aggregate in the cement-based materials is a good alternative rather than disposing as waste to the nature or burning them [12–15]. In the literature, there are many studies about the effect of rubber on the properties of conventional concrete such as workability, mechanical, and durability [12–16]. Gesoğlu and Güneyisi [13] and Güneyisi et al. [15,16] used the waste tire rubber aggregate in the production of the conventional concrete and they experimentally investigated the mechanical, durability and permeability properties. In these studies, it was noticed that the replacing the natural aggregate with waste tire rubber aggregate significantly influenced the aforementioned properties. Also, Yung et al. [14] experimentally investigated the influences of waste tire rubber utilization on durability performance of SCC production and they found out that durability of SCC remarkably affected by incorporating the waste tire rubber into SCC. Although there have been number of studies concerning the utilization of waste tire rubber in conventional concrete, the study on its use in the self-compacting concrete is still deficient.

This study mainly aims to investigate the rheological behavior of the fresh SCC produced with crumb rubber and tire chips at various replacement levels. For that reason, the natural aggregate was replaced with three different sized crumb rubbers (No.18, No.5 and mixed crumb rubber) and tire chips at the replacement level of 5%, 10%, 15%, 20%, and 25% at a constant water-to-binder (w/b) ratio of 0.35 and the total binder content of 520 kg/m^3. Besides, the class F fly ash was used as 30% of total binder content by weight to improve the workability of SCCs. Totally 21 self-compacting rubberized concrete (SCRC) mixtures mixes were designed and ICAR rheometer was used to obtain the torques and rotational speeds. The Herschel–Bulkley and modified Bingham models were applied on experimental data for each concrete mixture. The rheological properties of plain and rubberized self-compacting concretes in the fresh state were evaluated and discussed comparatively.

2. Experimental study

2.1. Materials

Ordinary Portland cement (CEM I 42.5R) and class F fly ash (FA) according to ASTM C 618 [17] with density of 3.15 g/cm^3 and 2.25 g/cm^3, respectively, were used in this study. They had Blaine fineness of 326 and 379 m^2/kg, respectively. Physical properties and chemical compositions of the cement and fly ash are presented in Table 1.

The coarse aggregate was river gravel with a nominal maximum size of 16 mm and the fine aggregate, a mixture of natural river sand and crushed limestone, was used with a maximum size of 4 mm. River sand, crushed sand, and river gravel had densities of 2.65 g/cm^3, 2.43 g/cm^3, and 2.71 g/cm^3, respectively. The particle size gradation obtained through the sieve analysis of the fine and coarse aggregates are given in Fig. 1.

Two types of scrap tire rubber, crumb rubber (CR) and tire chips (TC), came from used truck tires castaway after a second

Table 1 – Physical properties and chemical compositions of Portland cement and fly ash.

Analysis report (%)	Cement	Fly ash
CaO	62.58	4.24
SiO_2	20.25	56.20
Al_2O_3	5.31	20.17
Fe_2O_3	4.04	6.69
MgO	2.82	1.92
SO_3	2.73	0.49
K_2O	0.92	1.89
Na_2O	0.22	0.58
Loss on ignition	3.02	1.78
Specific gravity (g/cm^3)	3.15	2.25
Specific surface area (m^2/kg)	326	379