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Sustainable design and ecological evaluation of low binder self-compacting concrete

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ABSTRACT

Self-compacting concrete (SCC) is a kind of high-performance concrete that is able to consolidate under its own weight without vibration. Due to its high binder content, the production of SCC normally needs a larger number of cement, the production of cement are associated with high energy consumption and CO_2 emissions, which result in serious environmental pollution. To maintain the ecological sustainability of SCC, this research recommends a sustainable mix design method for SCC with a low binder content based on particle packing theory. The packing density of the concrete mixture is optimized by selecting an appropriate powder composition and particle gradation of the aggregate. Using the SCC mix design with the optimal packing density, a sustainable SCC can be achieved with the lowest possible of binder content while maintaining the desired level of workability and mechanical performance. The proposed design reduces the required binder content in the SCC mixture by 16%, the energy consumption during production of concrete by 30.57%, the CO_2 emissions by 33.98%, and the material cost by 6.24%, respectively, compared with the typical mix design recommended by the American Concrete Institute (ACI C237) standard for similar 28-day compressive strength. The proposed mix design strikes a good balance between the ecological sustainability and performance based behaviors of SCC.

1. Introduction

As an advanced concrete technology in civil engineering, self-compacting concrete (SCC) is able to consolidate and fill forms under its own weight without vibration (ACI C237 2007). SCC is highly flowable, homogeneous and stable. Because of its high performance and excellent self-compactability, many studies have been performed (Khayat, 2016; Long et al., 2014) on the concrete composition, mix design, overall performance and construction techniques of SCC (Zhao et al., 2015; Roussel et al., 2010; Wallevik and Wallevik, 2011; Khayat and Feys, 2010).

SCC typically uses higher binder content in the mixture than conventional concrete, which results in a higher construction cost. Additionally, the production of the SCC needs a larger number of cement, for which the recommended cement content is 400–600 kg/m^3 in EFNARC and 386–475 kg/m^3 in ACI 237R Standards (EFNARC, 2005; ACI C237, 2007), resulting in large amount of CO_2 emissions and severe environmental pollution (Tomasz and Jacek, 2014; Brabha et al., 2014). Material substitution has been one of the most effective measures to mitigate the environmental impact of concrete (Daniel et al., 2016). Adding high volume of supplementary cementitious materials (SCMs) such as ground granulated blast-furnace slag (GGBS), fly ash (FA), and silica fume (SF) in concrete, has been demonstrated to be effective in reducing CO_2 emissions (Yang et al., 2015).

Note that during the concrete casting process, the heat of cement hydration causes significant shrinkage and creep in the hardened concrete, which is prone to subsequent cracking, compromising its durability and longevity (Hwang and Khayat, 2010; Khayat and Long, 2010; Mehta and Monteiro, 2009). For this reason, recent studies have focused on the SCC made with a low binder content, particularly on its mix design methods (Shi et al., 2015). The prototype method was first proposed by Japanese researchers (Okamura and Ozawa, 1994), such as the method that uses fixed volume fractions of aggregates, which has been adopted in European and British specifications (EFNARC, 2005; BSI.BS EN206-9-2010, 2010). Ghazi et al. also developed a method

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for proportioning SCC mixtures, which was based on compressive strength requirements (Ghazi and Rand, 2010). The statistical factorial model proposed by Khayat (Khayat et al., 1999) can obtain the statistical interaction between the mixture parameters and the properties of concrete, which can be used for both mix optimization and quality control.

Besides, a type of mixture design method on the basis of packing model has been applied for proportioning SCC. Sedran et al (Sedran and Larrard, 1999). developed a design method based on the compressible packing model (CPM), in which the real packing density was calculated from a nonlinear relationship with the virtual packing density. Domone et al. (2008). discussed the blocking and the liquid criterion for the aggregate (solid phase) and paste (liquid phase) given by Petersson (Petersson et al., 1996), and proposed a SCC mix design method with a minimum paste content based on the aggregate properties. The SCC mix design developed by Su et al. (2001). was based on the fundamental theory of the CPM. Sebaibi et al. (2013) . further developed the design method proposed by Su, in which the EN 206-1 standard was introduced to calculate the paste amount of pozzolanic materials.

The mix design method of SCC with low cement and low total binder content can be of great interest as it can meet the requirements of both self-consolidation and environmental friendly. At present, there is no method that can fully meet the requirements for designing SCC (Shi et al., 2015). Compared with other methods, the CPM based design method can provide a mix with a small amount of binders and reduce the number of trial batches. In the present study, the packing densities of the mixed powder and aggregates for SCC are determined using the CPM. A systematic design method to produce sustainable low binder SCC is proposed. The workability characteristics and compressive strengths of the optimized SCC mixture are investigated. Ecological evaluation and the cost analysis of low binder SCC are also evaluated. It is shown that the mixtures with total binder content ranging from 320 to 380 kg/m^3 exhibit satisfactory workability characteristics and 28-day compressive strengths in the range of 30–40 MPa, which are suited for construction applications.

2. Raw materials and experimental program

2.1. Raw materials

2.1.1. Cement and fly ash

In this study, a 42.5 R Portland cement and a Class C fly ash confirming to ASTM C150 (2003) were used. The physical properties and chemical compositions of them are shown in Tables 1–3. Table 4 shows the distribution of particle sizes of their powder, which were obtained by using scanning and BT-9300ST Laser Particle Size Analyzer.

2.1.2. Aggregate

In this study, aggregates confirming to the requirements specified in ASTM C33 (2016), natural river sand with fineness modulus 2.5, type II, 0.9% mud, 0.5% clay lump, bulk density of 2640 kg/m^3 and packing density of 1520 kg/m^3 was used as fine aggregate; limestone with sizes of 5 mm-16 mm, bulk density of 2710 kg/m^3, packing density of 1400 kg/m^3, porosity of 48%, 0.3% mud, 0.1% clay lump and 6% flat-elongated particles was employed as coarse aggregate.

Table 2
Physical properties of fly ash.

Specific surface area (m^2/g)	ρ_0 (g/cm^3)	Water demand (%)	Loss on ignition (%)	Water content (%)
0.362	2.20	98.30	2.80	0.10

Table 3
Chemical composition of cement and fly ash (%).

Materials	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
Cement	–	0.97	7.04	25.20	0.03	2.51	2.35	57.8	0.26	0.11	3.16
Fly ash	0.29	7.68	22.59	48.20	–	2.74	0.24	4.13	0.82	0.27	0.83

Table 4
Particle size distribution of cement and fly ash.

Materials	Cement		Fly ash	
Particle size range (μm)	Passing of each sieve (%)	Accumulation (%)	Passing of each sieve (%)	Accumulation (%)
0.100–0.211	0.52	0.52	0	0
0.211–0.498	2.58	3.10	0.94	0.94
0.498–1.054	5.08	8.18	3.26	4.20
1.054–2.003	4.99	13.17	4.12	8.32
2.003–5.251	13.16	26.33	12.95	21.27
5.251–9.983	15.16	41.49	16.26	37.53
9.983–21.12	26.87	68.36	25.30	62.83
21.12–40.15	23.23	91.59	21.52	84.35
40.15–84.95	8.37	99.96	13.66	98.01
84.95–161.40	0.04	100	1.99	100

Fine and coarse aggregates were separated through standard hammer type of sieve machine, confirming to the requirements specified in ASTM C136 (2016), sieving sand into five different particle sizes ranging with 0.15mm-0.3 mm, 0.3mm-0.6 mm, 0.6mm-1.18 mm, 1.18mm-2.36 mm, 2.36mm-4.75 mm and sieving stones into two different particle sizes ranging with 4.75mm–9.5 m and 9.5 mm-16 mm. The grain-size distribution and properties of fine and coarse aggregates are shown in Fig. 1 and Table 5,respectively. The particle size distributions of the fine and coarse aggregates are within the recommended limits of ASTM C136 (2016).

2.1.3. Chemical admixture

In order to ensure the adequate workability and mechanical properties of the SCC, the polycarboxylate-based high-range water-reducing admixture (HRWRA) type of RMC-3 and CP-WRM50 was used, which was produced by Sika with confirming to the requirements of ASTM C494/C494M (2016). The characteristics of the chemical admixtures are given in Table 6.

2.2. Experimental program

2.2.1. The compressible packing model

The Compressible Packing model is an extension of the linear packing density model (LPDM) and solid suspension model (SSM)

Table 1
Physical properties of cement.

Specific surface area (m^2/g)	ρ_0 (g/m^3)	Setting time (min)		Stability	Flexural strength (MPa)		Compressive strength (MPa)	
0.581	3.00	Initial	Final	Qualified	3-day	28-day	3-day	28-day
		112	145		6.50	9.20	34.80	58.00