Construction and Building Materials 189 (2018) 409–419

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Proportioning of self-compacting steel-fiber reinforced concrete mixes based on target plastic viscosity and compressive strength: Mix-design procedure & experimental validation

Ángel de la Rosa [a], Elisa Poveda [a], Gonzalo Ruiz [a,*], Héctor Cifuentes [b]

[a] ETS de Ingenieros de Caminos, C. y P., Universidad de Castilla-La Mancha, Avenida Camilo José Cela s/n, 13071 Ciudad Real, Spain
[b] ETS de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

HIGHLIGHTS

- Novel proportioning method for SCSFRC based on target plastic viscosity & f_{cu}.
- Valid for fiber contents up to 1% and for cube strengths from 30 to 80 MPa.
- Practical mix-design charts to determine the dosage of the components are produced.
- Validation through six mixes of 30 and 70 MPa with 0.0, 0.3 and 0.6% of fibers.

ARTICLE INFO

Article history:
Received 25 June 2018
Received in revised form 31 August 2018
Accepted 1 September 2018

Keywords:
Self-compacting steel-fiber reinforced concrete (SCSFRC)
Mix proportioning
Plastic viscosity
Rheology

ABSTRACT

This paper presents a novel proportioning methodology for self-compacting steel-fiber reinforced concrete (SCSFRC), based on a previous methodology for plain self-compacting concrete [*Journal of Sustainable Cement-Based Materials* 5:4 (2016) 199–216 & 217–232]. The procedure is based on the target plastic viscosity and the compressive strength required for the mix and it accounts for fiber parameters such as volume fraction and aspect ratio. The procedure is valid for fiber contents up to 1% and for compressive cube strengths within the range of 30–80 MPa. The effective plastic viscosity of the SCSFRC is estimated from the plastic viscosity of the cement paste by means of micro-mechanical models that consider fibers as a phase of the mix. The procedure can be programmed numerically to generate practical mix-design charts to determine the dosage of the components. The paper provides an example of an application that uses these design charts. Likewise, the methodology is validated through the design of six mixes, which are actually prepared in the laboratory and whose properties are measured in fresh and hardened states.

1. Introduction

Since the appearance of self-compacting concrete, SCC, at the end of the 1980s, many mix-design methods have been developed [1] based on different principles: empirical methods, methods based on compressive strength, on the packing of aggregates, on statistical factorial models and on paste rheology. Empirical methods require intensive laboratory testing according to recommendations, such as the EFNARC guidelines [2], until the required behavior is achieved. Methods based on the required compressive strength reduce the number of tests, although their main disadvantage is the need for adjustments in the fresh state to reach the optimum mix proportions of their components. The aggregate packing method requires a smaller amount of cement, but leads to mixes that segregate easily [1]. Methods based on statistical factorial models propose predictive equations for fresh properties as a function of the dosage. However, they are not well-represented due to the high number of batches that they require [1,3]. Therefore, the methods based on paste rheology are the most efficient since they reduce the number of tests and provide a basis for quality control and an extensive development of new materials and chemical admixtures [1].

Unlike SCC, for self-compacting steel-fiber reinforced concrete, SCSFRC, there are no design guidelines or recommendations, and the design methodologies are scarce [4–7]. Most of them are related to empirical methods based on SCC where part of the granular skeleton is replaced by fibers. Others are based on SCC design

---

* Corresponding author.
E-mail address: Gonzalo.Ruiz@uclm.es (G. Ruiz).

https://doi.org/10.1016/j.conbuildmat.2018.09.006

Notation

CA	coarse aggregate
d_m	average diameter of the spread in the slump flow test
FA	fine aggregate
f_{cu}	compressive strength in 100 mm-edged cubes
h_1	depth of concrete at the beginning of the L-Box when concrete stops flowing
h_2	depth of concrete at the end of the L-Box when concrete stops flowing
i	index assigned to a definite suspension stage
j	index assigned to a definite concrete constituent
LP	limestone powder
m_c	cement mass per m^3
m_{CA}	coarse-aggregate mass per m^3
m_f	steel-fiber mass per m^3
m_{FA}	fine-aggregate mass per m^3
m_j	mass of constituent j per m^3
m_{LP}	limestone-powder mass per m^3
m_{SP}	super-plasticizer mass per m^3
m_w	water mass per m^3
m_T	sum of the masses per m^3 of all the constituents
n	total number of solid phases
SCC	self-compacting concrete
SCSFRC	self-compacting steel-fiber reinforced concrete
SFRC	steel-fiber reinforced concrete
t_{200}	time that concrete flow takes to reach 200 mm in the L-Box
t_{400}	time that concrete flow takes to reach 400 mm in the L-Box
t_{500}	time that concrete spread takes to reach a diameter of 500 mm after raising the Abrams cone
V_c	cement volume per m^3
V_{CA}	coarse-aggregate volume per m^3
$V_f = \phi_f$	steel-fiber volume per m^3 (volume fraction of steel fibers)
V_{FA}	fine-aggregate volume per m^3
V_j	volume of constituent j per m^3
V_{LP}	limestone-powder volume per m^3
V_{SP}	super-plasticizer volume per m^3
V_T	sum of the volume per m^3 of all the constituents
V_w	water volume per m^3
w/c	water to cementitious materials ratio
η	plastic viscosity
η_e	plastic viscosity of the self-compacting steel-fiber reinforced concrete
η_{eb}	plastic viscosity of the base self-compacting concrete
$\eta_{eb\,\max}$	maximum permissible value of plastic viscosity of the base self-compacting concrete
$\eta_{eb\,\min}$	minimum permissible value of plastic viscosity of the base self-compacting concrete
$\eta_{e\,\mathrm{calc}}$	calculated plastic viscosity of the base self-compacting concrete
$\eta_{e\,\mathrm{target}}$	target plastic viscosity for the base self-compacting concrete
η_i	plastic viscosity of the suspension in stage i
$[\eta_i]$	intrinsic viscosity of particles in stage i
η_p	plastic viscosity of the cement paste
η_{p+a}	plastic viscosity of the cement paste with air bubbles
λ	aspect ratio of the steel fiber (length/diameter)
ρ_c	cement density
ρ_{CA}	coarse-aggregate density
ρ_f	steel-fiber density
ρ_{FA}	fine-aggregate density
ρ_j	density of constituent j
ρ_{LP}	limestone-powder density
ρ_{SP}	super-plasticizer density
ρ_w	water density
τ_0	yield stress of a viscous fluid
$\phi_f = V_f$	volume fraction of steel fibers (steel-fiber volume per m^3)
$\phi_{f\,\max}$	maximum permissible value for the fiber volume fraction
$\phi_{f\,\min}$	minimum permissible value for the fiber volume fraction
ϕ_i $(i \leq 3)$	volume fraction of solids at stage i (solids 1 to i considered simultaneously)
$\phi_1 = \phi_{LP}$	volume fraction of solids at stage LP (LP only)
$\phi_2 = \phi_{FA}$	volume fraction of solids at stage FA (LP and FA)
$\phi_3 = \phi_{CA}$	volume fraction of solids at stage CA (LP, FA and CA)
$\phi_4 = \phi_f$	volume fraction of steel fibers (steel-fiber volume per m^3)
$\phi_{i\,\max}$	maximum packing fraction of phases 1 to i considered simultaneously
ϕ_λ	nondimensional function of the aspect ratio of the steel fiber

methods, that is on packing models where the inclusion of fibers is performed through the definition of new concepts related thereto, such as ‘perturbation volume’ [8], ‘equivalent packing diameter’ [5,9], or ‘maximum fiber factor’ [10].

The fresh behavior of cementitious suspensions, as in the case of SCSFRC, is greatly influenced by the composition and characteristics of their constituents. Therefore, it is essential to study and understand the rheology of this type of concrete [11–16]. The SCSFRC mix-design methods based on cement paste rheology models assume that concrete is a heterogeneous suspension of solids (granular skeleton of aggregates and fibers) in a homogeneous and viscous fluid phase (cement paste) [1,6]. By means of non-Newtonian rheological models, such as the Bingham and Herschell-Bulkley models, the flow of these suspensions can be accurately predicted [11,17]. These rheological models consist of two main parameters, namely the yield stress (τ_0) and plastic viscosity (η). The composition of the cement paste of an SCSFRC should be selected based on these parameters, since they determine the fluidity and the segregation-resistance of the resulting concretes [1,6,18]. The design of the mix, including that of the aggregates and fibers, is fundamental in order to obtain a high-quality SCSFRC [19].

The deformability, flowability and segregation resistance of SCSFRC depend on the physical properties of the coarse aggregate and fiber, in addition to the rheological characteristics of the mortar [17]. The thickness of the mortar layer is a suitable concept in order to evaluate the workability and segregation resistance. According to the theory of excess layer thickness, there must be a sufficient volume of mortar to fill in the gaps between coarse aggregate and fibers and, in addition, to form a film thick enough to provide fluidity to the whole and avoid segregation. Khayat et al. [6] propose a SCSFRC mixing design in which the volume of coarse aggregate is reduced as the fiber content increases, in order to maintain the thickness of the mortar layer constant. It covers both materials. This design concept allows calculating the proportion of aggregates for a given fiber type and content. Grünewald [10] adjusts the composition of the SCC mixture by adding steel fibers. He replaces the amount of fiber with the same volume of coarse aggregate, then by the same volume of coarse aggregate and fine aggregate, thereby maintaining the ratio of fine aggregate to total aggregate constant.