Construction and Building Materials 113 (2016) 113–120

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Variations of sorptivity with rheological properties of concrete cover in self-consolidating concrete

B. Aïssoun [a,b], K. Khayat [a,c,*], J.-L. Gallias [b]

[a] Université de Sherbrooke, Département de Génie civil, 2500 boul. de l'université, J1K 2R1 Sherbrooke, Canada
[b] Université de Cergy Pontoise, 5 Mail Gay-Lussac, 95011 Neuville-sur-Oise Cedex, France
[c] Missouri University of Science and Technology, 224 ERL, 500 W. 16th St., Rolla, MO 65409, USA

## HIGHLIGHTS

- The modified Bingham model can be used to successfully describe the rheological behavior of the investigated SCC.
- The sorptivity values of concrete cover are similar to those found for the bulk concrete.
- Increasing of the initial plastic viscosity can decrease water sorptivity measured during first 6 h.
- The rheological properties can have considerable effect on the transport properties of the investigated SCC.

## ARTICLE INFO

*Article history:*
Received 23 December 2014
Received in revised form 26 February 2016
Accepted 2 March 2016
Available online 16 March 2016

*Keywords:*
Capillary pores
Concrete cover
Durability
Rheology
Self-consolidating concrete
Sorptivity
Viscosity

## ABSTRACT

Transport properties of the concrete cover can influence the durability of concrete. Concrete cover of conventional vibrated concrete has greater porosity because of the looser packing density of coarse aggregate against the surface of the formwork, which is referred to as the "wall effect". In the case of self-consolidating concrete (SCC), the volume of coarse aggregate is lower, and the packing density of the aggregate can depend on the flow properties of the SCC under its own weight. The extent of the wall effect on the quality of the concrete cover can vary with the rheological properties of the concrete. The work presented in this paper seeks to evaluate the effect of changes in rheological properties of SCC on the sorptivity of the concrete cover that can be affected by the degree of consolidation of the SCC near formed surfaces as well as changes that can result from water migration and changes in the packing of solid particles in the vicinity of formed surfaces. The sorptivity of the concrete cover is also compared to that of the bulk concrete. In total, 17 SCC mixtures covering a wide range of rheological properties were investigated. Good correlation between initial plastic viscosity of SCC determined by the modified Bingham model and the sorptivity measured during the first 6 h of testing is established. It is likely that the initial plastic viscosity has a marked influence on the volume of the largest capillary pores of concrete, which can significantly affect transport properties and durability. Test results indicate that the sorptivity of the concrete cover in SCC is similar to that obtained in the interior bulk concrete.

## 1. Introduction

The concrete cover (or cover-crete) over the reinforcing bars is the first protective barrier against the ingress of aggressive agents into a concrete element. Adequate concrete curing is essential to secure high-quality concrete cover and high durability of the concrete structure [1–3]. Kreijger [4] investigated the porosity and transport properties of the concrete cover of conventional vibrated concrete (CVC). Concrete cover can be defined by three sections: the cement paste rich section measuring approximately 0.1 mm in thickness, the mortar rich section measuring about 5 mm in thickness, and the concrete section of about 30 mm in thickness [4]. The investigated concrete in [4] was prepared with a water-to-cement ratio (w/c) of 0.54 and was cured for 7 days in water at 20 °C followed by 21 days in air at 20 °C and 65% RH. The study reported that for CVC, the concrete cover can exhibit a relatively high porosity in the first 30 mm of depth from the material cast against a given surface. Such zone can have greater cement and water contents than that of the bulk material. The higher porosity of the outer concrete cover material can result in greater sorptivity

---

* Corresponding author at: Missouri University of Science and Technology, 224 ERL, 500 W. 16th St., Rolla, MO 65409, USA.
*E-mail address:* khayatk@mst.edu (K. Khayat).

http://dx.doi.org/10.1016/j.conbuildmat.2016.03.006
0950-0618/

and greater permeability. This is due to the formation of the "wall effect" where a looser packing of coarse aggregate can occur against the formwork. The wall effect was reported to be mostly limited to the first 30 mm in thickness from a given surface, beyond which the microstructure of the hydrated cement paste becomes similar to that of the bulk concrete volume [4].

The transport properties of the concrete cover can affect the durability of the material. Permeability and diffusion tests are used to characterize the transport properties of concrete exposed to aggressive fluids, such as $CO_2$, sulfates, and chloride ions. However, the evaluation of transport properties involves the determination of the bulk properties of the concrete. For example, the rapid chloride ion permeability test, ASTM C1202, involves the determination of the electrical conductivity of a concrete sample measuring 50 mm in thickness. The coefficient of permeability or diffusion of such sample reflects the mean property of the entire width of the concrete sample. Such bulk property is assumed to be homogenous. Such testing cannot identify the influence of the wall effect that can exist near cast surfaces, which can affect a smaller depth than the entire depth of the concrete test sample.

Unlike bulk permeability or diffusion type of testing, sorptivity testing characterizes the absorption of water by capillarity action. This test can be suitable to characterize the transport properties of the concrete cover. The test can enable the evaluation of the progressive penetration of water inside the concrete specimen from the outer surface, including that of the concrete cover. The sorptivity of concrete reflects the capillary rise of adsorbed water in a dried concrete sample, which is expressed in terms of the rate of volume of water absorbed by a given surface area of test specimen ($cm^3/cm^2 \cdot s^{1/2}$). This rate can vary with the distance from the test surface. The test can offer some information about changes in permeability through the thickness of the sample, and particularly through the first few millimeters near a formed or unformed concrete surface. The sorptivity test can be used to assess the ease of penetration of aggressive substances in concrete through the aqueous phase (chloride, sulfates...) and can be used to infer the degree of protection of reinforcement by the concrete cover [5]. Gagné et al. [6] showed good correlation between the sorptivity of CVC and the resistance to de-icing salt scaling. De-icing salt scaling resistance is closely related to the air-void system and concrete quality in the first few millimeters of test surface. Bentur and Jaegermann [1] found good correlation between the sorptivity of concrete and depth of carbonation for CVC.

The consistency of concrete and vibration conditions during consolidation can affect the properties of the surface layer. Martin [7], using image analysis, showed that when the vibration energy is not sufficient, compaction voids can occur in the concrete cover when the concrete has a slump value lower than 100 mm.

Unlike CVC, self-consolidating concrete (SCC) is cast without any mechanical consolidation. The rheological parameters of SCC have marked influence on flow properties and workability. Some researchers proposed the use of a "workability box" approach to relate key workability properties of SCC, such as filling ability, passing ability, and stability to rheological parameters [8]. For example, Hwang et al. [9] showed that SCC designated for structural applications should be designed to secure a slump flow consistency of 650–700 mm at the time of casting, a high filling capacity of at least 80%, and a high passing ability corresponding to a maximum spread between slump flow and J-ring flow of 50 mm or a V-funnel flow time lower than 8 s.

With the absence of mechanical consolidation, the flow properties of SCC can influence the physical characteristics of the concrete near formed surfaces and free unformed surfaces. Therefore, it is reasonable to assume that the concrete cover of SCC may have different transport properties than those of concrete cover in the case of CVC subjected to mechanical consolidation.

Chidiac et al. [10] evaluated the relationship between rheological properties of concrete and durability. The authors showed that there is a general relationship between the sorptivity of concrete and the plastic viscosity or yield stress. Such rheological properties are characterized using empirical relationships for flowable concrete with yield stress values ranging between 390 and 1570 Pa and plastic viscosity ranging between 5 and 68 Pa·s. The tested mixtures had w/c ratio >0.60. The study indicated that the water sorptivity varied inversely with the yield stress and plastic viscosity in the case of mixture with yield stress and plastic viscosity lower than 1100 Pa and 60 Pa·s, respectively. The study revealed that water sorptivity increased by 25% when the yield stress and plastic viscosity exceeded 1100 Pa and 60 Pa·s, respectively [10].

The objective of the study presented in this paper is to assess the influence of the rheological properties of SCC on the transport properties of the concrete cover compared to that of the bulk concrete. Changes in sorptivity of the concrete cover may be affected by the degree of consolidation of the SCC near formed surfaces as well as changes that can result from water migration and changes in the packing of solid particles in the vicinity of formed surfaces. In total, 17 SCC mixtures were investigated. The mixtures had different rheological properties by carefully changing the dosage rates of the superplasticizer (SP) and viscosity-modifying admixture (VMA), without the need to change the mixture proportioning vis-à-vis the contents of cement, water, and aggregate. Sorptivity tests were done on samples taken from the surface layer of concrete blocks cast with the various concrete mixtures as well as from bulk sections taken away from formed surfaces. This was done to compare the transport properties of the concrete cover to that of the bulk concrete. The results were also compared to those of CVC.

## 2. Materials and test methods

### 2.1. Materials

Ternary cement was used for the preparation of the SCC. The binder is composed of approximately 75% of a CSA Type GU (according to the CSA-A3001-08, which is similar Type I ASTM C150), 5% silica fume, and 20% Class F fly ash, by mass of binder. The relative contents of the CaO, $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ are 45.9%, 31.1%, 8.8% and 5.3%, respectively. The Blaine finesses of the binder is 452 $m^2/kg$. This cement is typically used for the construction and rehabilitation of transportation infrastructure subjected to severe environmental conditions.

Natural siliceous sand (0/5 mm) and a crushed limestone coarse aggregate with nominal maximum-size of 14 mm, according to the CSA A23.2-2A, were used. The sand and coarse aggregate contents were determined using the "Optimization René LCPC" software [11] to secure a maximum packing density of the aggregate skeleton. The sand/coarse aggregate volume ratio (S/A) was fixed to 1. It should be noted that the selected sand and aggregate satisfy the particle-size distribution requirements specified by CSA A23.2-2A, as presented in Fig. 1. The specific gravi-

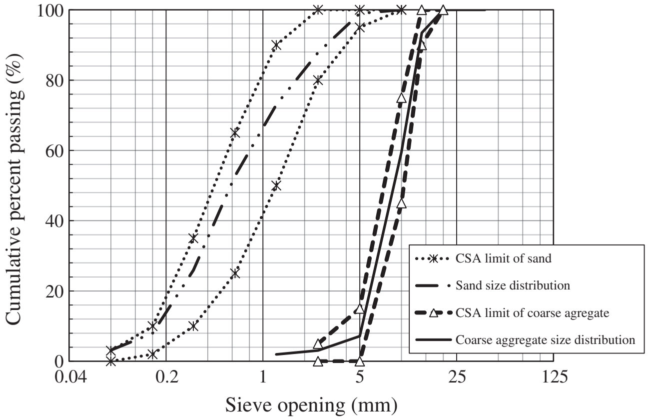

**Fig. 1.** Particle-size distribution of sand and coarse aggregate.