Construction and Building Materials 146 (2017) 329–337

Contents lists available at ScienceDirect

Construction and Building Materials

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

Influence of formwork material on transport properties of self-consolidating concrete near formed surfaces

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

[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. 16tyh St., Rolla, MO 65409, USA

HIGHLIGHTS

- New experimental method using image analysis to quantify wall effect is proposed.
- The use of Plywood (PW) formwork reduced sorptivity of concrete cover.
- The rough and absorbent PW modified significantly local w/c and wall effect of SCC cover.
- The decrease of w/c and the wall effect in the case of PW guaranteed higher durability.

ARTICLE INFO

Article history:
Received 7 September 2016
Received in revised form 10 April 2017
Accepted 12 April 2017

Keywords:
Aggregate packing
Capillary absorption
Concrete cover
Formwork
Rheology
Self-consolidating concrete
Sorptivity
Wall effect

ABSTRACT

This study aims at determining the influence of the formwork material on transport properties of concrete cover when using self-consolidating concrete (SCC). Two types of formwork were used. The plywood (PW) formwork material which is relatively rough and absorbent compared to the PVC material that has a very smooth and non-absorbent surface. A total of 17 SCC and highly flowable concrete mixtures with wide range of slump flow and T_{50} values were investigated. The concrete was used to fill $400 \times 500 \times 200$ mm^3 moulds made with either PVC or PW. Sorptivity tests were performed on core samples (100 mm in diameter and 50 mm in length) taken from the sides and center of the prepared moulds after 28 days of moist curing. This paper presents new experimental method using image analysis to quantify the relative surface area of coarse aggregate along different sections near formed surfaces. Sorptivity of concrete near the surface cast against the PW formwork was found to be significantly lower than that of PVC one due to the decrease of local w/c and wall effect. The examination of packing density of coarse aggregate near PVC and PW surfaces showed limited wall effect near the PVC formwork and significant wall effect within a thickness comparable to the maximum size of coarse aggregate near the PW formwork.

1. Introduction

The ingress of water and aggressive agents in concrete affect concrete durability. Ensuring low permeability of the so called concrete cover is of prime importance since it constitutes the first barrier to reducing the attack by aggressive agents. Transport properties and permeability of concrete depend on the mix design and curing conditions [1–4]. The durability of concrete, and in particular self-consolidating concrete (SCC), can vary with the rheological properties of the concrete that affect the consolidation, bleeding, surface settlement, segregation, as well as stability of entrained air [5,6].

Due to the presence of a formed surface, the change in packing of aggregate at the boundary layer against that surfaces (also known as the wall effect) can affect the in-situ transport properties [7]. Kreijger [8] showed that in the case of conventional vibrated concrete, the material found in the first 5 mm near the formwork is essentially composed of mortar with a water-to-cement ratio (w/c) greater than that found in the bulk concrete. This is the result of the wall effect induced by coarse aggregate packing against formed surfaces where a lower concentration of coarse aggregate was noted [8]. The study by Kreijger did not provide discussion regarding to the distribution of coarse aggregate in the first centimeter of formed concrete surfaces. Numerical studies dealing

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[*] Corresponding author at: Missouri University of Science and Technology, 224 ERL, 500 W. 16tyh St., Rolla, MO 65409, USA.

E-mail address: khayatk@mst.edu (K.H. Khayat).

http://dx.doi.org/10.1016/j.conbuildmat.2017.04.104

with the packing density of spherical aggregates against formed surfaces indicate that the disturbed zone's thickness of a material due to the presence of a rigid plane surface corresponds to the maximum size of coarse aggregate (Dmax) [9–13]. Zheng et al. [9] carried out numerical simulations of spherical particles of sizes ranging between 5 and 16 mm employed at mean volume fractions ranging between 35% and 50%. The 50% volume fraction corresponds to high volume of coarse aggregate, which is closer to certain conventional vibrated concrete. On the other hand, the 35% volume fraction corresponds to mix designs found in many SCC mixtures. The wall effect in the material with high density of spherical particles (volume fraction of 50%) was found to exhibit a linear increase from formwork to a distance of Dmax/2, where a maximum value of packing density was indicated in Dmax/2. At a distance of Dmax/2, the volume fraction of spherical particles can be 20% greater than that of the mean volume fraction. The decrease of the peak at Dmax/2 was found to depend on the volume fraction of the aggregate. For a mean volume fraction of 35%, the peak of volume fraction can be only 5% higher than the mean value in the bulk material. For greater distance from the simulated rigid plane, the volume fraction of spherical particles decreased to reach the mean value of the bulk medium [9]. Xu et al. [13] also found similar results using ellipsoid particles as aggregates. Accordingly, in their mesostructure model the specific surface area of the solid phase in the boundary zone had a 17% of coarse aggregate volume higher than bulk material at a distance of approximately Deq /2 where Deq is the equivalent diameter of ellipsoid particles. This peak decreased when the volume fraction of ellipsoid particle decreased.

Comparatively to the previous simulation, in the case of a real concrete, the thickness of the boundary zone effect is difficult to evaluate because of irregular shapes of coarse aggregates and their wide particle size distribution. However, in the case of SCC, the volume fraction of coarse aggregate is typically lower than that of conventional vibrated concrete and can be closer to the simulation study carried out by Zheng et al. [9]. This particularity, as well as the lack of mechanical consolidation, can change the characteristics of the wall effect against formed surfaces when SCC is employed. Therefore, further information is needed regarding the aggregate distribution in the vicinity of formed surfaces when casting SCC. The influence of the wall effect on transport properties of SCC also needs to be investigated.

On the other hand, the water absorption capacity of the formwork material can influence the physical properties of the concrete in the vicinity of the formwork. Capillary suction of some water from freshly cast concrete in the case of absorbent formwork material, such as timber or plywood, can cause local drop in the effective w/c and hence modification of local rheological properties and reduction in porosity and transport properties of the hardened material near formed surfaces [14]. Generally, the use of a release agent does not inhibit the water absorption of formwork material [15]. However, the surface characteristics of absorbent formwork material can be changed with the re-use of the formwork. A significant modification of the surface quality, including the surface absorption capacity and roughness, can occur during the life of the formwork. This was shown to be the case of plywood panels where the modification of the surface quality were found between 50 and 80 reuse cycles [15,16]. The authors used plywood panels to cast concrete samples measuring 300 mm × 300 mm × 300 mm to evaluate changes in concrete color and water absorption of the panels. The slump flow of concrete ranged between 160 and 210 mm with a compressive strength class of C25/30 according to the European Standard EN206-1. Regarding to the effects of absorbent formwork material, the reemployment of non-absorbent formwork made of steel or PVC is appreciable for repetitive elements (vertical walls, floors and columns) [16] and can contribute to the improvement of construction productivity. However, non-absorbent formwork can lead to more porous concrete cover in the case of conventional vibrated concrete. This is mainly because of the wall effect related to coarse aggregate packing against a rigid formed plane surface [14].

Moreover, the surface roughness of formwork plays an important role on flow characteristics of SCC at the concrete-formwork interface, particularly in the case of SCC which is not subjected to mechanical consolidation. Surface roughness was generally characterised by the average roughness (Ra) which represents the average deviation of the profile from a mean line. According to fib Model code [17], four categories are classified: (a) very smooth when surface obtained by cast against steel or PVC formwork (Ra is not measurable), (b) smooth untreated surface obtained by cast against wooden formwork ($Ra < 1.5$ mm), (c) rough surface obtained by sand-blasting high pressure water blasting or similar treatment ($1.5\text{ mm} \leq Ra < 3$ mm) and (d) very rough when surface obtained by high pressure water blasting or similar treatment or indented surfaces ($Ra \geq 3$ mm). This parameter is taken in account to calculate the shear friction at the concrete-formwork interface depending on the coefficients of cohesion (c) and friction (μ) of substrate surface [17,18]. These coefficients vary from 0.5 to 1.4 for very smooth surface to very rough one ($Ra \geq 3$ mm). The increase of friction (or average roughness Ra) at the concrete-interface may change the local flow conditions of fresh SCC consolidation and probably physical properties of hardened concrete, but the relationship between surface roughness and physical properties has not been studied.

To sum up the previous results it can be concluded that the physical properties of formwork material can influence the aggregate distribution of conventional vibrated concrete and rheological properties of the concrete in the vicinity of the formwork. On the other hand, in previous work the authors [6] showed that in case of SCC, the sorptivity of the bulk concrete can be affected by the rheological properties of concrete, particularly the initial plastic viscosity. Thus, it is reasonable to assume that formwork material could influence the transport properties of self-consolidating concrete near formed surfaces.

In the present work, the transport properties of SCC near formed plywood (PW) formwork surfaces were evaluated and compared to those of bulk concrete and near PVC formed surfaces. Sorptivity test is used to evaluate transport properties. New experimental method by using image analysis is proposed to quantify the relative surface area of coarse aggregate along different sections near formed surfaces. The study also aims to correlate transport properties of concrete near formed surfaces to the packing density of coarse aggregate found in the studied layers of the concrete cover.

2. Materials and test methods

2.1. Materials

A ternary cement complying with Canadian Standard CSA-A3001-08 was used. The cement is composed of approximately 75% CSA Type GU cement (similar to Type I ASTM C150 cement), 5% silica fume, and 20% Class F fly ash, by mass of total binder. The relative contents of CaO, SiO_2 Al_2O_3, and Fe_2O_3 are 45.9%, 31.1%, 8.8%, and 5.3%, respectively.

Natural siliceous sand (0/5 mm) and a crushed limestone coarse aggregate with a nominal maximum-size of 14 mm were used. The sand and aggregate are well-graded meeting the particle-size distribution requirements of CSA A23.2-2A. The specific gravities of the sand and coarse aggregate, measured according CSA-A23.2-6A-09 and CSA-A23.2-12A-09, are 2.66 and 2.74, respectively.