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SELF-COMPACTING CONCRETE WITH REDUCED FORMWORK PRESSURES

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Abstract. Self-compacting concrete (SCC) is normally characterized with high pressures exerted on the formwork during casting. The pressures can easily exceed bearing capacity of a regular formwork when casting a high structural member in one step. The contribution shows new ways of reducing the pressures using mineral additives based on calcinated clay minerals and clay nanoparticles whose addition together with interrupted casting process leads to a substantial reduction of the formwork pressures. Short interruptions in the casting lead to microstructural changes and flocculation, thixotropy and early strength evolution. The positive effects are studied systematically in microstructural studies performed on modified cement pastes using microscopy and viscosimetry. Rheological behavior of standard SCCs is improved towards thixotropy of the mixture by using the mineral additives. The newly developed recipes are tested on SCCs used on real construction sites. Examples of their practical utilization and on-site measurements show on up to 50 % pressure reductions in enriched SCCs compared to ordinary SCCs.

Keywords: Self-compacting concrete, metakaolin, nanoclay, formwork pressure, thixotropy.

1. Introduction

The rheology of the fresh concrete has been largely studied primarily to control workability and flowability of the mixtures [1]. With the development of self-compacting concretes (SCC) high mixture flowability with no need of external compaction has been achieved [2]. Simultaneously, an increase in lateral pressures that act on formwork has been produced by SCC. Thus, reduction of the formwork pressures is especially important in the case of using SCC for tall structures since the pressure that is much higher compared to ordinary concretes grows with formwork height when the casting process is uninterrupted. For an ideal fluid the pressure grows linearly with the height while for concrete it is reduced and depends on many parameters that can be categorized to the three groups:

- Material properties (such as binder type, water/binder ratio, aggregate type and shape, viscosity and thixotropy of the mixture),
- Placing characteristics (casting rate, holding periods, consistency, presence of reinforcement),
- Formwork characteristics (dimension and shape, surface, possible leakage).

This paper focuses on the first category and will study the influence of two mixture modifiers. Previous studies of the SCC rheology showed that the flowability and fresh state strength is controlled mainly by the particle flocculation and thixotropy of the cement paste [3–5]. Some additives can increase the floc size due to microscale agglomeration and rapid hydration [6]. Such an additive can be reactive calcined clay, the metakaolin [7, 8]. Other additives based on clay minerals have been proved to increase thixotropy of the mixture [9]. Kawashima et al. [10] showed that clay-modified cement pastes exhibited high recovery rate after shear loading. This paper extends the work and studies microscale and rheological properties of the modified fresh cement pastes and the evolution of lateral pressures monitored on a real construction site.

2. Methods

At first, the cement pastes modified with selected modifiers were prepared and studied by means of electron microscopy to reveal additive's shapes and their influence on the microstructure. Fresh cement pastes were further studied by means of rotational viscosimetry to find the effect on rheological properties. As the main parameters, the static and dynamic yield strengths and thixotropy index were evaluated. Each measurement was repeated three times and the results averaged. At second modified concrete mixtures were prepared and used in real conditions of a construction site. Pressures exerted on the formwork by modified mixtures were monitored and compared to reference ones.

2.1. Material selection and samples

All cement paste samples series were made of blended Portland cement CEM-II 42,5 R A-M (Čížkovice) in

	SCC-O [kg]	SCC-10 % MK [kg]	SCC-0.5 % NC [kg]
CEM II-42.5R A-M (Čížkovice, CZ)	340	306	338
Water	195±7	195±7	185
Agg. 8–16 mm (Klecany, CZ)	424	417	417
Agg. 4–8 mm (Zálezlice, CZ)	298	292	292
Agg. 0–4 mm (Černuc, CZ)	804	790	790
Limestone filler (Čertovy schody, CZ)	210	210	210
Stabilizer	3.8	4.2	3.81
Viscosity modifier	1.0	0.3	1.0
Plasticizer	2.5	4.5	2.5
Metakaolin	-	34	-
Nanoclay	-	-	1.7
Mean spread (mm)	74	67	65

Table 1. SCC mixture components (weight per m^3 of concrete)

water to binder ratio 0.4. A reference paste (labeled as C-O) was prepared with no addition. In the second series 10 wt. % of cement was replaced by metakaolin (České Lupkové Závody, Czech Republic), labeled as C-MK series. Chemical composition of the metakaolin was 53.1 % SiO_2, 41.7 % Al_2O_3, 1.1 % Fe_2O_3 and other minor oxides. In the third series, 0.5 wt. % of cement was replaced by nanoclay (C-NC series). Pure magnesium silicate called Sepiolite with the chemical formula $Mg_4Si_6O_{15}(OH)_2.6H_2O$ produced by Sepiolsa, Ltd., Spain, was used. It was dispersed in part of the water and ultra-sonicated prior mixing to support its dispersion. Fresh properties of the pastes immediately after mixing were evaluated thereafter.

SCC mixtures were prepared from the same ingredients complemented with silicious aggregate, limestone filler, high range water reducer (HRWR) based on polycarboxylic ethers (BASF MasterSure 900), viscosity modifier (BASF MasterMatrix SDC 180) and mixture stabilizer (BASF MasterSuna 6035) Table 1. The mixtures were previously optimized in cooperation with construction company Skanska, a.s. (Czech Republic). The Table 1 presents mixture composition, The labeling is as follows: SCC-O stands for no additive, SCC-10 % MK stands for 10 % cement replacement by metakaolin, SCC-0.5 % NC stands for 0.5 % nanoclay replacement. Modification of the water and plasticizer content in SCC mixtures was done to maintain comparable workability of the mixtures quantified by the inverted cone slump-flow tests (standard Abrams cone 30 cm in height, 20/10 cm in diameter was used). The values of the spread are also summarized in Table 1.

2.2. Viscosimetry on cement pastes

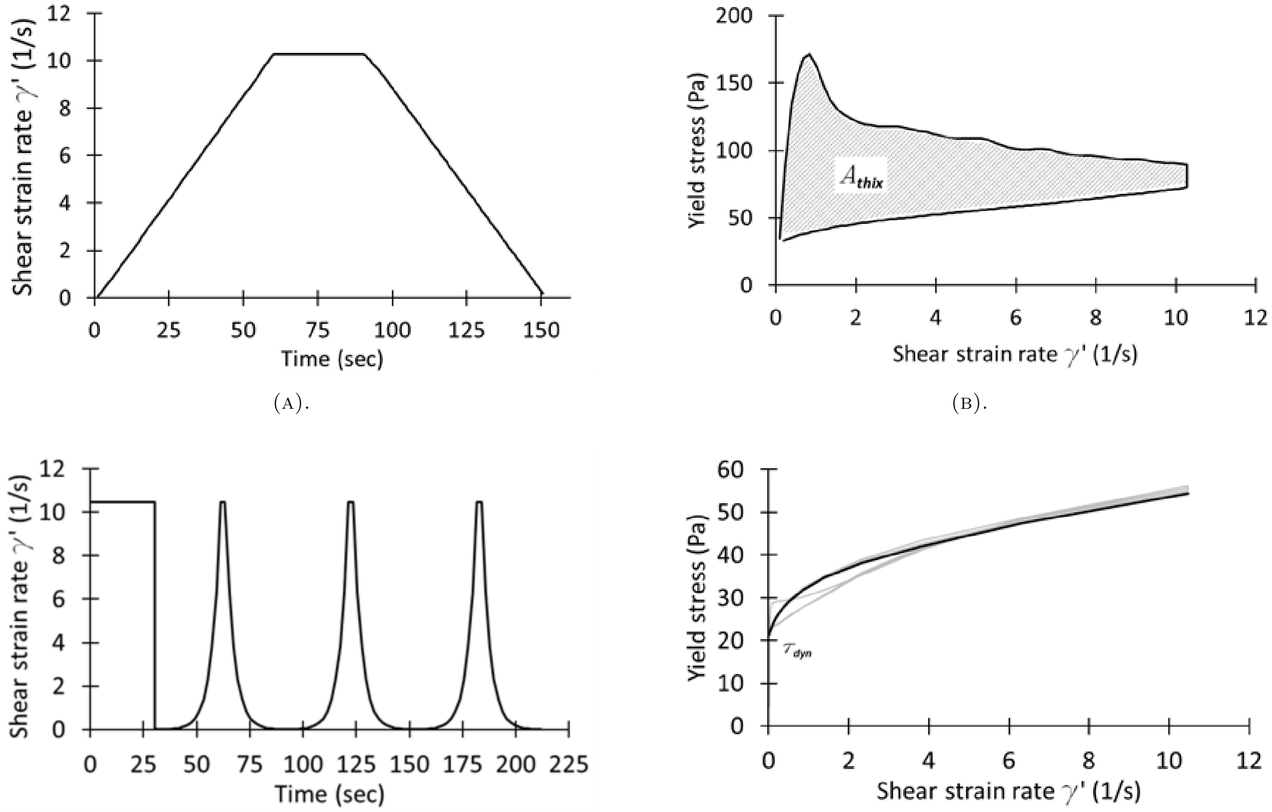
The description of the rheological behavior of mixtures was performed by means of viscosimetry. The aim of the viscometry measurements was to find the optimal dosage of ingredients that were selected for their potential to increase the thixotropy of the SCC mixture. A study was carried out to measure the static and dynamic viscosities of modified cement pastes. Rheological flow curves were measured with a Viscotester iQ rotary rheometer (HAAKE Viscotester iQ) using coaxial cylinder geometry (Couette geometry, CC38/Ti/SE). Static yield strength, dynamic yield strength and thixotropic index were quantified from the flow curves. Dynamic parameters were fitted with the Herschley-Buckley model (generalized non-Newtonian fluid model) from the respective flow curve segments as

$$\tau_{dyn} = \tau_0 + k\dot{\gamma}^n \quad (1)$$

where: τ – shear stress, τ_0 – dynamic yield strength, $\dot{\gamma}$ – shear strain rate, k – consistency parameter, n – flow index.

The recipes of all tested pastes were adjusted so that their spread after five taps on the Haegerman shaking table was 20±0.5 cm. The mixture was prepared in a volume of about 1 liter and after 5 minutes of stirring a spread test was performed. If the specified spread value is met, the mixture is placed in the measuring cylinders of the viscometer and the first measurement, the static test, took place within 10 minutes. When the static test ended, the dynamic protocol was started immediately. Both protocols are described in Figure 1 below. Measurements on a viscometer were repeated on the same mixture at 30 and 60 minutes. The mixture was mixed by hand before loading into the testing cylinder, a new batch of mixture from the prepared volume was added for each time period.

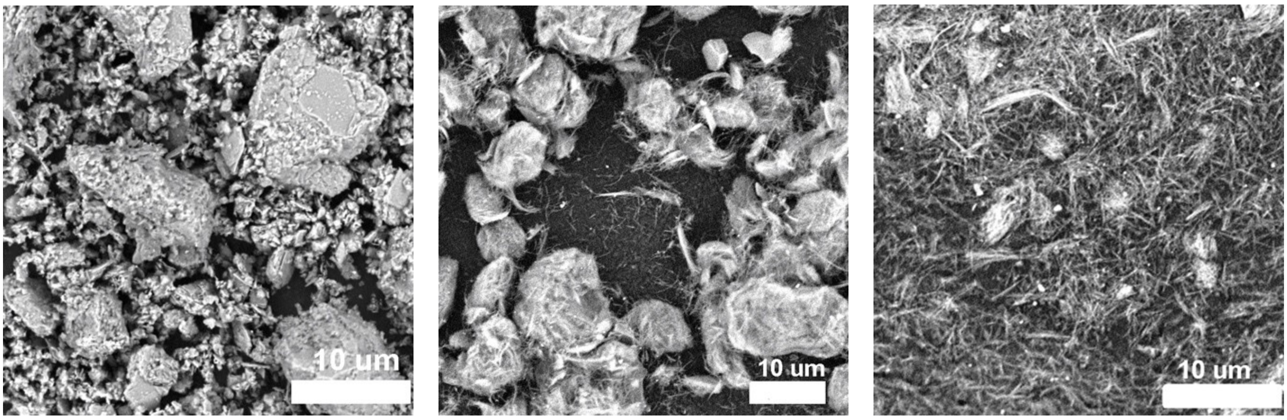
The static protocol has a total of three linear segments, see Figure 2a. In the first segment, the intact mixture is gradually loaded, and the static yield strength of the material, τ_{stat} (the first local maximum of the shear stress curve vs. the relative deformation) can be deduced from this part of the protocol. When the prescribed maximum speed of the load rotor is reached, the protocol passes to the second segment, in which a constant speed is maintained for 30 seconds. This part of the protocol aims to create a more significant deformation in the mixture, during which the



(a). (b).

(c). (d).

Figure 1. Rheology protocols.



(a). (b). (c).

Figure 2. SEM micrograph of (left) metakaolin particles, (middle) dry nanoclay, (right) nanoclay after dispersion in water.

stress drops. The final third segment prescribes deceleration of the rotor. These three segments thus form a closed working loop, the area of which is then interpreted as the thixotropy index, A_{thix}, of the mixture (Figure 2b).

The dynamic protocol consists of a total of eight segments. In the first step, the mixture is stirred at a high constant speed for 30 seconds, followed by stopping the rotor. The rotor is stopped for one second, during which the measured torque stabilizes up to zero. The following up/down segments on a logarithmic scale load the mixture in a total of three cycles (Figure 2c). These cycles are then used to evaluate the dynamic yield strength from the last unloading segment, τ_{dyn} (Figure 1d).

2.3. Field tests

In cooperation with Skanska company, several real construction sites were selected, and measurements of lateral pressures conducted on reinforced concrete walls made from SCC mixtures. The walls were instrumented with the lateral and vertical pressure sensors

Figure 3. View on wall formwork (left), instrumentation at the bottom of the wall (middle), schematics of the wall cross section and position of built-in pressure sensors (right).

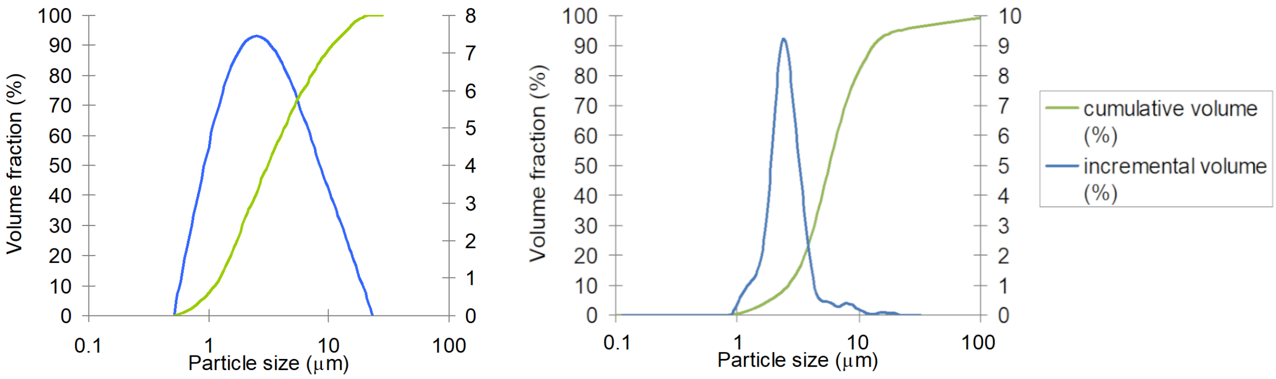


Figure 4. Particle size distribution of (left) metakaolin particles and (right) nanoclay.

placed at the bottom of the formwork. In all cases, the height of the walls was about 3 m, thickness about 25 cm and the length varied from 4–8 m. Usual density of ordinary steel reinforcement was used in the walls. For the pressure, the wall height is the governing factor, so the walls were all comparable. The lateral view on the wall is presented in Figure 3 – left. The pressure sensors were embedded in the formwork wall (0.17 from the bottom) in a special formwork piece (Figure 3 – middle). Both lateral and vertical pressures were monitored during the whole casting process (roughly 2 hours) and for the next 2 hours after. The casting process was prescribed so that always a 0.5 m layer of concrete was cast in once from one batch and then 10 mins break with no vibration was held. The process repeated in the cycles up to filling the full wall height (Figure 3 – right). The rest time in the casting led to possible development of thixotropy in the mixtures and decreasing of lateral pressures exerted on the formwork.

3. Results

3.1. Microscopy and particle size

It was found that both additives have wide distribution of the particles in the dry (undispersed) state. Clearly visible grains of metakaolin with approximate size of 1–10 μm are shown in Figure 2. Particle size distribution measured by laser diffraction is depicted in Figure 4. The mean particle size is 2.3 μm. Nanoclay particles are strongly agglomerated in the dry state as shown in Figure 2. Water dispersion and ultrasonication leads to disjoining of the fibrous particles as seen in Figure 2. Clearly, the fibers are characterized by several micrometer length and nanometric diameter. Such particles with high aspect ratio can hardly be quantified by laser diffraction. It seems that the graph shown in Figure 4 (right) shows mainly the length distribution of the nanoclay fibers. The peak particle size in this distribution is 5.6 μm. In both cases, the additives have smaller average size compared to cement grains.

Scanning electron microscopy (SEM) imaging of the samples did not reveal any significant differences between the samples (Figure 5). Slightly less portion of portlandite zones is visible in C-MK samples as a possible consequence of portlandite-metakaolin reaction. No further rigorous analysis was performed.

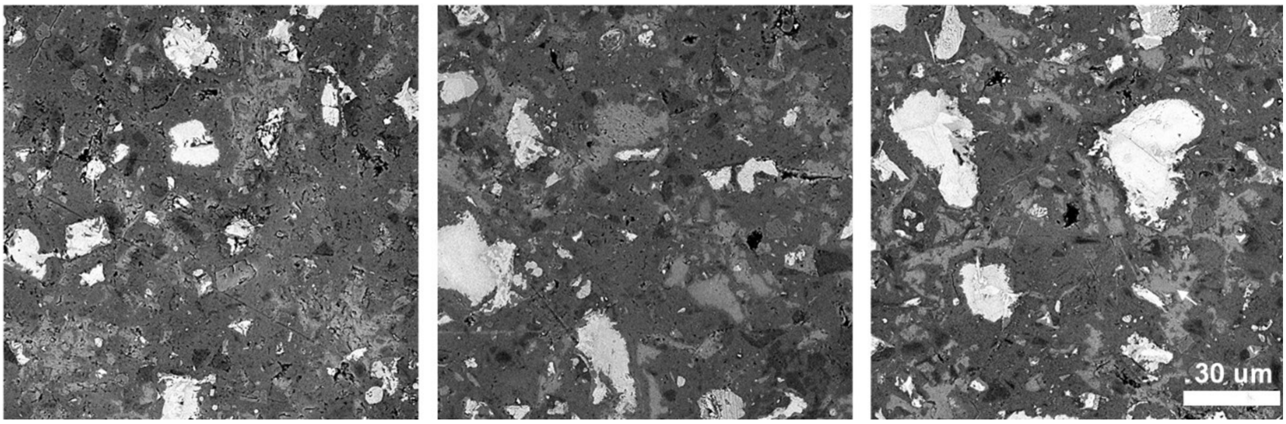


Figure 5. SEM images of the samples (left to right: C-O, C-MK, C-NC).

4. Viscosimetry

The comparison of the results from static and dynamic tests for the studied mixtures is shown in Figures 6 and 7, respectively. Apparently, the static yield strength increases dramatically for both modified mixtures compared to a reference. It means, that the modified mixtures have a much higher resistance to static shearing and their strength is higher when the mixtures are in rest. On the other hand, the differences in the dynamic strength are much less pronounced and the reference and modified mixture behave very similarly. The dynamic measurement thus indicates that when the mixtures are in motion (during mixing and flowing in the formwork space), the viscosity appears very similar. However, when they are brought to a rest, they require a significantly different amount of input energy to overcome the static yield strength. The related average break through stress is approximately 90 Pa for cement alone, 112 Pa for metakaolin and 132 Pa for nanoclay modified paste. This difference represents +24.2 % to +46.3 % increase of the yield strength due to the addition of the modifiers. The comparison of the mean values from all tests is presented in Table 2.

	τ_{stat} [Pa]	τ_{dyn} [Pa]	A_{thix} [Pa]
C-O	89.95±12.64	19.19±1.63	306.77±38.20
C-MK	111.68±22.34	21.29±0.67	383.75±92.65
C-NC	131.66±9.91	29.59±3.96	431.20±75.87

Table 2. Results of viscosimetry.

Effect of nanoclay or metakaolin on static yield strength at the 60 minutes age of paste is apparent from Figure 6. When the mixture is already in motion, the yield stress from the presented mixtures follows rather similar path, which is also observed in the Figure 7 where the dynamic yield strength is very similar.

The thixotropy index increases with the addition of the modifiers by +25.1 % for metakaolin and +40.6 % for nanoclay addition, see Table 2 for exact values.

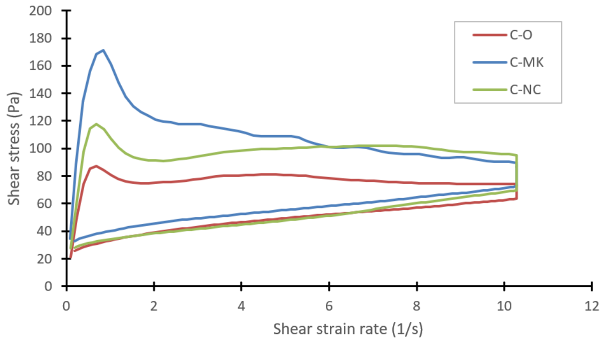


Figure 6. Examples of viscosimetry flow curves from static test.

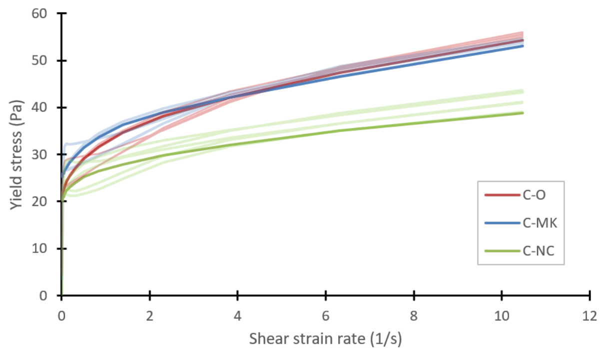


Figure 7. Examples of viscosimetry flow curves from dynamic test (last segment highlighted).

This again favors using the additives for the reduction of the formwork pressures.

4.1. Field tests on standard walls

An important test was conducted on real SCC mixtures modified by aforementioned additives. It was proved by the study on cement pastes that both metakaolin and nanoclay increase static yield strength and thixotropy and have a high potential for reduction of lateral pressures. Results of the field measurements are depicted in Figure 8. The increasing saw-like course of the pressure curve corresponds to the casting process done in steps with the break between the

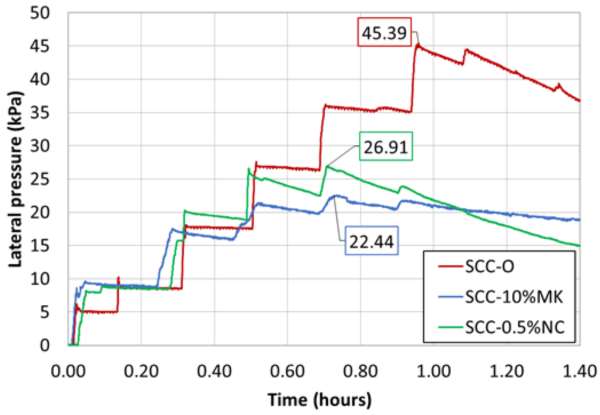


Figure 8. Lateral pressures exerted on the formwork in field tests of SCCs.

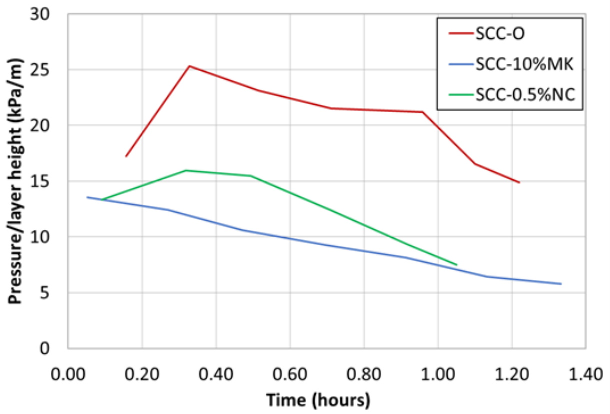


Figure 9. Relative differences in lateral pressures.

cast layers. The stress increases by steps as the wall layers are built. A stress drop can be observed during each cycle and is more pronounced in later stages (cycles 4–6) and for modified mixtures. The evolution of relative differences between the lateral pressures exerted on the formwork by individual mixtures is shown in Figure 9.

It must be noted that the lateral pressure is highly correlated with the casting method, that is the dropping height of concrete during casting, casted layer thickness, casting speed, duration of breaks between layers, vibrations, and deformation of a formwork. These variables were therefore kept as identical as possible. The wall thickness and reinforcement of the tested walls were also reasonably close and are assumed not to be the factor for a difference in recorded pressures. The main factors influencing the lateral pressures in the formwork were found the introduction of the breaks between casting the layers and also material selection including the mixture spread. A high correlation of the pressure with the mixture spread has been observed. The lower spread the lower lateral pressure can be anticipated.

Mixtures denoted in the Table 1. have been tested on walls of similar height (about 3.2 m) and the recorded pressure is depicted in the Figure 8. Saw-like pattern of increasing pressure can be observed for all mixtures, but the steps of modified mixtures are gradually diminishing in size up to the point where another increase in load from a new layer isn't observable. Lower average spread lead to a significant lateral pressure reduction for both mixtures by nearly 50 % and 41 % for the metakaolin and nanoclay respectively. Because of minor differences in layer height, the pressure after reaching each layer was normalized by the currently achieved height, see Figure 9. The lower curve shows a more effective mixture in terms of the lateral pressure reduction (i.e. SCC-10 % MK and SCC-0.5 % NC).

Our previously tested standard walls (in section 3) were all about 3.2 m tall and cast in comparable conditions. Since the effect of dimensions and casting process is of high importance and could distort the efficiency of the additive, another field trial was carried out on a much higher wall of about 8 m height (Figure 10). The mixture with the same ingredients specified in Table 1 but only with 5 % metakaolin cement replacement was chosen in this specific case and labeled as SCC-5 % MK-8 m. The consistency of the mixture was SF2 with the spread 700 to 750 mm. Comparison with a standard wall made of the same mixture (SCC-5 % MK-3.2 m) was performed on the same site. Some differences compared to previous casting of standard walls occurred:

- lower layers were cast with significantly higher energy (drop of the mixture from a higher height),
- smaller wall layers were laid (0.4–0.5 m),
- the waiting periods were shortened to 5–7 min,
- the mixture had a higher spread compared to SCC-10 % MK and SCC-0.5 % NC.

Figure 10. A 8 m high wall made from SCC-5 % MK mixture.

For the tall wall, the peak lateral pressure was reached later than in a standard wall, after the 7th layer (in 3.2 m). Following 11 layers (from 3.2 m to 7.8 m) did not cause an increase of pressure in the bottom layer. A comparison of lateral pressures also with the reference mixture is shown in Figure 11. It is evident that the casting process has a tremendous effect on the pressures if we compare the SCC-5 %

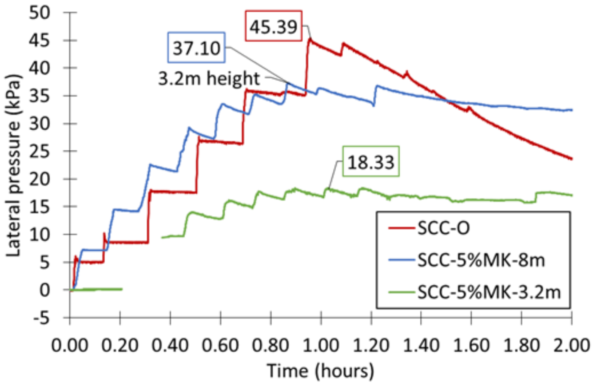


Figure 11. Lateral pressures exerted on the formwork in field tests of 8 m high wall and comparison to other mixtures.

MK-3.2 m and SCC-5 % MK-8 m results. Maximum pressure on a high wall was moved to the 7th layer and is by 100 % higher compared to the pressure in a standard wall. It might be a consequence of the concrete flow movements that are higher on a higher, layers are done in smaller time intervals and the concrete is poured from a larger height. Still the MK additive works well, and the pressures are below the reference pressure exerted by the unmodified mixture on a standard wall (-18 %), Figure 11. It could be anticipated that if the casting parameters were the same as in case of standard walls, the pressure reduction would be higher. More tests are needed to prove this.

As a side benefit, the wall from SCC-5 % MK mixture exhibited high visual quality, was free of defects and met the architect's requirements (Figure 10).

5. Conclusions

Three types of SCC mixtures (a reference, with added metakaolin and with nanoclay) were formulated and results of their performance in terms of lateral pressures exerted on the formwork presented. The additives were dosed as 10 % and 0.5 wt. % cement replacement in case of metakaolin and nanoclay, respectively. The dosage was found to be optimal based on previous viscosimetry measurements done on cement pastes. The mixtures were tested in real construction sites conditions and formwork pressures monitored. The binding phase (cement paste) was tested separately in the fresh state by viscosimetry. Results show that both metakaolin and nanoclay increase static yield strength. This average increase was quantified as 24.2 % and 46.3 %, respectively. On the other hand, the ability of the pastes to flow under vibration is only slightly influenced by the additives and the dynamic flow properties exhibit similar values for all mixtures. Thus, the measurement indirectly proves the thixotropy effects for both additives. Also, the thixotropy index evaluated from static tests show that the additives increase the average thixotropy by 25.1 % and 40.6 %, respectively.

The casting process on selected reinforced concrete walls (3.2 m in height) was prescribed with 10 mins interlayer breaks (with exception for a tall wall due to time constraints, Figure 10.) to allow development of thixotropy effects in the tested mixtures of SCCs. While consistency (spread in the cone-flow test) of the mixtures was maintained on a similar level (by addition of superplasticizers) lateral pressures of modified mixtures measured at the bottom of the formwork exhibited much lower values. Absolute values of the pressures depend, among other factors, on the structure height and casting schedule. In our case, most of variables were kept as similar as possible. The lateral pressure decrease was compared based on normalized values. In the monitored examples, the metakaolin modified mixture showed 50 % pressure reduction, the nanoclay modified mixture exhibited 41 % reduction. The study proved a large potential of both additives to effectively reduce lateral pressures developed on formwork as follows from both laboratory and field tests.

A single test was carried out on a high wall (8 m) with one mixture and different casting process parameters. Although, the pressure reduction was not as significant as in case of standard walls mainly due to different casting conditions. Still 18 % pressure reduction was achieved compared to a reference mixture.

Acknowledgements

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