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Pourable wood-cement compounds – properties, potential and challenges of a new structural material

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ABSTRACT: Wood-cement compounds (WCCs) are composite materials made of wooden aggregates and mineral (cement) binders. These materials are widely used as prefabricated panels in the construction industry. A main obstacle for using casted WCC in construction elements is high shrinkage of the young product and frequently difficult workability of the mixes. This project addresses both of these problems by developing self-compacting low-shrinkage WCCs. Another objective of the study is to reduce cement content, which is typically very high in WCCs (500 to 700 kg/m^3 of Portland cement). By replacing Portland cement with inert fillers or pozzolanic waste materials, the environmental impact of the WCCs can be lowered and a “greener” cement-based material is created. To assess the effectiveness of the developed recipes, WCC specimens are evaluated with regard to shrinkage, workability and mechanical performance.

1 INTRODUCTION

1.1 *Workability enhancement and self-compacting properties*

Fresh concrete workability is an important factor in concrete element prefabrication. Self-compacting concretes have become widely adapted in prefabrication facilities for productivity benefits by eliminating vibrating tables.

The structural quality of walls and slabs made of timber and WCC, with potentially complex geometries of the interfaces between WCC and timber, is also much better met with a self or nearly self-compacting material. Companion papers (Eymard & Zwicky 2016, Zwicky & Macchi 2016) to the present contribution show practical applications of WCCs in composite action with timber for slab and wall elements.

1.2 *Shrinkage reduction*

Shrinkage of WCC may be an issue, being mainly due to the high porosity in the cement paste resulting from the air-entraining effect of wood resin (Zwicky 2015). Furthermore, no mineral skeleton is in place to restrain the volume shrinkage of the cement paste as it would be the case with traditional cementitious materials.

The very low Young’s modulus of sawdust, basically a randomly oriented wooden material, implies that the sawdust fraction in the hardened WCC can be presumed to be a macro-porosity that cannot restrain shrinkage of the cement paste.

2 WCC RECIPES

Four recipes were investigated in this study. Table 1 shows the composition for the different recipes as well as the composition of a reference recipe developed earlier (Zwicky 2015).

Table 1: Recipes for pourable WCCs (mass per m^3)

Recipe	Saw dust$^{(2)}$	CEM I 52.5R	Sand	Limestone filler	Fly ashes	Water	Other
SE1	110 kg	300 kg		390 kg		190 kg	WRA$^{(*)}$
SE2	110 kg	300 kg	500 kg	390 kg		190 kg	WRA
SE3	110 kg	300 kg		390 kg		190 kg	WRA, SRA$^{(**)}$
SE4	110 kg	270 kg		270 kg	150 kg	190 kg	WRA
Ref	110 kg	540 kg				190 kg	

$^{(*)}$ water-reducing agent, $^{(**)}$ shrinkage-reducing agent

The mineral powder fraction of all mixtures was kept constant at 690 kg/m^3. One mixture contained an additional 500 kg of fine sand. SE1 is the reference mixture that does not use any sand, fly ashes or shrinkage-reducing agent.

The sawdust used for the WCCs is from spruce wood, cut with an industrial frame saw. Most particles (more than 90%) pass the 2 mm sieve (Figure 1).

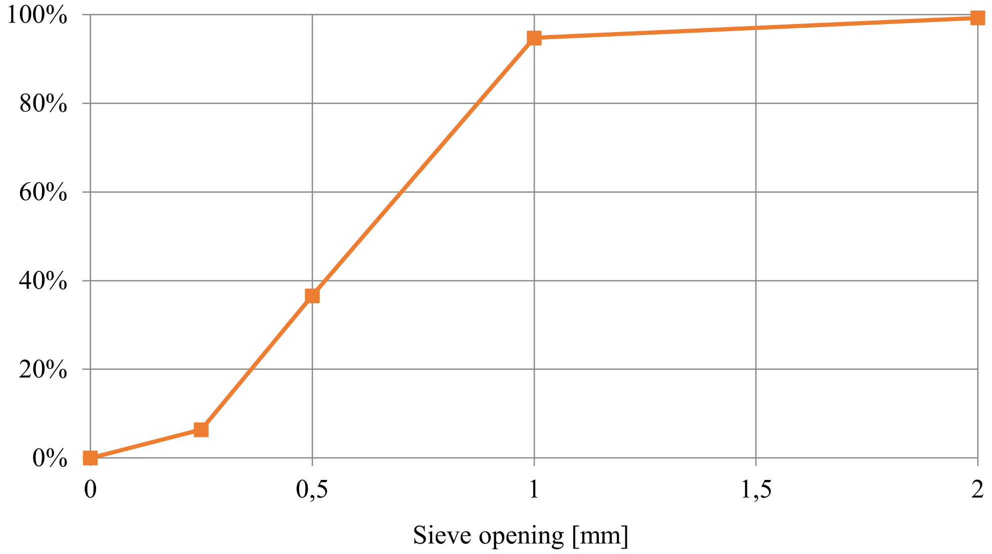

Figure 1: Granulometry of sawdust used in WCCs

No treatment prior to the mixing process was applied to the sawdust. CEM I 52.5R according to EN 197-1 (2002) was used. Sand with a maximum grain size of 2 mm was used in mixture SE2, to see the impact of a mineral macro skeleton on the WCC properties.

Lime filler (LL) was used primarily to reduce cement content in the mixtures and, secondarily, to improve workability of the fresh WCC.

Fly ashes (V) were used in mixture SE4 to see the potential of replacing a certain amount of Portland cement with pozzolanic materials, and to improve workability of the fresh WCC.

Water-reducing agents (WRA) are used in concrete formulation with very high success to either lower water content or improve workability of fresh concrete (or any combination of these effects). A naphthalene-based water-reducing agent has been used here, as polycarboxylate-based products have shown to excessively delay hardening in internal preliminary tests.

Shrinkage inhibitor solutions for regular concrete are available. Shrinkage-reducing chemicals (SRA) have shown significant effects in free shrinkage conditions and significant reduction of crack width in restrained shrinkage conditions (Shh et al. 1992). A shrinkage-reducing agent that lowers the water surface tension during drying was used during this study.

3 WORKABILITY OF FRESH WCC

The flow table test (or flow test) is performed on a cone of fresh concrete being placed on a pivoting table. The table is raised on its pivot and released on a distance of 4 cm for 15 times. The average diameter of the resulting concrete patch in centimetres is called the spread.

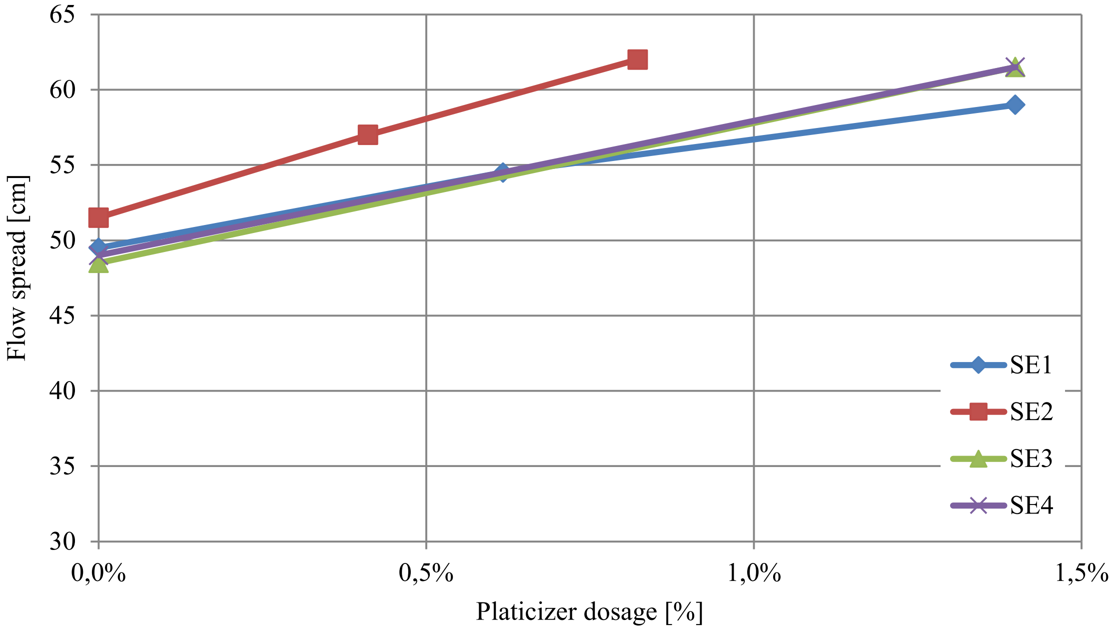

Figure 2: Flow table test results on fresh WCCs for different plasticizer dosage

All mixtures have initially been targeted for a spread of 50 cm. The test has been repeated as plasticizer has been added. When the flow spread exceeds a certain value, the test cannot be performed anymore, due to space restriction on the flow table. This happened with mixture SE2 at high plasticiser levels. Figure 2 shows an overview of the different results.

For the slump flow test, a fresh concrete cone is placed on a plane surface, similar to the flow table test. Contrary to the latter, no supplementary shocking is conducted. The cone volume and dimensions are different than in the flow table test. The relation between slump flow and flow table test with and without shocking has been described as linear by volume (Domone 1998).

Generally, a self-compacting concrete should have a slump flow of minimum 55 cm. Figure 3 shows slump flow values of different recipes at different plasticizer dosage. Recipes SE2 and SE4 (barely) satisfy this SCC criterion, SE3 does not. Table 2 shows a recapitulation of the test values.

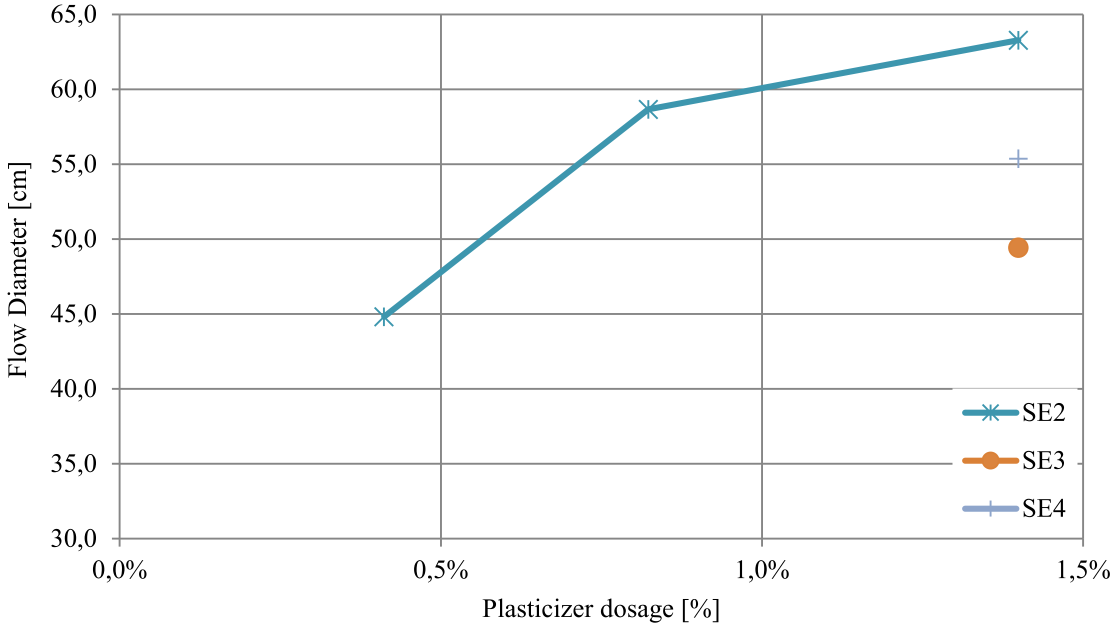

Figure 3: Slump flow values for tested WCCs

Table 2: Workability results for different fresh WCC tests

Recipe (at max. FM dosage)	Flow table spread [cm]	Slump flow spread [cm]
SE1	59	N/A
SE2	N/A	63.5
SE3	56	49.5
SE4	61.5	55.5

This kind of tests has not been performed for the reference WCC. Slump test results were in the range of S3 to S4 (SN EN 206-1 2000), indicating a good workability but self-compaction properties could not be attained yet.

4 SHORT-TERM MECHANICAL PROPERTIES

4.1 *Density*

Mechanical properties of WCC largely depend on density and thus, a primary concern when developing WCC recipes are target densities.

In this study, all except recipe SE2 aimed at the same density (roughly 750 kg/m^3 oven-dry). It is thus not surprising that the densities do not vary a lot between recipes. Oven-dry densities of WCC usually range between 60% and 70% of "humid" densities. The target densities seem to be attained quite precisely, this was however not verified experimentally.

Table 3: Densities measured directly out of 90% relative humidity environment at 28 days of age

Recipe	SE1	SE2	SE3	SE4	Ref
Density [kg/m^3]	1'040	1'600	1'090	1'030	1'150

4.2 *Compressive strength*

4.2.1 *Age development of compressive strength*

The age development of the WCC mixtures has been measured from day 1 to day 28 on mortar cubes and from day 14 to day 56 on cylinder specimens (Figure 4). The reference mixture has a compressive strength of 4.9 MPa at 28 days (Zwicky 2015).

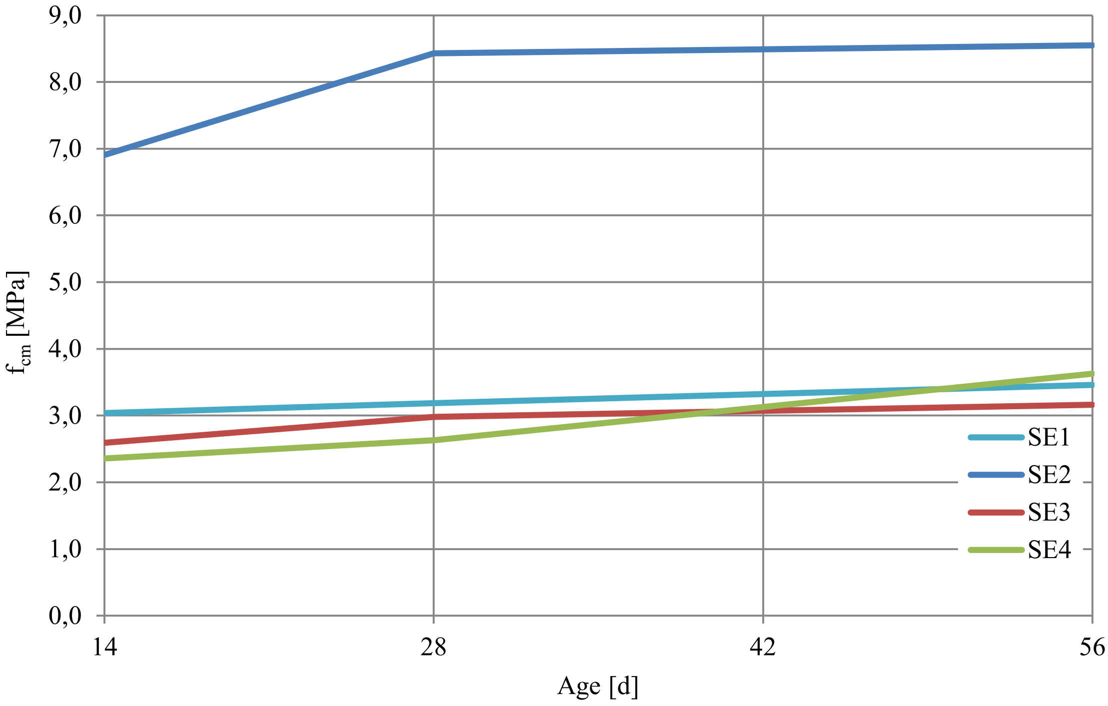

Figure 4: Compressive strength of WCC cylinders at different ages

A comparison with the hardening model for ordinary concrete shows that the model used in EN 1992-1-1 (2004) can be adapted and gives reasonable results, with s-values reported in Table 4.

Table 4: S-values acc. to EN 1992-1-1 (2004) for the analysed WCC recipes

Recipe	SE1	SE2	SE3	SE4
S-value [-]	0.30	0.20	0.30	0.38
Setting speed	Slow	Fast	Slow	Very slow

4.3 *Elastic modulus*

Quantification of elastic modulus of WCCs is difficult as it is typically very low. The forces applied during standard concrete testing are usually not compatible with WCC cylinders.

A modified loading scheme procedure, not including a minimum force of 30 kN, was applied. The measures for the elastic modulus determination are made after 15 seconds waiting time at a defined load level. Before the measurements, two cycles between lower and upper stress level are performed.

Table 5: Elastic moduli of WCC

Recipe	SE1	SE2	SE3	SE4	Ref
AVG [MPa]	1’463	3’615	819	828	2’700
COV	12%	12%	8%	11%	N/A

Table 5 shows measured elastic moduli of the different WCC recipes. There is a significant and repeatable difference between the elastic modulus of the recipes SE1 and SE3 that seems not be reasonably justified by the addition of the shrinkage-reducing agent.

As there is no other difference in these recipes and the measured densities and resistances are nearly identical (compressive and tensile strength), there might be another systematic error in these measures.

As the test results of elastic moduli might be somehow biased by systematic errors, different theoretical approaches to calculate elastic moduli of very lightweight concrete (AAC and foam concrete) are compared to the measured data in Table 6.

Table 6: Measured and calculated E-moduli for WCC-type “foam” concrete

Recipe		SE1	SE2	SE3	SE4
E-Module [MPa]		1’463	3’615	819	828
Tada (1986) [MPa]	Eq. (1)	4’677	7’639	4’939	4’607
McCormick (1967) [MPa]	Eq. (2)	1’980	6’128	2’053	1’765
Jones and McCarthy (2005) [MPa]	Eqs. (3) & (4)	2’153	5’198(*)	2’058	1’893

(*) Jones & McCarthy give different formulas if sand is used as aggregate or not, only recipe SE2 has been calculated with the aggregate formula

Tada (1986) is based on density only:

$$E = 5.31 * W - 853 \tag{1}$$

McCormick (1967) bases on density and compressive strength:

$$E = 33 \; * W^{1.5} * \sqrt{f_c} \tag{2}$$

Jones and McCarthy (2005) have an approach based only on compressive strength, very similar as for ordinary concrete; for concretes with sand aggregates:

$$E = 0.42 * {f_c}^{1.18} \tag{3}$$

Without sand aggregates

$$E = 0.99 * {f_c}^{0.67} \tag{4}$$

Where W is the density, f_c is the compressive strength.

The predictions of the moduli seem to be closest to the McCormick (1967) model, Eq. (2), combining compressive strength and density. Recipe SE2 containing sand is better described with an approach similar to ordinary concrete as used by Jones and McCarthy (2005), Eq. (3).

4.4 *Tensile strength*

Table 12 shows an overview of tensile strength at 28 days. Tensile strength has been tested as flexural strength on mortar prisms (4x4x16 cm^3) and through indirect tensile strength as double punch tests (Chen and Trumbauer 1972).

Table 7: Overview of tensile strengths of WCCs at 28 days

Recipe	SE1	SE2	SE3	SE4	Ref
Average flexural strength [MPa]	2.60	4.18	2.54	2.04	N/A
COV	3%	5%	6%	3%	
Indirect tensile strength [MPa]	0.58	1.25	0.52	0.58	0.50
COV	19%	11%	13%	15%	5%

5 LONG-TERM MECHANICAL PROPERTIES

5.1 *Shrinkage*

Figure 5 shows results for free shrinkage behaviour for the available time of measurements. In an earlier study, shrinkage of WCCs has been identified as a major concern (Zwicky 2015). With the new recipes analysed her, shrinkage could be reduced by a multiple with regard to the reference WCC.

The addition of shrinkage-reducing agents seems to further positively influence the shrinkage behaviour (see SE3 in comparison to SE1). Complementing the WCC recipe with a sand skeleton (see SE2 in comparison to SE1), however, seems even more effective and confirms the initial considerations (section 1.1.2). The final test results, after a measurement period over one year, will be available in spring 2016.

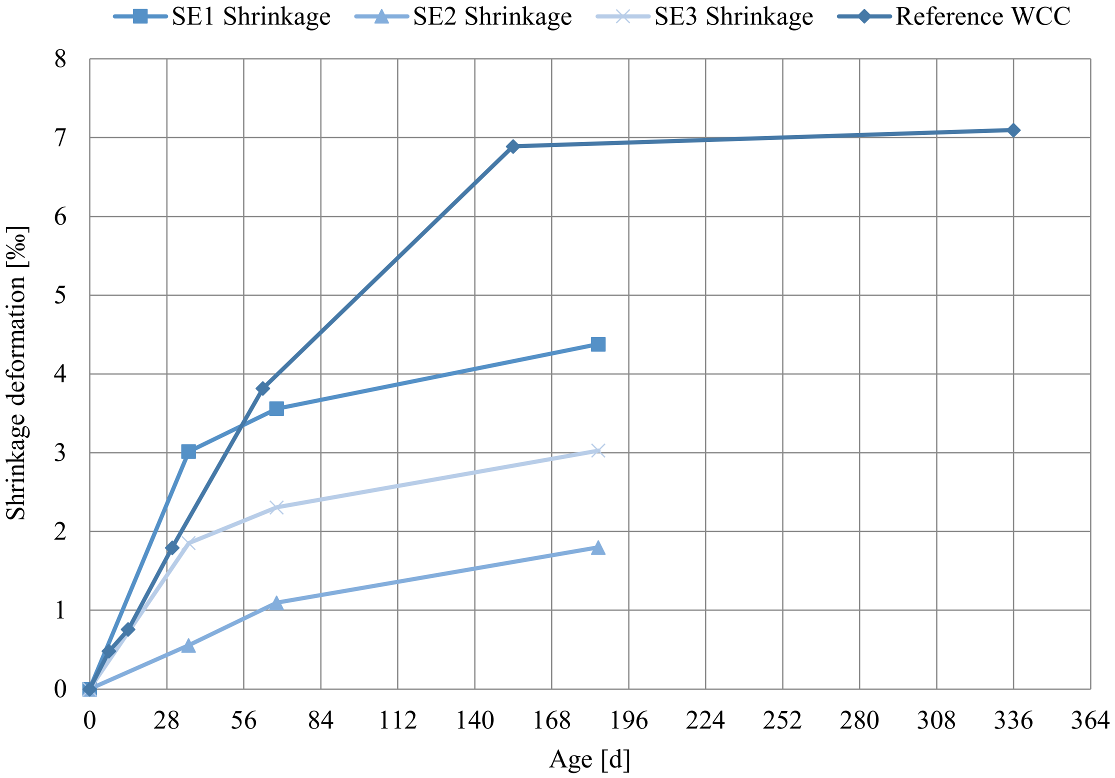

Figure 5: Shrinkage of WCCs after removing from climate chamber

6 CONCLUSIONS

In comparison with previously developed pourable WCC recipes (Zwicky 2015), the WCC recipe refinement reported here shows:

- Naphthalene-based water reducing agents enhance workability as expected and do not interfere with WCC hydration. SCC workability can be achieved in combination with an appropriate filler and sand mixture.
- In comparison to a reference recipe for WCC (recipe 5 from Zwicky 2015), all SE recipes show better workability than the filler-less but comparable mixture (Table 1). Compressive strength of recipe SE1 has dropped to approx. 70% of the reference by replacing 55% of the Portland cement with inert filler, resulting in a comparable density. Material stiffness was roughly halved. These noticeable decreases in mechanical properties are most likely not linear with filler replacement.
- Limestone fillers are, even if they reduce mechanical properties at these high replacement rates, an interesting component for WCC recipes. Probably a lower replacement rate around 20 to 30 % would be more appropriate for minimal strength loss and maximum workability enhancement and clinker replacement.
- Fly ash fillers are even more effective than limestone fillers for enhancing workability. They proof to have reactivity at the high replacement rates used in this study, but need more time for hardening. No significant reduction of mechanical properties between recipe SE1 and recipe SE4 can be observed, except for a somewhat slower hydration pace.

Table 8 shows an overview of the qualitative effects of the different additions.

Table 8: Synopsis of effects towards the objectives of the different additions

	Workability	Shrinkage	Portland cement reduction
Plasticiser	SCC possible	No effect	No effect
Lime filler	Improved	Improved	Possible, but reduction of mechanical properties
Fly ashes	SCC probable	Improved	Replacement of PC possible
Sand skeleton	SCC possible	Improved	No effect
Shrinkage-reducing agent	No effect	Considerably improved	No effect

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