Published in the Proceedings of the 10th Conference on Advanced Building Skins, Berne, Switzerland, 3-4 November 2015, Bern, Switzerland, which should be cited to refer to this work.

Mechanical properties of wood-cement compounds

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Abstract

The most widely used construction material is reinforced concrete which is heavy, has rather high embedded carbon, strongly draws upon non-renewable resources, is challenging to re-use, and exhibits rather poor building-physical properties. A high potential for a more sustainable development of building construction is located in timber-based composite structures. These should be, however, not be produced with regular concrete, as this still introduces the mentioned disadvantages. Mixes of cement with wood components, so-called wood-cement compounds (WCC), may be one of the answers for an even more sustainable evolution of timber-concrete composite construction. Some of the non-renewable parts (gravel, sand) of concrete are substituted with renewable ones in WCCs, with the objective to create a light-weight, pourable, self-compacting, cheap, easily recyclable, and thus, “greener” cement-based construction material that has further benefits with regard to building-physical properties to be exploited in so-called hybrid structural elements. This paper reports on results of laboratory testing for determining short- and long-term mechanical properties of newly developed WCC recipes, i.e. density, elastic moduli, compressive and tensile strength, shrinkage, and creep properties. Furthermore, their economic feasibility is assessed as well and potential challenges in structural applications of WCCs are pointed out.

Keywords: wood-cement compounds, recipes, strength, stiffness, long-term behavior, economic feasibility.

1. Introduction

Timber is a traditional structural material that has multiple benefits for building construction. In addition to being light-weight and a quite good thermal insulator, it is produced from a renewable resource that is currently underused in Switzerland and the recycling of the material is relatively simple, explaining why timber construction currently sees a revival in Switzerland and worldwide.

Timber has, on the other hand, some penalizing disadvantages for the construction of modern multi-story buildings. Achieving acoustic insulation requirements in wooden buildings is challenging and, being a combustible material, fire safety may be an issue as well. Furthermore, timber as a construction material is rather soft, creating potential challenges in serviceability requirement verifications, e.g. displacement (also over time) and vibration control. These were the main reasons for developing timber-concrete composite (TCC) structural elements.

However, from a structural engineering point of view, it seems a bit illogical to combine light-weight timber with heavy-weight concrete being the major part of dead load. Furthermore, concrete has rather high embedded carbon, strongly draws upon non-renewable resources, is challenging to re-use, and exhibits rather poor properties with regard to thermal and acoustic insulation, and thermal storage capacity. Last but not least, the concrete types used today in building construction are essentially far too good from a structural point of view and could potentially be substituted by lower quality products.

1.1 Structural potential of wood-cement compounds

Mixes of concrete with wood components, so-called wood-concrete compounds (WCCs), may be one of the answers to the challenge of a more sustainable evolution of TCC construction.

Cement-bonded wood-based materials are already used in construction since the beginning of the 20th century [1]. Until today, however, they are essentially applied as non-structural finishing layers, e.g. as support for stucco, as fire protection or acoustic insulation panels, providing good fire resistance, thermal and acoustic insulation properties [2],[3] with a relatively low and thus, structurally advantageous material density. These materials, however, also exhibit rather low stiffness and strength properties and may show long-term form stability issues.

By placing WCC in the compressive layer of a timber-WCC composite (TWC) element, it may be possible to increase the structural stiffness while maintaining the element relatively light-weight and the ease of recyclability of traditional timber structures. By combining timber with WCCs in the construction of the (internal) primary, load-bearing system, the structural challenges of both materials may potentially be mitigated.

1.2 Building-physical potential of hybrid construction

It should also be possible to create elements with high thermal inertia which is particularly important for decreasing the energy consumption by heating and cooling systems in a building, as it is becoming more and more important in building-physical concepts and verifications for user comfort and heating requirements. Heating and cooling energy demands during service life usually are the governing parameter in life-cycle analyses [4]. In such an application, the lower thermal conductivity of WCC is advantageous to retain the stored thermal energy.

By doing so, hybrid structural elements are created [5],[3], i.e. TWC elements which not only fulfill a structural task but also provide further architectural or building-physical performances, respectively. These elements are similar to traditional TCC construction, but have much less demand on the secondary structure, as fire protection and a part of the acoustic and thermal insulation cladding is already integrated.

1.3 Economic and ecological requirements

Replacing non-renewable aggregates in concrete by cheap wood waste allows gaining an ecological advantage, and increases the added value by using by-products of the wood processing chain, such as (glue contaminated) sawdust, wood chips, wood strands etc. A further benefit is that the wooden aggregates also act as CO_2 storage by immobilizing the one present in the wood for decades. The thermal energy retrieved by combustion of WCCs [6] at the end of the service life further partly solves another challenge of sustainable construction, i.e. the treatment of construction waste.

Today, the main commercially available forms of cement-bonded wooden materials are prefabricated panels (Heraklith®, Velox®, Isospan®, Durisol®, Agresta® etc.). These products use wood waste but treat it (sometimes) in quite sophisticated processes, making them rather expensive. Furthermore, their application in structural TWC elements is only possible by using appropriate bonding methods, i.e. epoxy-based adhesives or similar. This kind of products has an unfavorable eco-balance [7], is expensive, may not provide the desired structural performance (i.e. plastic deformation capacity in structural elements) and may also create potential challenges in thermal recycling. Furthermore, the use of adhesives in the fabrication process implies an additional work stage with associated cost and potential fabrication faults which may also have consequences for structural safety and reliability of the elements.

From economic, ecological and production points of view, WCCs should thus be cheap, pourable, self-compacting, and hardening reasonably fast as their main application potential lies in prefabricated elements for dry modular building construction. Such materials should also be easy to recycle or dispose of a good eco-balance, respectively. The challenge, however, is finding suitable WCC compositions that solve the problem of delayed concrete hardening due to the natural sugar contained in wood.

2. WCC recipe development

For cost effective use of WCCs as a primary structural material, pourable WCCs have been developed [8] which can be handled like concrete or mortar, inspired by earlier research [9].

WCC recipes based on sawdust and mineralized wood fiber were analyzed, Table 1, including a commercially available product (Agreslith®). Different binders (standard Portland cement and aluminate cement) and wood/cement ratios were considered.

The idea behind using aluminate cement instead of regular Portland cement or active charcoal (chosen at a ratio of 5% cement content), respectively, is to accelerate hydration [10], being initially slowed down due to the natural sugar contained in wood. WCC recipes with a wood/cement ratio $t/c = 0.33$ were formulated to reach a water/cement ratio $w/c = 0.55$ while WCC recipes with $t/c = 0.20$ targeted $w/c = 0.35$.

WCC	Saw dust*	Sand	CEM I 52.5	CEM II 42.5N	Aluminate cement	t/c**	Active charcoal	Net water	Agreslith®
1	105 kg	--	340 kg	--	--	0.33	--	190 kg	--
2	105 kg	--	340 kg	--	--	0.33	17 kg	190 kg	--
3	105 kg	--	--	--	340 kg	0.33	--	190 kg	--
4	105 kg	--	240 kg	--	100 kg	0.33	--	190 kg	--
5	110 kg	--	540 kg	--	--	0.20	--	190 kg	--
6	110 kg	--	540 kg	--	--	0.20	27 kg	190 kg	--
7	110 kg	--	--	--	540 kg	0.20	--	190 kg	--
8	--	350 kg	--	300 kg	--	--	--	180 kg	150 kg

* dry weight ** wood/cement ratio

Table 1 Composition recipes per m^3 of tested WCCs.

The first phase of the WCC recipe development targeted preliminary assessment of structural and economic properties, and associated results are reported hereafter. Further potential benefits of the new structural material, such as acoustic and thermal insulation properties and thermal storage capacity, are currently evaluated in explorative tests (summer 2015). Already concluded tests for thermal and acoustic insulation properties of TWC elements using prefabricated WCC panels [11] allow first insights on the potential building-physical performance of WCCs.

3. Mechanical properties of pourable WCCs

3.1 Workability and appearance

Figure 1 shows the specimens' appearance for the different WCC recipes. The visual aspect is quite similar to regular concrete, apart from a somewhat yellower or browner color.

Workability of the commercial WCC Agreslith® mix was very poor, due to the fibrous nature of the aggregates. The mineralized fibers have a length of approximately 10 times the diameter while sawdust has no obvious orientation in its granulometry. Figure 2 shows results of a sieve test for the two wood components.

Agreslith *Recipe 1* *Recipe 2* *Recipe 3*

Recipe 4 *Recipe 5* *Recipe 6* *Recipe 7*

Figure 1 Visual aspects of hardened WCC specimens from different recipes.

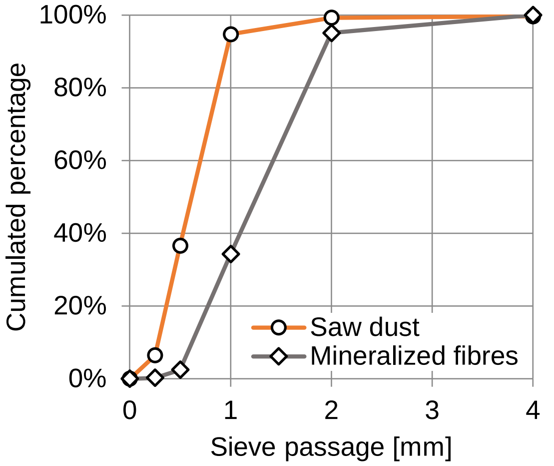

Figure 2 Granulometry of mineralized wood fibers and saw dust used in tests.

Slump test results for the other recipes WCC1 to WCC7 were in the range of S3 to S4 [12], indicating a good workability but self-compaction properties could not be attained yet.

Refined WCC recipes have been developed [13] in the meantime, targeting improvement of self-compacting properties and other structural and ecological performance properties. As further contributions [6],[14] in the session associated with this article refer to the first generation of developed WCC recipes, these results are not shown here.

3.2 Short-term mechanical properties

Evaluation of mechanical properties of the developed WCC recipes was performed through standardized tests on cylinder specimens, primarily targeting determination of density and mechanical strength. All tests were performed at a specimen age of 28 days.

3.2.1 Density

Table 2 summarizes density results. The measured densities represent nearly saturated specimens, after being stocked in a very humid climate for 28 days. For recipes 1, 5 and 6, the dry weight was determined as well, indicating that the moisture content may be up to 24% [15].

WCC	1	2	3	4	5	6	7	8
AVG [kg/m^3]	1’125	1’209	1’184	989	1’149	1’324	1’233	1’385
COV	0.4%	1.1%	0.6%	5.7%	0.4%	1.1%	1.4%	2.5%

Table 2 Density of tested WCCs.

The density of the WCC recipe with a commercial product (WCC8) is considerably beyond the targeted density of 800 kg/m^3 according to the supplier and results variability is considerably higher than for other recipes (except WCC4). Own recipes, Table 1, show rather low densities between approx. 1’000 and 1’300 kg/m^3 and exhibit very low variability (except WCC4).

It seems paradox that, for somewhat lighter WCCs with t/c = 0.33 (WCC1 to WCC4), there is less wood present per volume, Figure 3. This is explained by a much higher porosity of the hardened WCCs. The resin contained in the (spruce) sawdust works as an air entraining agent for the cement paste [9]. The recipes were formulated by weight, with corrections for humidity contained in the sawdust.

Volume predictions for the different recipes are difficult due to this air entraining effect. Furthermore, resin content of the sawdust depends on multiple factors, such as wood harvesting season, humidity and other stocking conditions. Active charcoal (WCC2 and WCC6) reduces the air entraining effect of the resin.

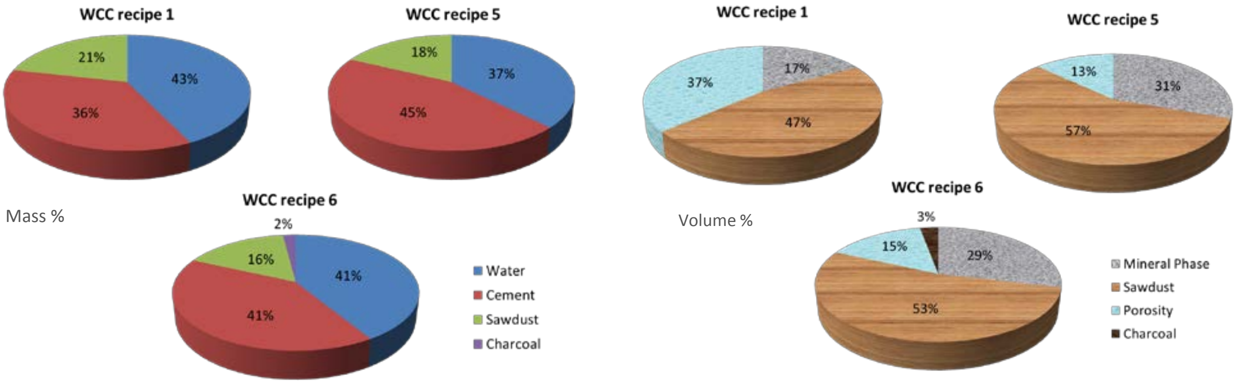

Figure 3 Mass and volume distribution of components in selected WCC recipes.

3.2.2 Compressive strength

Compression tests according to EN 12 390-3 [16] were performed on cylinders with 150 mm diameter and a height of 300 mm, Table 3.

WCC	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
AVG [MPa]	2.1	3.3	1.0	0.2	4.9	6.8	1.2	4.9
COV	0.3%	4.5%	18%	4.5%	6.4%	5.5%	3.1%	20%

Table 3 Compressive strength of tested WCCs.

Result variability of sawdust-based recipes (except WCC3) are very low in comparison to the commercial mineralized fiber product. Note that COVs for regular concrete usually vary between 10% and 25%, decreasing with increasing compressive strength.

WCC recipes with Portland cement (WCCs 1, 2, 5 and 6) perform better than the ones with aluminate cement (WCCs 3, 4 and 7). Compressive strength and density correlate quite linearly, i.e. the denser is the WCC, the higher is his compressive strength. The mineralized fiber compound is below this general trend [8].

3.2.3 Tensile strength

The tensile strength was evaluated by indirect double punch test [17]. The samples were obtained from cutting cylinders of 150 mm diameter and 300 mm height in half. Table 4 summarizes the results.

WCC	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
AVG [MPa]	0.3	0.4	0.1	--*	0.5	0.8	0.2	0.8
COV	7%	4%	15%	--*	5%	2%	1%	12%

* too low to be measured correctly with used test setup

Table 4 Tensile strength of tested WCCs.

As could be expected, the average strength values of the different WCCs are very low. Nevertheless, the COVs are quite small (except for WCC3) in comparison to regular concrete where a COV of approx. 18% usually has to be anticipated. The tensile strength of WCCs corresponds, on the average, to approx. 60% of the tensile strength that would be expected for a regular light-weight concrete of the same compressive strength. The ratios between experimental and expected average tensile strength vary between approx. 30% and 90% and tend to increase with increasing tensile strength.

3.2.4 Elastic modulus

The experimental determination of elastic modulus of WCCs is quite challenging, considering their low compressive strength. Standardized test procedures demand applying a certain percentage of the (a priori expected) compressive strength. Habitually available testing equipment with standardized protocols, however, may require a minimum compression force (for obtaining reliable test data) which is already far beyond the targeted stress level.

Further investigations of the compressive behavior of WCCs allowed to determine elastic moduli for selected WCC recipes. Average values vary between 900 MPa (WCC1) and 2’700 MPa (WCC5), and correspond to only a fraction of what would be expected for a regular light-weight concrete of the same compressive strength.

3.2.5 Preliminary economic evaluation

In general, the WCC recipes 1 to 7 containing untreated wood particles did not provide worse results than WCC8 with mineralized, i.e. treated, wood fibers. The main economic challenge with treated wood matter is, however, associated to its price. It is intuitively obvious that treating a low cost material in a sophisticated process (i.e. mineralization of wood fibers from wood production chain waste, in this case) will always increase its price by several multiples. With this in mind and also considering the poor overall performance, the economic competitiveness of WCC8 was not further studied.

The mechanical performance of the pourable WCCs is quite low, even for light-weight concrete criteria. To assess their economic performance, not only the absolute price should be considered but the overall

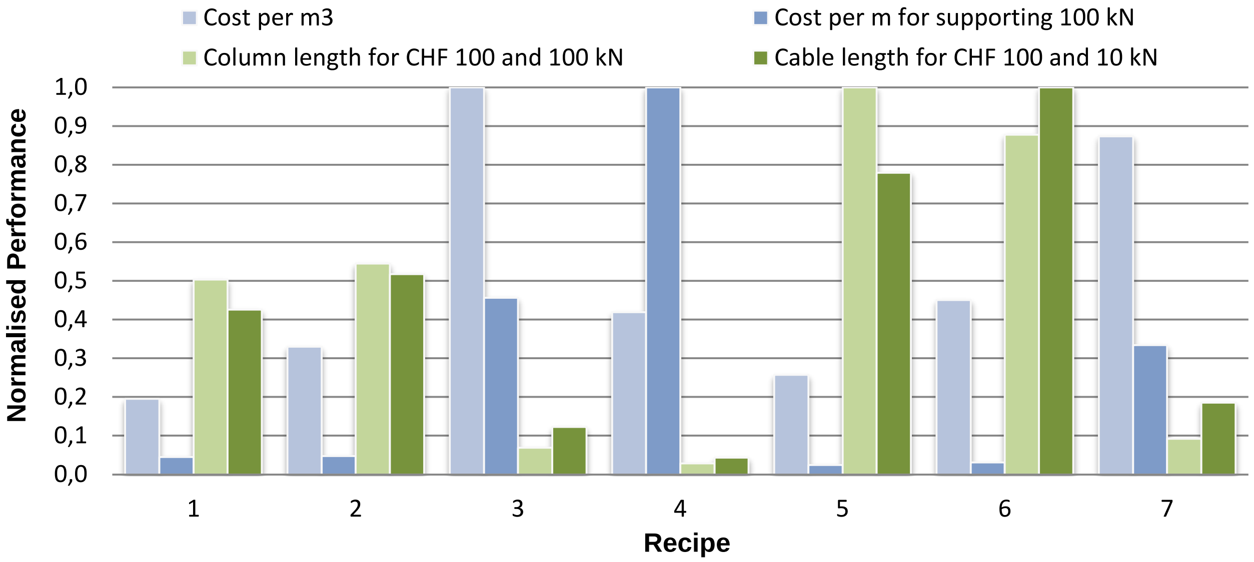

Figure 4 Econo-mechanical performance of developed WCC compositions.

performance, also considering their low density and ecological criteria [18]. In the evaluation of complete structural elements or building parts, it should further be considered that the use of WCCs may be additionally advantageous due to their further benefits, e.g. contributions to thermal and acoustic insulation [11],[19].

First insights on the competitiveness of the developed WCC recipes were gained by four indicators, Figure 4:

- *Cost per m³*: The cost per m³ is normalized to the highest value in the series (i.e. the lower the performance, the better). WCCs 1, 2, 4, 5 and 6 perform clearly better than WCCs 3 and 7.
- *Cost per m* for supporting 100 kN of compression load: the cost for a WCC wall section resisting 100 kN of compressive load is normalized to the highest value in the series (i.e. the lower the performance, the better). WCCs 1, 2, 5 and 6 perform clearly better than WCCs 3, 4 and 7.
- *Possible column length* for CHF 100 and an applied load of 100 kN: the length of a column (neglecting stability problems) resisting 100 kN of compressive load, while considering the respective WCC density, that costs CHF 100 is normalized to the longest length in the series (i.e. the higher the performance, the better). WCCs 5 and 6 perform clearly better than the other WCC compositions.
- *Cable length* for CHF 100 and an applied load of 10 kN: the length of an tension element resisting 10 kN tensile load, while considering the respective WCC density, that costs CHF 100 is normalized to the longest length in the series (i.e. the higher the performance, the better). WCCs 5 and 6 perform clearly better than the other WCC compositions.

As a consequence of this evaluation approach, WCC recipes 1, 5 and 6 were chosen for further studies, for being light-weight and cheap (WCC1), for reasonably well performing for compressive loadings (WCC5) and for best overall econo-mechanical performance (WCC6).

Absolute cost per m³ of the selected WCC recipes were estimated at approx. CHF 200 (WCC1), CHF 260 (WCC5) and CHF 460 (WCC6). Note, however, that these are cost for laboratory specimens.

3.3 Long-term properties

As WCCs are not widely used for structural applications yet, little is known about their long-term structural behavior. Both, concrete and timber, shrink and creep (or rather, in the case of timber, geometry changes due to hygroscopic behavior), and thus, it may reasonably be expected that WCCs show similar long-term behavior.

With this in mind, long-term tests according to the standardized testing procedure for concrete [20] were performed. In these tests, longitudinal deformation changes of concrete prisms with dimensions of 120 mm x 120 mm x 360 mm are monitored during one year. Creep deformations are measured at a load level of ca. 30% of compressive strength while an unloaded reference specimen group is monitored for shrinkage deformations. Creep loading is applied at an age of 28 days while shrinkage deformations are also monitored during the initial four weeks, i.e. over a complete year.

3.3.1 Shrinkage

Figure 5 shows the deformations due to shrinkage. The tests were performed from August 2013 to August 2014.

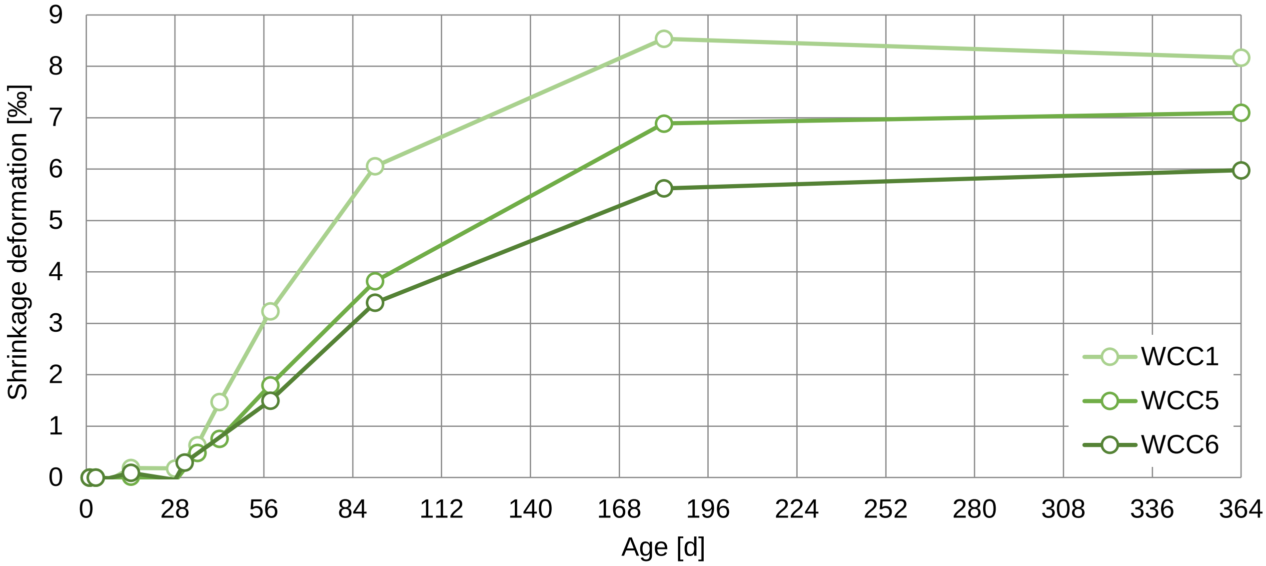

Figure 5 Shrinkage behavior of selected WCCs.

Considerable shrinkage of the specimens started as soon as ambient humidity decreased. Up to 28 days, the prisms were stored in a controlled climate chamber at 24°C and 90% RH. With the start of the creep tests, the shrinkage prisms were placed near the creep testing rig in the laboratory where ambient humidity is considerably low, especially during winter time.

This result indicates that autogenous shrinkage is of minor importance but that the major part of shrinkage is due to the drying process. In the latter, the water pressure in relation to the pore volume plays a major role. The pore volume is obviously related to the density, i.e. the higher the density, the lower the shrinkage deformations. The results in Figure 5 show that WCC1, with the lowest density (Table 2), shrinks the most while the heaviest WCC 6 (still, with a humid density of approx. 1’300 kg/m^3 only) shrinks about 25% less. The small reduction in shrinkage deformation of WCC1 over the last half year is attributed to temperature changes (or the associated humidity change, respectively) in the laboratory from winter to summer.

In general, it can be concluded that shrinkage deformations of WCCs are very high, in comparison to typical values of 0.3…0.4‰ for regular concrete and also in comparison to light-weight concrete where shrinkage deformations are approx. 50% higher than for regular concrete of the same compressive strength [21].

The experimental results also show that the major part of shrinkage deformation (if not all) takes place in the first six months. This was an important conclusion for the 2nd phase of the research project where the long-term behavior of complete structural TWC elements will be investigated in full-scale flexural tests (starting in September 2015).

In the follow-up, the experimental results for shrinkage behavior shall be approximated by analytical expressions to extrapolate to a service life of 30 to 50 years. Also note that the WCC recipe formulations have been refined in the meantime w.r.t. reduction of shrinkage deformations [13], see section 3.1.

3.3.2 Creep

As explained above, the creep behavior of the selected WCC recipes has also been investigated in parallel to the shrinkage tests. The final test results over the entire test period are presented in Figure 6, showing creep coefficients, i.e. additional deformations due to creep expressed as a function of the initial elastic deformation at the time of creep load application: $\varphi(t) = \varepsilon_c(t))/\varepsilon_{c,28} - 1$. Absolute values of creep deformation were rather high but should also be related to the low elastic moduli of WCCs (section 3.2.4).

WCC1, with the lowest density, only results in an average creep coefficient while WCC6, with the highest density, not only provides the lowest shrinkage but also creeps the least. Hence, there is no direct relation

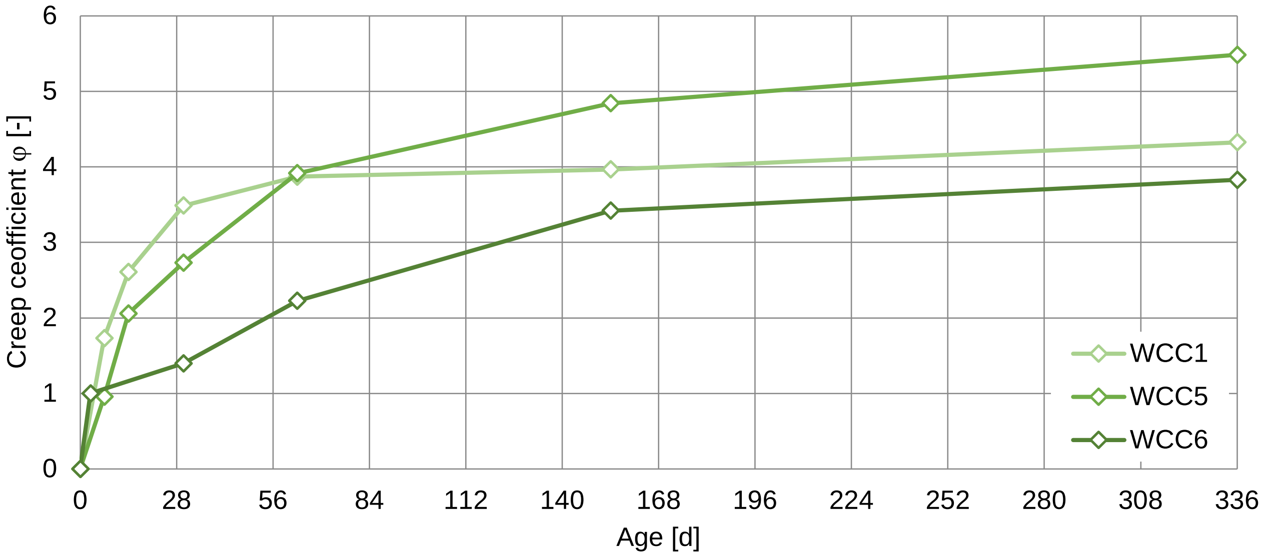

Figure 6 Creep behavior of selected WCCs.

between creep coefficient and density. The unexpected “kink” in the beginning of the curve for WCC6 is related to a temporary leakage in the hydraulic testing rig.

The creep coefficients of WCCs are considerably higher than habitual creep coefficients for regular concrete, being around 1.6 for the same load duration. Light-weight aggregate concrete should even exhibit creep coefficients approx. 50% lower than those of a normal-weight concrete of the same resistance [22]. The experimental creep coefficients of WCCs are also higher than usual creep coefficients for timber of 1 to 1.5.

The major part of creep deformations also takes place in the first six months. Again, this is an important conclusion for the 2nd phase of the project where the long-term behavior of complete structural TWC elements will be investigated experimentally and analytically.

The experimentally derived results for the creep behavior shall also be approximated by analytical expressions for extrapolations to a service life of 30 to 50 years. Results on the shrinkage and creep behavior of improved WCC recipes were also collected in the associated project [13], see section 3.1.

4. Potential challenges in structural applications of WCCs

As mentioned above (section 1.1), the major potential for structural applications of WCCs is in composite elements together with timber. Potential structural engineering challenges are located in the following domains:

- *Fabrication* of structural elements: self-compaction of pourable matter nowadays is almost a must for economic pre-fabrication of structural elements, as most suppliers eliminated their vibrating tables due to the availability of self-compacting concrete. Early shrinkage properties of WCCs should also be considered in the conceptual design, definition of tolerances and camber. Reinforcement of WCC layers may be required, but WCC recipe formulations must also be further developed to reduce shrinkage [13].
- *Short-term stiffness* of structural elements: the material stiffness of WCCs is considerably lower than what the practical engineer is used to. The low elastic modulus of WCCs requires larger cross-sections but this must not necessarily lead to low economic competitiveness as the WCC layers also contribute to the building-physical performance, resulting in reduced (potentially even eliminated) cost for the secondary structure necessary to satisfy requirements w.r.t. acoustic and thermal insulation.
- *Long-term behavior* of structural elements: shrinkage deformations of WCCs are high. As a consequence, these imposed deformations must definitely be considered in the structural design of TWC elements. However, the influence of WCC shrinkage on the behavior of complete structural elements should also be evaluated in this context, i.e. also considering the low material stiffness of WCC and its ratio to the stiffness of timber components in a composite structural element. One should further be aware of the fact that imposed deformations due to shrinkage usually are considerably reduced or even eliminated by the formation of one or to cracks. If these are forced to form at pre-defined locations, they may even be

tolerated. Absolute values of creep coefficients are high, too, and must also be considered in structural design. This again, should be analyzed in the context of complete composite structural elements, i.e. also considering the usually rather high creep deformation of timber as well as the stiffness of all involved materials.

- *Strength* of structural elements: as it is the case for the application of regular (light-weight) concrete in TCC elements, WCCs should primarily be applied in the compression zone of structural elements. They may further serve as shear core in surface elements (i.e. floor slabs or wall elements subjected to transverse loads) where the internal stresses will remain relatively low due to the high quantity of available material.
- *Structural design*: as the evaluation of experimental results showed, code rules for light-weight concrete, e.g. [21],[22], cannot be applied to estimate mechanical short- and long-term properties of WCCs. Existing structural analysis approaches, particularly considering the influence of the interface behavior between timber and WCC (e.g. [23]), may probably be applicable to TWC elements as well. However, experimental verification of new conceptual designs and associated structural design recommendations are required. More information on experimental behavior of load-bearing TWC wall elements are provided in [14].

5. Conclusions

Wood-cement compounds (WCCs) have a great potential for being applied in structural elements as a new kind of very light-weight structural concrete. With increased experience in the fabrication of WCCs, the average humid densities of the more profoundly studied WCC recipes could be further reduced to 510 kg/m^3 (WCC1), 890 kg/m^3 (WCC5) and 990 kg/m^3 (WCC6).

Principally, WCCs should not be seen as an alternative to regular structural concrete – as stiffness and strength of WCCs are low – but should essentially be applied in structural elements with composite action, e.g. together with timber or other light-weight structural elements (to not unnecessarily increase the overall weight). Shrinkage and creep deformations of the newly developed WCCs are high which may result in specific structural verification challenges, and require further improvements by refining WCC recipe definitions.

WCCs provide good fire resistance, acoustic insulation, and thermal insulation and inertia which can be exploited in the conceptual design of hybrid structural elements, i.e. elements which not only fulfill a structural task but also provide further architectural, building-physical or fire-safety performances, respectively.

From economic and ecological points of view, complete construction elements should be evaluated, e.g. not only considering construction volumes and associated prices of the load-bearing elements, but also decreased cost for secondary construction elements (i.e. finishing layers for acoustic and thermal insulation, and for fire protection). This essentially corresponds to economic and ecological evaluations in life-cycles.

From a production point of view, WCCs should be pourable, self-compacting, and hardening reasonably fast as their main application potential lies in prefabricated elements for dry modular building construction. In this contribution, three different WCC recipes were analyzed in more detail, for being light-weight and cheap (WCC1), for performing reasonably well for compressive loadings (WCC5) and for best overall econo-mechanical performance (WCC6).

Acknowledgments

The funding received from the national research program 66 ‘Resource Wood’ [grant no. 406640_136918/1] of the Swiss National Science Foundation is gratefully acknowledged. This research project is a collaborative effort of the School of Engineering and Architecture of Fribourg and Vienna University of Technology. The authors also wish to thank the University of Applied Sciences of Western Switzerland for the additional financial support and our industrial partners ERNE AG and VIAL SA for their support and expertise in conceptual design and provision of test specimens.

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