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MULTI-FUNCTIONAL FEATURES OF POURABLE WOOD-CEMENT COMPOUNDS – MECHANICAL, BUILDING-PHYSICAL, ECONOMIC AND ECOLOGICAL PERFORMANCE

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ABSTRACT: Cement-bonded wood products are used in construction since the beginning of the 20th century. 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 with a relatively low and thus, structurally advantageous material density. If to be applied structurally, these materials should not be regarded as substitution material for regular structural concrete but rather be used in composite elements. They also exhibit rather low stiffness and strength properties.

Structural wood-cement compounds (WCCs) may also provide further functional features e.g. contributing to thermal and acoustic insulation or fire protection, thereby compensating for their reduced mechanical properties. The contribution presents results from different tests performed with the objective to determine short- and long-term mechanical properties, thermal insulation, specific heat capacity, acoustic insulation, and combustibility features of WCC-based constructions. It further examines and assesses the economic and ecological potential of WCC-based structural elements and discusses potential challenges in the structural use of WCCs.

KEYWORDS: wood-cement compound, structural properties, short-term, long-term, building-physical properties, combustibility, economic performance, ecological performance.

1 INTRODUCTION

The most widely used construction material is reinforced concrete which is heavy, has high embedded carbon, strongly draws upon non-renewable resources, is challenging to re-use, and exhibits rather poor building-physical properties (except for specific heat capacity).
A high potential for a more sustainable construction development of building is located in timber-based composite elements. These should, however, not be produced with regular concrete, as this still results in the mentioned disadvantages. Mixes of cement with wood components, so-called wood-cement compounds (WCCs), may be an answer for an even more sustainable evolution of timber-based composite construction. Some of the non-renewable parts (gravel, sand) of concrete are substituted with renewable ones, with the objective to create a light-weight, pourable, self-compacting, cheap, easily recyclable, and thus, "greener" cement-based construction material that also provides further benefits with regard to building-physical properties to be exploited in multi-functional structural elements.
This contribution summarizes and complements previous research [1]-[11], and analyzes the potential and challenges of WCC application in timber construction in view of the expected WCTE audience.

2 CONCEPTUAL REFLECTIONS

Timber-WCC composite (TWCCC) elements may be an answer to the challenge of finding TCC elements which are more sustainable. Nowadays, WCC elements are usually used as non-structural finishing layer such as fire protection or acoustic insulation panels.
As WCC shows rather low stiffness and strength properties [4], this material should be placed in the compressive layer of a TWCCC slab. This allows to increase the stiffness while maintaining a light-weight construction element. Furthermore, it is still possible to recycle the whole element. By combining WCC with timber for internal load-bearing systems, the advantages of both materials may be coupled. Such hybrid elements [8] not only fulfil a structural task but merge all advantages - e.g. fire resistance, thermal and acoustic insulation - of each material (timber and WCC).
The low thermal conductivity of WCC allows to retain the stored thermal energy which has a positive effect on life-cycle assessments (LCA). The demand of thermal energy

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during service life is usually the governing parameter in LCAs [11].
WCC materials contain cheap wood waste which allows to replace non-renewable aggregates in order to gain an ecological advantage compared to traditional concrete. Furthermore, the wooden aggregates act as CO_2 storage and at the end of life cycle, the wooden aggregates can be combusted [5]. This solves another challenge of sustainable construction, i.e. the treatment and recycling of construction waste.
Contrary to other cement-bonded wooden materials (Agresta®, Durisol® etc.), the wood waste for the present WCC does not require any pretreatement. Therefore, the mixing process of WCC does not create additional costs. The WCC used for TWCCC slab elements and WCC wall elements thus remains cheap and pourable and presents many ecological advantages compared to traditional TCC elements.

3 MECHANICAL PROPERTIES

3.1 SHORT-TERM PROPERTIES

This section summarises the main mechanical properties of the investigated WCC. The WCC recipes are the same as those presented in [4].

3.1.1 Workability

The workability of all tested WCC recipes (WCC1 to WCC7) is quite good. This is due to the fact that saw dust has no distinct orientation in its granulometry. Slump test results shows that all WCC recipes can be classified in range S3 to S4 [13]. This proves good workability but, unfortunately self-compacting properties have not been attained yet.

For practical applications, it is necessary that the WCCs show self-compacting properties. This goal has been achieved by developing new recipes [3].

3.1.2 Density

The tested specimens have been stored in thus humidity chamber for 28 days, the specimens were nearly saturated. The following table shows the test results where WCC8 has been made with a commercial product [4]. Note that dry densities are 20…25% lower than humid density [5].

Table 1: *Density of tested WCCs*

	WCC1	WCC2	WCC3	WCC4
AVG [kg/m^3]	1125	1209	1184	989
COV	0.4%	1.1%	0.6%	5.7%
	WCC5	**WCC6**	**WCC7**	**WCC8**
AVG [kg/m^3]	1149	1324	1233	1385
COV	0.4%	1.1%	1.4%	2.5%

Obviously, WCCs have a much lower density than concrete (2400 kg/m^3) but similarly to lightweight concrete (800…1500 kg/m^3).

The density depends primarily on resin contained in the sawdust acting as air entraining agent in the WCC (i.e. creating porosity) [4].
A remaining challenge is the density prediction of WCC because this mainly depends on this entrained air.

3.1.3 Compressive and tensile strength

For each WCC recipe, compression tests according to EN 12 390-3 [14] were performed. Table 2 shows the results.

Table 2: *Compressive strength of tested WCCs*

	WCC1	WCC2	WCC3	WCC4
AVG [MPa]	2.1	3.3	1.0	0.2
COV	0.3%	4.5%	18%	4.5%
	WCC5	**WCC6**	**WCC7**	**WCC8**
AVG [MPa]	4.9	6.8	1.2	4.9
COV	6.4%	5.5%	3.1%	20%

The saw dust content has no major influence on compressive strength but the type of cement (Portland or aluminate cement) plays a central role. Generally, WCCs with Portland cement present a better performance [4].

To determine the tensile strength of WCCs, double punch tests have been performed. The specimens had a diameter of 150 mm and a height of 150 mm. As expected, the average tensile strength of the tested WCCs is rather low, Table 3 [4].

Table 3: *Tensile strength of tested WCCs*

	WCC1	WCC2	WCC3	WCC4
AVG [MPa]	0.3	0.4	0.1	-
COV	7%	4%	15%	-
	WCC5	**WCC6**	**WCC7**	**WCC8**
AVG [MPa]	0.5	0.8	0.2	0.8
COV	5%	2%	1%	12%

WCC4 could not be tested with the chosen test set-up [4].

Compressive and tensile strength are rather low compared to lightweight concrete or timber. It remains a particular challenge to increase compressive and tensile strength without losing the advantages – e.g. fire resistance, ecological performance, acoustic and thermal insulation etc. – and to maintain a lightweight WCC.

3.1.4 Elastic modulus

The elastic modulus has only been evaluated for two WCC recipes, WCC1 and WCC5. The econo-mechanical properties [4] and the workability indicate that these two recipes show the most promising performance [4]. In comparison with the other recipes, WCC1 and WCC5 contain no aluminate cement or active charcoal.
However, due to the low compressive strength, a standardized experimental determination of elastic modulus was not possible. Further investigations of WCCs' compressive behavior allowed to determine the

elastic modulus of the chosen WCCs, being about 900 MPa (WCC1) and 2700 MPa (WCC5), respectively. The elastic modulus of WCC is lower than the elastic modulus of timber or lightweight concrete.

The elastic moduli have been improved with the new WCC recipes described in [3] by adding sand.

The constitutive modelling of WCCs is similar to lightweight concrete. The pre-peak behavior is represented by a parabolic function and the post-peak behaviour (unloading module) by a linear function.

3.2 LONG-TERM PROPERTIES

3.2.1 Shrinkage

As WCCs are habitually used as secondary structure, little is known about their long-term structural behavior. Therefore tests have been made with the standardized long-term testing set-up for concrete.
The specimens have been observed during one year. The tests included the measurement of creep deformation and a reference specimen group for shrinkage deformation.
The following figure shows the evolution of shrinkage deformation during one year.

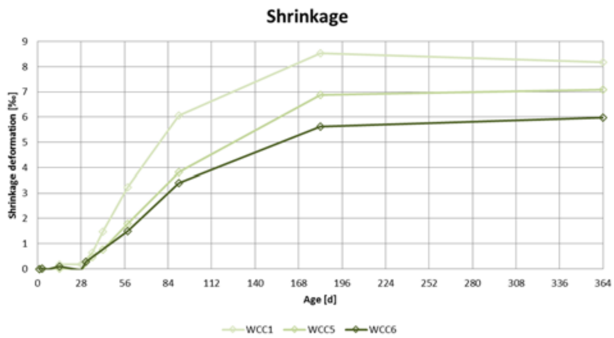


Figure 1: *Shrinkage behavior of tested WCCs*

The deformation initiates after 28 days after the specimens have been moved from the climate camber to the laboratory with ambient humidity. Obviously, the major part of shrinkage is due to the drying process while autogenous shrinkage is of minor importance [4]. The shrinkage deformation of all WCCs is high compared to regular lightweight concrete which is characterised by a value about 0.4…0.6 ‰. Density seems to influence shrinkage, i.e. the lower density, the higher shrinkage.

The addition of shrinkage-reducing agents in the further developed WCC recipes reduce shrinkage deformation by a multiple in comparison to the results shown above [3].

3.2.2 Creep

To determine the creep coefficient, specimens were loaded at 30% of compressive strength. The creep coefficients are rather high but this value should also be related to the corresponding low elastic modulus. Furthermore, the results show that WCC density cannot be related to creep coefficient in the sense of low density corresponds to high creep coefficient.

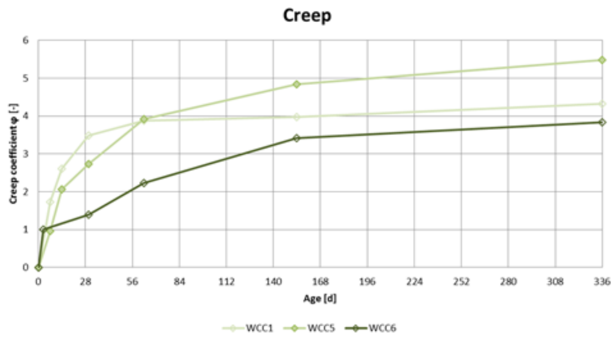


Figure 2: *Creep behavior of tested WCCs*

The creep coefficient of regular concrete normally is around 1.6 after 1 year and lightweight concrete should even reveal creep coefficients which are 50% lower than those of a regular concrete [4]. WCCs creep coefficients are also considerable higher than those of timber which usually are around 1 to 1.5. An analytically approximation allowed to extrapolate the creep coefficients to service lifes of 20 or 50 years. These values varies between 5.4 and 7.1 for WCC1, 9.6 and 13.6 for WCC5 and 7.1 and 7.7 for WCC6, respectively.

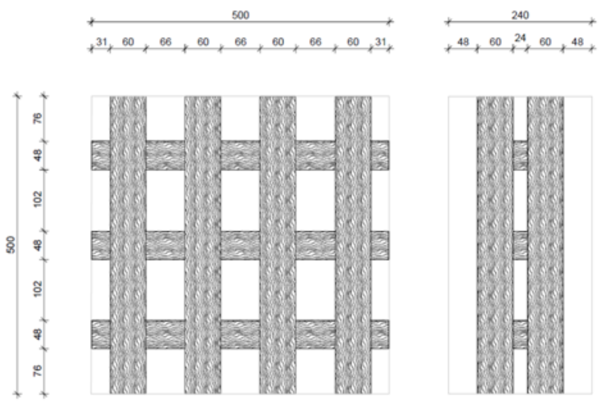
It must be a goal to reduce WCCs creep coefficient for future applications but these parameter could not be studied yet.

4 BUILDING-PHYSICAL PROPERTIES

A great advantage of WCCs are their thermal and acoustic insulation properties. To provide insight of this the behavior of the material, several tests have been performed to determine the representative parameters.

4.1 THERMAL INSULATION

The thermal insulation test series included two geometrically different wall types with the same WCC recipe (WCC1) but containing different timber grids. Besides this, WCC1 and WCC5 have been tested without any timber grid. The wall thickness and its timber grid depends on the number of stories desired (20 cm wall for 3 stories, 24 cm wall for 6 stories) [2]. Figure 3 shows the geometry of the two different wall type specimens for thermal insulation tests.



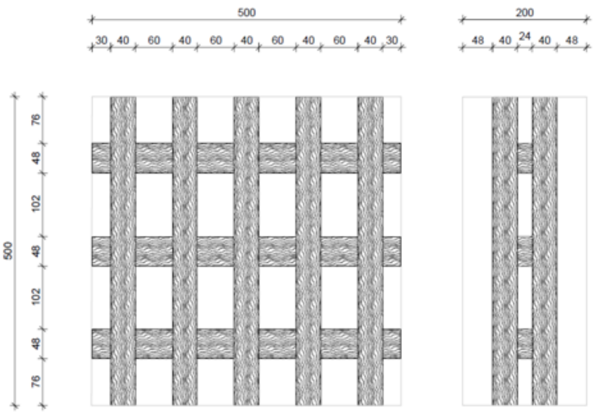


Figure 3: *Timber grids in 24 cm wall (above) and 20 cm wall (below)*

Test results show that the thickness of the wall surprisingly has no major impact on thermal resistance. The small difference between the two wall types can be attributed to geometry differences of the vertical battens and material distribution in the middle layer. This implies that the vertical battens act as thermal bridges as their thickness is the only changing parameter.
Table 4 shows average results of thermal resistance (R_t) and thermal conductivity ($\lambda_t = t/R_t$). Details are reported in [2].

Table 4: *Thermal resistance and thermal conductivity*

Specimen	Thickness t cm	R_t AVG m^2K/W	λ_t AVG W/mK
M1 WCC1	24	0.81	0.30
M2 WCC1	20	0.79	0.25
WCC1	6	0.29	0.21
WCC5	6	0.13	0.45

According to thermal resistance requirements for new buildings in Switzerland, the U-Value ($U=1/R_t$) should be less than 0.15 W/m^2K. This means that a wall thickness of approximately 1.40 m (WCC1) is needed to fulfil the thermal resistance requirements. As this dimension is unrealistic, a suitable thermal insulation material is still necessary, but can be of reduced thickness.

WCCs also show high specific heat capacities. The values are between 1.35 kJ/kgK for WCC5 and 1.87 kJ/kgK for WCC1 and thus, superior to regular lightweight concrete (of comparable density) but rather comparable to spruce (1.6 kJ/kgK) [15].

4.2 ACOUSTIC INSULATION

The acoustic insulation properties of three slab types (type 1, type 3 and type 5 [1]) have been investigated. Properties for airborne sound were determined with frequency bands in third-octave band width with medium frequencies between 100 and 3150 Hz. Impact noise properties were determined with an ISO tapping machine.
Table 5 shows the test results for airborne sound level and impact noise level without any secondary structure on the slab, corrected for reverberation time and volume of reception room.

Table 5: *Acoustic insulation properties*

	Airborne sound R'_w dB	**Impact noise $L`_{n,w}$ dB**
Type 1	31	63
Type 3	30	69
Type 5	31	67

These values can be compared to the requirements of SIA 181 [16] for residential buildings or school buildings, respectively. The requirements for moderate noise impact for exterior and interior airborne sound and impact noise are presented in Table 6.

Table 6: *Building code requirements*

Residential buildings			**School buildings**		
De	**Di**	**L'**	**De**	**Di**	**L'**
≥ 32	≥ 52	≤ 53	≥ 35	≥ 57	≤ 48

For all slab types, impact noise level is problematic. Therefore, additional tests have been performed with the same TWCCC slabs, additionally placing a 50 mm screed layer on the slabs. A third test was performed with an additional foam insert of 3 mm and 7 mm wood laminate. Table 7 illustrates the tests result for TWCCC slabs with additional layers.

Table 7: *Acoustic insulation properties with screed and foam*

	Airborne sound With screed D_i dB	**Impact noise With screed L` dB**	**Impact noise With screed + foam + laminate L` dB**
Type 1	33	61	56
Type 3	30	71	56
Type 5	33	69	51

Impact noise requirements can only be guaranteed if the foam insert is thicker than 3 mm. With the investigated set-up, the impact noise requirements could not be fulfilled.
Furthermore, it would be beneficial to use a floating screed instead of a bonded screed as it was used to determine the above results.

5 STRUCTURAL PERFORMANCE OF TWCCC SLABS AND WALLS

5.1 TWCCC SLABS

Different cross-sections have been tested to determine the performance of TWCCC slabs. The tested single-span slabs had an 8 m span.
Table 8 shows the equivalent span of the testes cross-sections.

Table 8: *Test results at ULS [1]*

Slab	q_d [kPa]	L_{eq} [m]
Ref	12.23	5.05
Type 1	12.69	5.60
Type 2	12.39	7.05
Type 3	12.43	4.35
Type 4	12.60	4.40
Type 5	13.08	5.79

It seems that ULS requirements are more difficult to satisfy because deflection due to permanent loads and long-term deformations can be compensated by camber [1]. Test results are explained in detail in [1].

5.2 TWCCC WALLS

TWCCC walls have been tested for developing a structural design approach. Therefore, 2nd order effects, i.e. buckling, have been considered. Full scale tests with WCC1 and WCC5 and 2 different timber grids have been performed.
It seems that current concrete design approaches are best suited for the structural design of hybrid timber-WCC wall elements. Furthermore, WCC contribute to the overall buckling resistance of timber-WCC walls why timber battens with smaller cross-sections can be used. Test results and design approaches are explained in [2], [6].

6 ECONOMIC AND ECOLOGICAL PERFORMANCE

This chapter reports on main findings of a case study [11] and an already established life-cycle assessment (LCA) [12] as well as an analysis about combustibility of WCCs [5].

6.1 COMBUSTIBILITY OF WCCS

Combustibility is a further advantage of WCCs. This permits to recover energy at end of service life and thus has a major impact on LCA.
Specimens with dimensions of 20 x 18 x 37 mm^3 have been combusted. For these test, only the three most promising recipes (WCC1, WCC5 and WCC6 [4]) have been tested. Test results (Figure 4) show that WCC1 has the highest and WCC6 the lowest combustion speed. Combustion speed thus depends on material density (Table 1 in [5]). Figure 4 shows temperature evolution vs. time for the different WCC specimens.

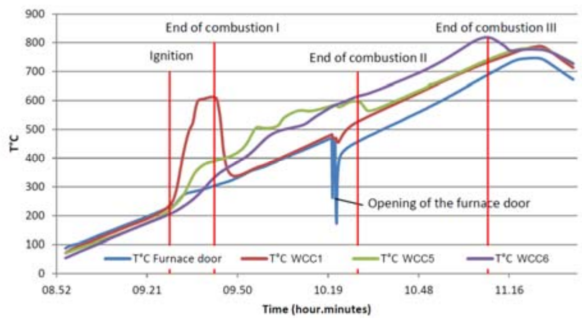


Figure 4: *Temperature vs. time [5]*

Material ignition, for all tested WCCs, takes place at a temperature of approximately 210°C, which corresponds to the initiation of wood gasification.
Compared to wood, WCCs stop combusting as soon as they are removed from the furnace. For this reason, WCCs can be considered as inflammable even if they will burn if exposed to flames or high temperature for a long period [5], i.e. for 30 minutes and more.
As already mentioned the combustion process releases energy which can be reused. Therefore, gross and net calorific values have been determined according to EN 14918 [17]. Table 8 shows the different values which have been evaluated by using a C/H/N analyser.

Table 9: *Calorific values and C/H/N content of WCCs [5]*

	WCC1	WCC5	WCC6
Gross calorific value	5.88 MJ/kg	2.83 MJ/kg	4.08 MJ/kg
Net calorific value	5.87 MJ/kg	2.82 MJ/kg	4.20 MJ/kg
C content	15.2%	8.3%	13.3%
H content	3.1%	2.5%	2.6%
N content	0.0%	0.0%	0.0%

Those calorific values are below typical values of wood products, e.g. 12.5 MJ/kg for wood chips or 17 MJ/kg for pellets [5], but still remarkably high.

The apparent volume of combusted WCC does change due to the cement matrix. The ash content of combusted WCCs, Table 9 [5], is considerably higher than that of wood which is around 1%. For this reason, WCCs should always be combusted at high temperature and mixed with other combustible materials, to prevent furnace saturation.

Table 10: *Ash content of WCCs [5]*

WCC recipe	Solid mineral fuel	Solid biofuel
1	56.0%	65.4%
5	68.5%	78.8%
6	65.9%	77.2%

The values for solid mineral fuel, e.g. coke, were determined according to ISO 1171 [18] and solid biofuel according to EN 11775 [19], respectively.
Furthermore, it was found that WCCs should be combusted at 600°C, at least, for more than 20 minutes to obtain an efficient combustion with minimum NO_x emissions [5].

6.2 LIFE CYCLE ASSESSMENT

Sustainable construction materials and methods are becoming more and more important. To prove that WCCs are sustainable, several investigations have been made. The examined cross-sections from an earlier case study [11] have been used as a basis for complementary life-cycle assessment of TWCCC slabs [12].

Five slab types are compared with each other to evaluate ecological and economic performances.

- Traditional concrete slab with a cement screed
- Traditional timber structure with ceiling cladding, timber joists, planking and a cement screed
- TCC slab with screw-type connectors
- TWCCC slab type 2 with glulam beams embedded in WCC5 (Fig. 5)
- TWCCC slab type 5 characterized by a "+/-" shear connection provided by a glulam beam (Fig. 5)

The dimensions of the first 3 slab types can be found in [11].

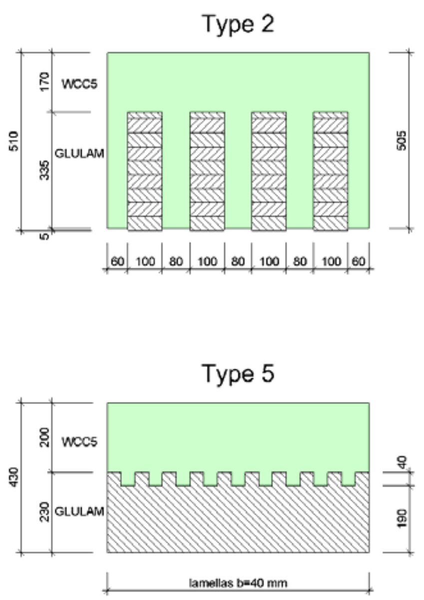


Figure 5: *TWCCC slabs [12]*

All considered slabs fulfil the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) requirements for a 9 m single span slab with a variable action of 5 kPa (according to SIA 261 [20]).

The life cycle assessment data from CFSC 2014 [21] have been used to determine all environmental influences. A service life of 90 years was considered with the consequence that the influence of the secondary structure has been taken into account 3 times (1x new construction, 2x replacement). This has a positive effect on the ecological performance of TWCCC slabs because they do only need 50 mm screed as secondary structure to respect all building code requirements.

The calculation of the environmental impact has been separated into two steps. First, the impact of the load-bearing structure has been analysed, followed by an analysis of the secondary structure. At the end, the impact of material transport was added to the previously determined values. Greenhouse gas emissions (EGG), non-renewable primary energy and environmental impact points (UBP) were analysed.

Figure 6 shows relative EGG values for all slabs. For further investigations, the influence of material transport can be neglected because the influence is very small and more or less at the same level for each slab.

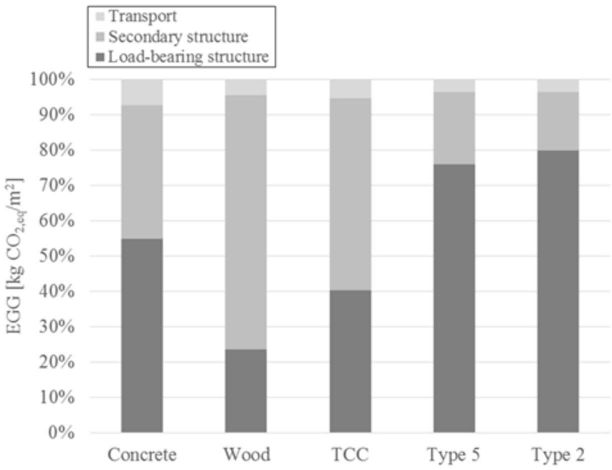


Figure 6: *relative EGG [12]*

The secondary structure of TWCCC has the smallest influence on EGG. This is due to the beneficial properties of WCC – e.g. thermal and acoustic insulation properties – where a 50 mm screed is enough to fulfil building code requirements. Figure 7 illustrates EGG per square meter for all considered slabs.

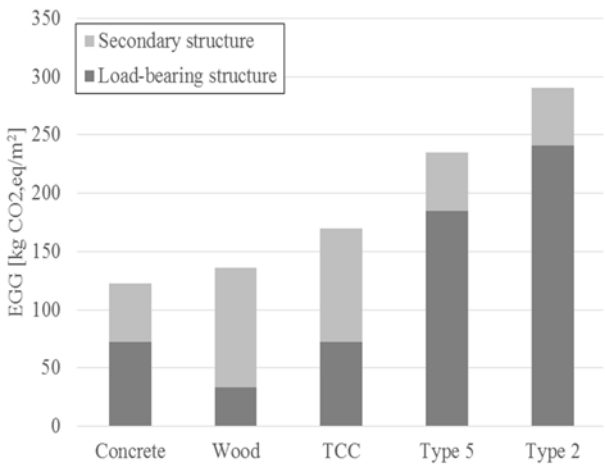


Figure 7: EGG for different slab types [12]

It is obvious that the load-bearing structure of TWCCC slabs is the largest contributor to EGG. This is due to the large amount of construction material needed and the high cement content in WCC5 [4], [12].

Another examined parameter is the total amount of non-renewable primary energy. Note that the possibility to recover energy by combustion has been taken into account. The calorific values of Table 8 have been used. Figure 8 shows that both TWCCC slabs exploit less non-renewable primary energy in their life cycle than traditional slabs, due to recovered energy during combusting after demolition.

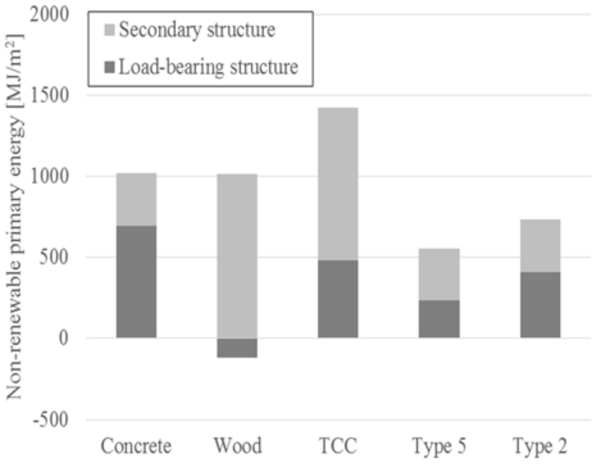


Figure 8: *non-renewable primary energy [12]*

To conclude, TWCCC slab type 2 is not competitive w.r.t. LCA parameters. There is a high potential in EGG for both TWCCC slabs. This is primarily attributable to the large amount of cement needed for WCC, not only due to the cement content but also to the high quantity of construction material needed.

Referring to non-renewable primary energy both TWCCC slab types show the best performance of all investigated slab types.

These results also show that ecological performance evaluation also depends on the referred index.

It must the goal to reduce EGG and UBP – explained in detail in [12] – such that these new slab types show an improved overall ecological performance.

7 FUTURE CHALLENGES IN STRUCTURAL APPLICATIONS OF WCCS

There are still several challenges which have to be handled. A first is to find an approach for producing WCCs with reliable quality. This is mainly related to the use of untreated sawdust, implying that volume predictions are difficult and thus density is unknown without doing any measurements. The quantity of resin in the sawdust is unknown but resin acts as an air entraining agent and therefore density differences are unavoidable.

Recent production of reinforced WCC slabs exhibited a new challenge: post-concreting settlement of pourable WCC resulting in extensive cracking. Further investigations have to be made to find a solution to this. Creep and shrinkage behavior also has to be improved for future applications.

These challenges can be partly resolved by using newly developed WCCs [3].

It must further be a goal to reduce cement content in WCCs in order to improve ecological and economic performance.

8 CONCLUSIONS

The developed TWCCC wall and slab elements have some great advantages compared to traditional construction methods.

Both elements have the benefit of heat storing capacity which allows to reduce the needed thermal insulation material. Furthermore, these elements show a great fire resistance and acoustic insulation properties. WCCs can even be used for multi storey buildings as they can be considered as non-flammable.

Moreover, the slab elements only require a minimal secondary structure to fulfil all building code requirements. Compared to traditional timber slabs, where vibrations represent a serious problem, TWCCC slabs do not need any additional layers to solve this problem. Actually, the impact noise level requirements provide the only slight problem. This can simply be solved by placing a foam insert which generally is needed for any slab.

If the challenges described in the above subsection can be solved TWCCC slabs and walls represent a construction method which ideally combines the benefits of timber and concrete and that even with great ecological and economic performances.

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