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Mineralized Wood Particle Reinforced Concrete as Stiffening Elements with Reduced Density

Armirani beton s mineraliziranim česticama drva kao element za ukrućenje smanjene gustoće

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ABSTRACT • *The aim of the cooperative research project was the development of a wood-cement in-situ concrete used as local filler and stiffening element in wooden ceiling elements. For further processing, only water should be added to the mineralized particles, whereby the amount of added water is relevant to the adjustment of the consistence and flowing characteristics. Portland cement was used as binding component. Particle residues of Scots Pine (Pinus sylvestris L.) and spruce (Picea abies (L.) Karst.) from sanding with 60 grit paper, as filling components, were supplied by Lignotrend GmbH, an industrial manufacturer of solid wood structural elements (cross laminated timber) and project partner. The mineralization of these wood particles has also been studied. Three different ways to accelerate the hydration of the cement and therefore to counteract the effect of the so called cement poisons were examined. Moreover, the compressive strength of hardened concrete had to be set to not less than 3.2 N/mm², which was also examined.*

Key words: *wood concrete compound, mineralization, compressive strength*

SAŽETAK • *Cilj zajedničkog istraživanja bio je proizvesti beton od drva i cementa koji će se upotrebljavati kao punilo i kao element za ukrućivanje drvnih stropnih elemenata. Za daljnju obradu mineraliziranim česticama drva treba samo dodati vodu, pri čemu je količina dodane vode relevantna za prilagodbu konzistencije i svojstva tečljivosti betona. Kao vezivna komponenta upotrijebljen je portlandski cement, a kao punilo drvne čestice nastale brušenjem drva običnog bora (Pinus sylvestris L.) i smreke (Picea abies (L.) Karst.), i to brusnim papirom granulacije 60. Drvne čestice dobavljene su od tvrtke Lignotrend GmbH, industrijskog proizvođača strukturnih elemenata od masivnog drva (unakrsnoga lameliranog drva), koja je ujedno i partner u projektu. Mineralizacija čestica drva također je dio istraživanja. Istražena su tri različita načina ubrzavanja hidratacije cementa, a istraženi su i tim procesima suprotni učinci, tzv. otrovi cementa, kao i tlačna čvrstoća otvrdnutog betona, koja ne smije biti manja od 3,2 N / mm².*

Ključne riječi: *spoj drvo – beton, mineralizacija, tlačna čvrstoća*

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1 INTRODUCTION
1. UVOD

Since the use of wood particles is considered attractive for the reinforcement of cement (Campbell and Coutts, 1980), their application leads to various challenges due to wood components like water soluble carbohydrates (e.g. sugars, starch, hemicellulose and pectin) and due to resins, oils, waxes and fats - depending on wood species (Schubert *et al.*, 1990). Those substances react with cement and cause delays in hardening. Miller and Moslemi investigated the effects of wood components like glucose, quercetin, xylan and acetic acid on cement regarding hydration characteristics and tensile splitting strength. They discovered that glucose decreased the cement tensile strength by nearly 50 % (Miller and Moslemi, 1991). By differential calorimetric analysis, Kühne and Meier showed that cement hydration is inhibited by galactomannan and especially xylan hemicelluloses, as well as by glucose (Kühne and Meier, 1990). Cong *et al.* (2007) have conducted experiments to reduce the hydration retarding sugar in the wood by microorganisms and enzymes (Cong *et al.*, 2007). Alpar *et al.* applied an additive combination of montmorillionite and polydiallyldimethylammonium chloride to Portland cement to improve the bending strength of cement bonded poplar wood (*Populus* spp*.)* composite. Bending strength could be increased above 20 % (Alpár *et al.*, 2012). Wei *et al.* suggested to eliminate the so called cement poisons (Sandermann and Brendel, 1956) by using alkali salts, for example calcium chloride, as setting accelerators (Wei *et al.*, 2000). Alpár and Rácz claimed that the use of calcium-chloride and calcium-formate with poplar clone (*Populus x euramericana cv. „I 214"*) for the production of cement-bonded particleboards leads to a significantly reduced price by improved physical and mechanical properties of boards compared to those made with conventional water-glass (Alpár and Rácz, 2009). On the other hand, the increased corrosion of ferrous materials (for example various fasteners like nails or screws) by leachable chlorides is disadvantageous for later use. Del Menezzi *et al.* (2007) replaced Portland cement with silica fume (SiO_2) to reduce the inhibitory effects of wood (*Pinus taeda* L.) on the setting of cement in the wood-cement board production. They showed that a replacement of cement with 10 % of SiO_2 not only improved mechanical properties but also eliminated the inhibitory effect of wood on cement setting.

In the context of a scientific study, it had to be found out which kind of mineralization is meaningful for the present use and which concentrations are useful. Furthermore, it was examined how much of the wood particles can be inserted into the concrete in order to achieve a maximum reduction in density, simultaneously maintaining the required consistency, and to keep a compressive strength of hardened wood concrete over the minimum compressive strength of Scots pine (*Pinus sylvestris* L.), since the material should be able to bring stability to wooden ceiling elements. This compressive strength transverse to the fibre $f_{c,90,k}$ of softwood for the highest strength class C50 is described in the standard DIN EN 338:2010-02 with 3.2 N/mm².

In a preliminary experiment, the following mineralizers, which are mentioned in various patents and have been successfully used there, were examined: cement, water glass, magnesium hexafluorosilicate, silica, calcium chloride, aluminium sulphate. Another aspect of the treatment is the reduction of the water uptake of the timber to minimize the total water requirement. The first four of the just mentioned substances should prevent the leaching of wood components, producing a better adhesion and reducing the water absorption of the particles. The latter two substances are salts to accelerate the hydration of the cement - and hence, counteracting the effect of cement poisons.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

It is known that the particle size fraction can be influenced by the sanding direction (Očkajová *et al.*, 2008). In this research however, Scots Pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) Karst.) particles, generated by both perpendicular and longitudinal sanding, were used as fillers in the wood concrete compound. They were produced by the project partner Lignotrend Produktions GmbH using 60 grit paper. For mineralisation, the particles have been treated with:

- 31.2 % aqueous sodium silicate solution (Na_2O x SiO_2), thinned to 10 % ("WG 10 %"),
- Sodium silicate solution 10 %; after drying, the particles were powdered with cement ("WG 10 % / Cement powdered")
- Cement mixed with moistened particles were additionally powdered ("Cement powdered")
- Cement; after drying, the mixture has been separated from cement dust ("cement dust reduced").

Pantarhit PC160 PLV from the Ha-Be Betonchemie GmbH & Co. KG was used as plasticizing agent. It is based on a polyacrylic acid derivative. 146 different mixing ratios and recipes were tested in total. In the preliminary series, wood particles were mineralized and then mixed with cement. The mass gain after mineralization, miscibility and consistency were determined as well as the water/cement ratios whenever water was added to the dry mixture. After 20 hours. the setting and curing behaviour was examined.

As a result of preliminary series, concrete with a wood/cement ratio of 15 mass % kiln dry could be produced. Concrete with a higher wood particle level did not set after 20 hours. Based on the results of the preliminary series, five recipes were selected for the main experiment. Due to the findings of the preliminary tests, following recipes were considered for the production of wood concrete in the main test (Table 1):

1. Filling material: wood particles soaked in sodium water glass (10 %); wood/cement ratio of 15 mass %; binder: sodium silicate water glass.
2. Filling material: wood particles soaked in sodium water glass (10 %); powdered with cement; wood/

Table 1 Mixtures for the production of pressure test specimens
Tablica 1. Smjese za proizvodnju uzoraka za tlačni test

Sample ID *Oznaka uzorka*	**Filler** / *Punilo*				**Cement** *Cement*	**Plasti-cizing agent** *Sredstvo plastifi-kacije*	**Water** *Voda*	**Mis-cibi-lity** *Miješa-nje*	**Consi-stency** *Konzi-stentnost*	**Com-ment** *Komen-tar*
	batch / *serija*	composition / *sastav*								
	short name *skraćeni naziv*	wood particle kiln dry *suhe drvne čestice* g	minerali-zation agent *sredstvo minerali-zacije* g	water *voda* g	g	g	g			
A	pure cement *čisti cement*	---	---	---	9501.02	---	3800.90	---	watery *vodenast*	
B	WG 10%	541.20	232.28	28.91	3607.95	9.02	3635.92	good *dobro*	crumbling dividing *mrvi se, dijeli se*	
C	WG 10%/ cement powdered *cement u prahu*	523.28	483.31	72.80	3488.58	---	3416.34	bad *loše*	crumbling *mrvi se*	
D	cement powdered *cement u prahu*	529.10	212.43	7.57	3527.73	---	3540.87	bad *loše*	crumbling *mrvi se*	
E	cement dust reduced *smanjena cementna prašina*	409.40	310.59	12.47	2730.38	---	2736.88	bad *loše*	crumbling *mrvi se*	did not set *nije postav-ljena*
F	cement dust reduced *smanjena cementna prašina*	410.00	337.86	8.04	2733.60	---	2979.62	bad *loše*	crumbling *mrvi se*	did not set *nije postav-ljena*

cement ratio of 15 mass %, binder: sodium silicate water glass and Portland cement.

3. Filling material: moistened wood particles; powdered with cement; wood/cement ratio of 15 mass %, binder: Portland cement.
4. Filling material: wood particles soaked in 25 % cement / 75 % water slurry, then after drying separated from cement dust; wood/cement ratio of 15 mass %; binder: Portland cement.

As consistency has great influence on certain properties like pumpability, the flow spread was measured with a flow table according to DIN EN 12350-5. For pressure testing, five cube-shaped specimens with a side length of 100 mm (nominal) of each recipe (Table 1) were prepared according to DIN EN 12390-1:2001-02, DIN 1048-5:1991-06 and DIN EN 12390-2:2009-08.

When producing specimens for the pressure test based on the results of the preliminary tests, it was found that the dust reduced specimens (sample ID E and F) did not solidify. Thus, only the sample rows B, C and D were examined further and compared with the samples consisting of pure cement (sample row A). Water-resistant plywood, coated with phenolic resin, was used for the mould. After 20 hours, the test specimens were removed from the mould and then stored in sealed bags, where they were kept for two weeks at 21 °C. Subsequently, they were removed from the bags and preserved for a further two weeks with the prevailing ambient laboratory climate (21 °C / RH 35 %) to prepare the pressure test. For a better load transmission, the specimens were ground plane and parallel, and a compensating layer of quick-setting cement was also applied on pure cement specimens (Figure 1).

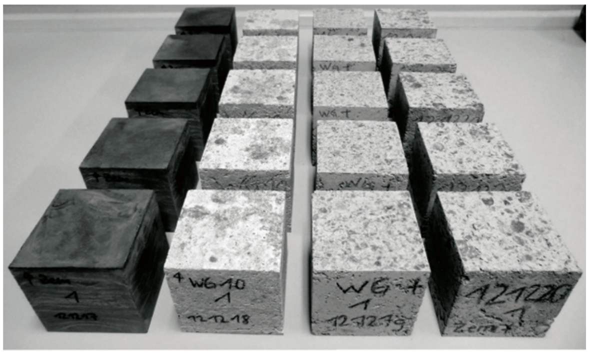

Figure 1 Specimens for compressive strength testing
Slika 1. Uzorci za ispitivanje tlačne čvrstoće

After a total of 28 days, the pressure test was carried out in compliance with DIN EN 12390-3:2009-07 using a WPM 600 testing machine equipped with a 650 kN load cell for the pure cement series (sample row A) and a Zwick 4084 universal testing machine equipped with a 200 kN load cell for the sample rows B, C and D.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

A consistency that allows the concrete to be processed with a spatula could only be created with a max-

Table 2 Moisture content and bulk density of the specimens
Tablica 2. Sadržaj vode i nasipna gustoća uzoraka

	Humidity, % / *Sadržaj vode*, %			**Average bulk density** / *Prosječna nasipna gustoća* kg/m³
	average total *prosjek, ukupno*	average internal *prosjek, unutarnji*	average external *prosjek, vanjski*	
pure cement / *čisti cement*	19			1913
WG 10 %	26	41	19	1223
WG 10 % / cement powdered *cement u prahu*	28	42	19	1210
cement powdered / *cement u prahu*	22	34	18	1166

imum wood/cement ratio of 15 %, with a very high water/cement ratio of 1.3. This surplus water will escape gradually over the time and burden the environment with moisture. A plastic consistency can be achieved with less use of water only when at the same time the wood components are considerably reduced. The most advantageous fact for the cured product combination, namely a high content of wood substance and a small amount of water, inevitably leads to a fresh concrete, which is no longer ductile but crumbling in consistency.

The moisture content of the pressure test specimens was determined immediately after the pressure test, using the kiln-dry method. Since the inner region of the specimen seemed to have a different moisture than the outer area, the moisture was determined on each sample from both the edge regions (up to 20 mm below the surface) and from the innermost area. In order to determine the average total moisture, each wood concrete sample was granulated and a portion (about 1/5 of the sample mass) of the well-mixed pellets dried to kiln. A significantly higher moisture content was recorded inside the cubes than in the outer areas.

The average moisture content of each wood concrete sample ranges from 22 to 29 %. The moisture content of the specimens with cement powdered wood particles were the lowest. The specimens with water glass pre-treated particles showed significantly higher moisture content than those with only cement powdered particles. A reason could be that water glass makes it difficult for the remaining moisture to escape. Another aspect is the tendency of wood particles to absorb water from the air.

The gross density was determined from the mass and dimensions of the specimen before the pressure test. They are within 1200 ± 50 kg/m³ (Table 2). Due to the use of fillers, the gross density could be reduced by an average of 36 % (WG 10 %) to 39 % (cement powdered) in comparison to those of the pure cement cubes.

As a result of the pressure tests, the mean value of the breaking stress of pure cement specimens was 45.15 N/mm². When comparing the reference test of pure cement with those of the wood cement specimens, it is clear that the introduction of 15 mass % of wood in relation to the mass of cement brings a very strong decrease of almost 90 % to 5 N/mm². Due to the high humidity in the samples, the strength is expected to rise during the drying process. It has been determined as not appropriate to compare the cement modulus of elasticity with wood cement modulus due to measuring errors caused by deformation of the testing machine steel crossbar. Therefore, only the properties of differ-

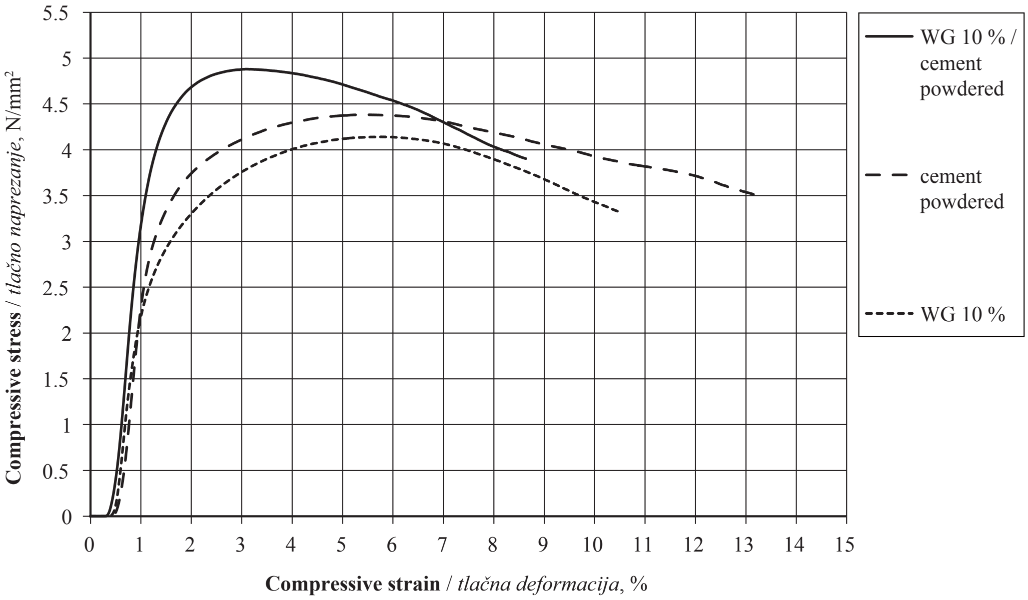

Figure 2 Compressive stress-strain curves of selected specimens
Slika 2. Tlačne krivulje naprezanje – deformacija za odabrane uzorke

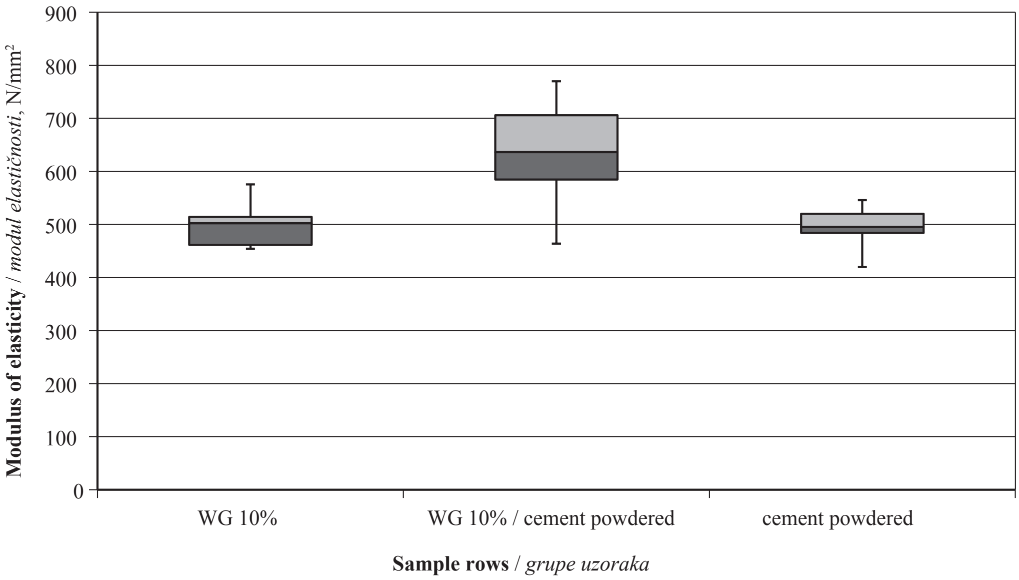

Figure 3 Moduli of elasticity - box plot of sample rows
Slika 3. Prikaz rezultata modula elastičnosti za različite uzorke

ent mineralized wood concrete test specimens are compared with each other when considering the material properties.

As shown in the stress-strain diagram (Figure 2), the maximum stresses of the water glass mineralized samples (WG 10 %, sample row B) are on average 4.17 N/mm² with a standard deviation of 0.08 N/mm². The strengths were significantly higher when using particles soaked with water glass and then powdered with cement (WG 10 % / cement powdered, sample row C). A mean of 4.93 N/mm² could be achieved. The statistical scatter was slightly higher, but still low (standard deviation is 2.4 % of the mean). The cement powdered test row had an average maximum stress of 4.48 N/mm². The highest scattering of the three series of measurements is with a standard deviation of 5.2 % on average.

Results of the modulus of elasticity MOE (Figure 3) for the WG 10 % series show that the linear-elastic range ends at 2 to 2.5 N/mm², an average modulus of 502.35 N/mm² is achieved. In comparison with the only water glass mineralized wood concrete, the WG 10 % / cement powdered samples showed a greater range of linear-elastic behaviour, amounting to 3 to 3.5 N/mm². The maximum stress is reached at a strain of 3 to 4 %. So a less severe deformation was observed. In addition, the modulus of elasticity with an average of 636.22 N/mm² is bigger.

The mean modulus of the cement powdered series of 495.38 N/mm² resembles the WG 10 % series and the linear-elastic range ends between 2.5 and 3 N/mm².

4 CONCLUSION
4. ZAKLJUČAK

It can be concluded that a wood concrete, whose binder is Portland cement, could be developed. The filling material consists of water-glass and / or Portland cement mineralized wood particles. Through the use of only 15 mass % wood particles as filler, the gross density of the concrete can be significantly reduced by 36 to 39 %. The fresh concrete mixed with water, at a water/cement ratio of 1.0 to 1.1, has a crumbling, easily malleable consistency - but it is not flowing. The achieved compressive strength of the wood concrete of 4 to 5 N/mm² is higher than the required compressive strength transverse to the fibre $f_{c,90,k}$ of softwood (3.2 N/mm² for C50 strength class).

5 REFERENCES
5. LITERATURA

1. Alpár, T.; Rácz, I., 2009: Production of cement-bonded particleboards from poplar (Populus euramericana cv.„I 214 “). Drvna industrija, 60: 155-160.
2. Alpár, T.; Selmeczi, É.; Csóka, L., 2012: Advanced wood cement compatibility with nano mineral. International Scientific Conference on Sustainable Development & Ecological Footprint. March 26-27, Sopron, Hungary.
3. Campbell, M. D.; Coutts, R. S. P., 1980: Wood fibre-reinforced cement composites. Journal of Materials Science, 15: 1962-1970. http://dx.doi.org/10.1007/BF00550621
4. Cong, N. T.; Unbehaun, H.; König, S., 2007: Biologische Modifikation lignocelluloser Faserstoffe für zementgebundene Faserplatten. Holztechnologie 48: 10-16.
5. Del Menezzi, C. H. S.; De Castro, V. C.; De Souza, M. R., 2007: Production and properties of a medium density wood-cement boards produced with oriented strands and silica fume, Maderas. Ciencia y tecnología, 9: 105-115.
6. Kühne, G.; Meier, W., 1990: Ursachen und Möglichkeiten zur Beeinflussung der chemischen Wechselwirkungen in Holzfaserstoff-Zement- und Holzfaserstoff-Gips- Gemischen, Holz als Roh- und Werkstoff, 48: 153-158. http://dx.doi.org/10.1007/BF02627302
7. Miller, A.; Moslemi, A., 1991: Wood-Cement Composites: Effect of model compounds on hydration characteristics and tensile strength. Wood and Fiber Science, 23: 472-482.

8. Očkajová, A.; Beljaková, A.; Luptáková, J., 2008: Selected properties of spruce dust generated from sanding operations. Drvna industrija, 5: 3-10.
9. Sandermann, W.; Brendel, M., 1956: Studien über mineralgebundene Holzwerkstoffe – Zweite Mitteilung: Die „zementvergiftende" Wirkung von Holzinhaltsstoffen und ihre Abhängigkeit von der chemischen Konstitution. Holz als Roh- und Werkstoff, 14: 307-313. http://dx.doi.org/10.1007/BF02605217
10. Schubert, B.; Wienhaus, O.; Bloßfeld, O., 1990: Untersuchungen zum System Holz-Zement. Einfluss unterschiedlicher Holzarten auf das Abbindeverhalten von Holz-Zement-Mischungen und Möglichkeiten zur Modifizierung des Systems, Holz als Roh- und Werkstoff, 48: 423-428. http://dx.doi.org/10.1007/BF02617774
11. Wei, Y. M.; Zhou, Y. G.; Tomita, B., 2000: Study of hydration behavior of wood cement-based composite II: effect of chemical additives on the hydration characteristics and strengths of wood-cement composites. Journal of Wood Science, 46: 444-451. http://dx.doi.org/10.1007/BF00765802
12. *** DIN 1048-5:1991-06. Testing concrete; testing of hardened concrete (specimens prepared in mould).
13. *** DIN EN 12350-5:2009-08. Testing fresh concrete - Part 5: Flow table test.
14. *** DIN EN 12390-1:2012-12. Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds.
15. *** DIN EN 12390-2:2009-08. Testing hardened concrete - Part 2: Making and curing specimens for strength tests.
16. *** DIN EN 12390-3:2009-07. Testing hardened concrete - Part 3: Compressive strength of test specimens.
17. *** DIN EN 338:2010-02. Structural timber - Strength classes.

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