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Determination of the bond strength of treated wood strands embedded in a cement matrix by means of a pull-out test

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Determination of the bond strength of treated wood strands embedded in a cement matrix by means of a pull-out test

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Abstract

Effects of chemical treatment of wood on the bonding strength of Norway spruce strands (*Picea abies* Karst.) embedded in a cement matrix were investigated by means of a pull-out test. Strands of varying thickness were used whereas a strong influence of thickness on bonding strength could be observed. Using thick strands (800 µm) showed negative effect on bonding strength which is due to the swelling effect. The treatment of thin strands (400 µm) showed that using wet strands (~90% moisture content) leads to the best results compared to untreated dry (12%) strands. By addition of setting accelerators (ammonium chloride) bonding strength of wet strands was even improved. Furthermore, effects of hot water and sodium hydroxide extraction as well as sodium silicate treatment were examined.

Zusammenfassung

Zur Bestimmung der Bindefestigkeit zwischen Holz und Zement wurden anhand von unterschiedlich behandelten Strands aus Fichtenholz (*Picea abies* Karst.) Auszugstests durchgeführt. Strands mit unterschiedlicher Dicke wurden in die Zementmatrix eingebettet, wobei ein starker Einfluss der Stranddicke auf die Bindefestigkeit nachgewiesen werden konnte. Die Verwendung dicker Strands (800µm) zeigte einen negativen Einfluss auf die Bindefestigkeit, welcher auf Quellungseffekte zurückzuführen ist. Die Behandlung dünner Strands (400µm) ergab, dass die Verwendung feuchter Strands (u ~ 90%) zu den besten Ergebnissen führte. Bei einer zusätzlichen Verwendung eines

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3 Erstarungsbeschleunigers (Ammoniumchlorid) konnte die Bindefestigkeit weiter
4 verbessert werden. Ferner wurden die Effekte von Heißwasser- und
5 Natronlaugeextraktion sowie die Behandlung mit Natronwasserglas untersucht.
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For Peer Review

1 Introduction

The popularity of cement bonded composites (CBCs) is rising throughout the industry due to its extended applications compared to conventional Engineered Wood Products (Eusebio 2003). Waste wood and low quality wood resources (e.g., wood from plantations) can be used for the production of CBCs. CBCs are widely used in Third World Countries which is partly caused by the insufficient supply of wood resources for housing and load bearing constructions. Due to the increasing use of thinnings, plantation wood, and waste wood, CBCs are getting more important even in countries with highly established wood industry. Beside economical also environmental reasons force the development of natural fibre or particle reinforced CBCs. To enable the use of CBCs also for structural purposes, bonding between wood and cement must be improved. Hence it is important to understand the bonding mechanisms between wood and cement.

Similar to adhesive bonding by means of synthetic resins also inorganic adhesion is thought to result from physical bonding mechanisms as well as mechanical interlocking (Frybort et al. 2008). Unexpected high bonding strength can be observed between wood and cement, which Wei et al. (2004) related to the hydration products (calcium hydroxide and calcium silicate hydrates), accumulating close to the wood-cement interface.

In comparison to matrix materials without reinforcement, composites with a reinforcing phase show better mechanical performance partly caused by increased toughness. This fact enables these composites to carry load to a higher strain limit. At the proportional limit micro-cracks in the matrix phase occur. However, particles begin to efficiently carry loads and block fracture propagation (Wolfe and Gjinolli 1996). A more or less “weak” interface between the matrix and the reinforcing phase, which can be observed for cement bonded wood composites, contributes to an enhanced fracture toughness of the fibre reinforced composite materials. Frictional dissipation along the interfaces is the primary source of toughness and energy absorption. Strong interfaces lead to creep resistant and brittle composites (Evans et al. 1991). By increasing bonding and pull-out strength of the fibres or particles in CBCs, toughness is additionally increased (Lange et al. 1996). To increase toughness and strength of CBCs, enhancing bonding strength of the particles and the matrix is a priority objective.

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3 When concrete is stressed, small cracks arise introduced due to randomly
4 distributed flaws. Under load these micro-cracks grow together forming macro-
5 cracks which lead to failure of the structure. Reinforcing concrete with fibres
6 inhibits crack initiation and growth, hence increasing fracture toughness of
7 concrete (Issa et al. 1996). Conventional test methods (Jorge et al. 2004) of
8 inorganic bonded wood composites measure the compatibility between wood and
9 cement by measurement of the hydration characteristics (Alberto et al. 2000; Wei
10 et al. 2000a, b; Brandstetr et al. 2001; Karade et al. 2003), as well as testing
11 mechanical properties of cured composites (Lee and Hong 1986; Wei et al. 2003).
12 These methods are useful for a general estimation of the compatibility of different
13 wood species and cement. However, conventional test methods give no
14 information concerning the adhesive bonding and the mechanical interlocking of
15 the cement matrix to the wood surface.
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18 The idea of using the pull-out test is to evaluate the actual bond strength of the
19 two components and how particular treatments enhance the load transmission
20 between the enforcement, in this case the strands, and the matrix.
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23 As this test setup, with a strand thickness of 400 μm , is based on comparatively
24 realistic wood dimensions (Geimer et al. 1996), applicable results can be gained,
25 concerning e.g., cement bonded wood wool board or cement bonded OSB
26 (Oriented Strand Board). Differently treated wood samples, which are cut by a
27 microtome, are subsequently embedded into a cylindrical cement block. After
28 curing, pull-out strength or shear strength and shear energy is measured by means
29 of a universal test machine.
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32 On the one hand the application-oriented approach enables test results which are
33 useful for further work, e.g., for finite element modelling. On the other hand the
34 data is valuable to clearly determine the influence of different treatments or the
35 application of several coupling agents on the wood strands.
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38 The pull-out test in general is a quite common method to determine bond strength
39 of fibres and cement (Banholzer et al. 2004), but almost no literature is available
40 about measuring bond strength of cement and wood particles like strands,
41 excelsior or flakes. As there are no comparable results, the following work
42 describes the effects of common chemical treatments and the use of an
43 accelerator, namely ammonium chloride (NH_4Cl). Those substances were chosen
44 because they are cited in the literature as quite common methods to enhance
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3 compatibility (Geimer et al. 1996; Alberto et al. 2000) but acting in different
4 ways. While NaOH extracts inhibitory substances out of the wood, Na₂SiO₃ is
5 modifying the wood surface.
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8 The motivation of this study was to evaluate the effects of different treatments of
9 the reinforcing wood phase on the adhesive bond. Measuring frictional forces
10 between wood and concrete which can be observed after debonding between both
11 phases was not part of this work.
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17 **2 Materials and methods**

18 **2.1 Production of the strands and embedment into cement**

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20 Flawless blocks of spruce (*Picea abies* Karst.), with the dimensions
21 18 mm x 30 mm x 120 mm, were cut out of frozen thinning material. The blocks
22 were cut in a way that the growth rings were perpendicular to the
23 120 mm x 18 mm radial surface (Fig. 1a). Prior to cutting the wood blocks they
24 were stored in water at room temperature for 24 h. After soaking, strands with a
25 thickness of 400 µm were cut along the grain from the radial surface of each
26 block.
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29 Due to the high bonding strength of some treatments several strands broke before
30 debonding occurred. For this reason an additional test run was performed where
31 strands with a thickness of 800 µm were tested. As this method also failed, strands
32 with a thickness of 400 µm were embedded less deep (10 mm) into the cement
33 block, whereas strands of the first run stuck 15 mm deep in the cement block.
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45 **2.2 Preliminary treatment of test specimens**

46 The strands of each block and treatment were randomized to prevent a systematic
47 bias. The strands were stored and treated, respectively, depending on the
48 particular treatment (Table 1). For Na₂SiO₃ and NaOH treatment the strands were
49 immersed in the particular dilution for 1½ h and again conditioned to a moisture
50 content of $\omega = 12\%$. For the accelerated samples 2% of NH₄Cl based on cement
51 weight were added to the cement prior to mixing with water. The so called wet
52 samples were stored under water for 10 min.
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60 To determine the actual embedment depth, small marks were drawn on each
strand above and below the desired 15 mm and 10 mm embedment mark,

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3 respectively. Subsequently, the strands were embedded into small film containers
4 which were filled with mixed Portland limestone cement (PZ 275 CEM II/A-L
5 42,5N) water slurry at a water-cement (w/c) ratio of 0.5. The specimens were left
6
7 24h for setting. Subsequently, for complete curing, the specimens were stored in a
8
9 climate room (20°C, 65% RH) for 28 days.
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12 13 **2.3 Mechanical testing**

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15 All mechanical tests were performed on a Zwick/Roell Z020 universal testing
16 machine equipped with a 5 kN load cell. One end of the strands was fixed by
17 means of a clamp (lower part of the test set-up) and the cement block was hinged
18 in a bracket. Avoiding a bending moment during testing the bracket was attached
19 to the machine with a cardan joint. The pull-out samples were tested to failure
20 (Fig. 1b), which was defined as force drop of 5% from F_{max} . The mechanical tests
21 were performed at constant cross-head speed of 2mm/min. Pull-out shear strength
22 (τ) was calculated by dividing the maximum load by the embedded superficies
23 surface of the strand. During the mechanical experiment a force-displacement
24 curve was recorded by the testing machine (Fig. 2).
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27 For the individual groups the average value as well as the standard deviation was
28 calculated and compared by one-way ANOVA ($p = 0.05$).
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31 32 **3 Results**

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34 Strands treated with Na_2SiO_3 and NH_4Cl showed high bonding strength. Most of
35 these strands which were embedded 15 mm in the cement block failed, before
36 shear failure at the wood-cement interface was observed. Therefore, an additional
37 series of pull-out tests was performed with thicker wood strands (800 μm) to
38 prevent failure of the strands. However, shrinkage of the strands during curing of
39 the cement caused de-bonding at the wood-cement interface yielding shear
40 strength values far below values gained from thin (400 μm) strands. On the other
41 hand, no effect of the treatment was observed for those strands (Fig. 4). Therefore,
42 the embedding depth was reduced to 10 mm for a second series of pull-out tests
43 with strands with a thickness of 400 μm . Values gained from strands which failed
44 in tension were not used for statistical analysis. Shear strength values yielded
45 from pull-out tests of strength with an embedding depth of 10 and 15 mm were
46 compared by one way ANOVA proving no significant difference between groups
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with the same strand treatment. For further statistical analysis strands with the same treatment were classified in one group.

In Fig. 3, the pull-out strength is plotted against untreated and the differently treated strands which were embedded in cement with and without added accelerator (NH_4Cl), respectively. For clearness mean pull-out strength values and standard deviations of the experimental results are listed in Table 2, including also the results from the previous study with an embedment depth of 15 mm.

According to the results of a one way ANOVA by using Scheffé's procedure, the effects of the different treatments on pull-out strength were generally classified into four groups based on the arrangement of the pull-out strength. Group one consisting of untreated strands ($0.36 \pm 0.072 \text{ N/mm}^2$, $n = 14$) and Na_2SiO_3 treated strands ($0.47 \pm 0.079 \text{ N/mm}^2$, $n = 14$), group two of Na_2SiO_3 treated strands and untreated strands which were embedded into accelerated cement ($0,57 \pm 0,096 \text{ N/mm}^2$, $n = 13$), group three of untreated strands embedded in accelerated cement and wet (MC ~ 92%) embedded strands ($0,59 \pm 0,103 \text{ N/mm}^2$, $n = 11$) and the last group consisting of wet strands (MC ~ 92%) embedded into accelerated cement ($0,73 \pm 0,076 \text{ N/mm}^2$, $n = 8$). Comparing the results of the accelerated wet and the untreated (12%) samples, pull-out strength of the former one is twice as high. As NaOH treatment did not lead to a significant improvement, this specific treatment was not repeated in the following studies. A similar result was measured at samples with slightly higher MC of 20%; just a minimal trend of improvement of bonding strength could be observed, but not at a significant level.

4 Discussion

When a load is applied, measured shear stress is increasing until the shear strength of the interface is reached. At this point the strand debonds and, in most cases, is pulled out without any further increase in load. Because of the frictional forces, which are getting effective when slipping of the strand starts, the stress strain curve shows a so called saw tooth pattern (Fig. 2). In some cases frictional forces lead to a slight increase in load until complete pull-out of the strand. In this case, after debonding, the stress strain curve shows some increase which again can be followed by a saw tooth like pattern or just a decrease of the stress strain curve. For statistical analysis the peak force after the first force drop was used, which clearly indicates shear failure at the wood-cement interface.

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3 The shear stress along the embedded strands under load is not homogenous and
4 reaches a maximum at the point where the strands enter the cement matrix. The
5 shear stress at the wood-cement interface is not linear and depends on the
6 embedment depth as well as the elastic properties of the strand and the matrix
7 (Lawrence 1972). Laws (1982) investigated fibres which were embedded in a
8 matrix. For his study he assumed that the embedded end of the strand carries no
9 load at all. In our case mechanical interlocking between cement and wood at the
10 end of the strands can be assumed. Due to the small area of the butt end in
11 comparison to both faces of the strands the contribution of the butt end is thought
12 to be marginal. Taking this into account, debonding of the strand will start near
13 the surface of the matrix where shear stress reaches a maximum. Due to the non-
14 uniform debonding near the surface the contact area of the strand and the matrix is
15 reduced and thereby the effective interface. Considering this fact the measured or
16 calculated bonding strength is an underestimate of the bond as formerly assumed
17 contact area is decreasing due to debonding (Laws 1982). A theoretical approach
18 to avoid this error was developed by Lawrence (1972) and extended by Laws
19 (1982). Accepting the simplifying approach the calculated shear strength gained
20 from the pull-out tests was used to characterize the compatibility between wood
21 and cement matrix.

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37 Due to the minimal inhibiting properties of spruce, dry strands (12% MC) are
38 suitable for the production of CBCs without any further treatment (Frybort et al.
39 2008). Comparing the computed values in Fig 3, even untreated spruce shows
40 comparatively good bonding strength. Using Na_2SiO_3 to enhance bonding strength
41 between wood and cement caused an average shear strength value which was 1.3
42 times as high as the one of untreated strands. Research done by Pehanich et al.
43 (2004) on the influence of fibre treatment showed similar results by comparing
44 untreated and Na_2SiO_3 treated fibres regarding to their mechanical properties
45 (MOR, MOE) when mixed with cement. Wienhaus (1979) refers this
46 enhancement to the sealing effect of Na_2SiO_3 whereby diffusion of sugars out of
47 the wood into the cement paste and vice versa is inhibited. Water glass is also
48 known to accelerate the formation of calcium silicate hydrate (CSH) gel in the
49 system (Yue et al. 2000), which is in large part, besides calcium carbonate,
50 responsible for the strength properties of cement (Hermawan et al. 2001).
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3 Although Na_2SiO_3 itself has no accelerating effects on hydration, it is often
4 mentioned besides others substances, as an accelerator (Wei et al. 2002).

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6 As there is no silica available in spruce, introduction of silica into or at least onto
7 the wooden substance is a common method to improve strength of the cement
8 matrix and additionally bonding quality between wood and matrix. The presence
9 of sodium, in this case sodium silicate, promotes the formation of ettringite
10 needles (Prince et al. 2003). By the presence of ettringite needles bonding
11 between the wood and the matrix is improved (Coatanlem et al. 2006). Due to the
12 alkaline conditions of the cement water slurry acidic functional groups of the
13 lignocellulosic material ionize and cations are adsorbed. By lowering the
14 concentration of essential cations, especially of calcium, these adsorption sites
15 disturb the complex set of reactions of cement (Pereira et al. 2003; 2005). Studies
16 investigating the bond strength between wood strands and cement matrix are
17 scarcely described in the literature. Also studies investigating embrittlement at the
18 wood-cement interface due to accelerating effects are barely present in the
19 literature. However, further research could be useful to clearly determine how the
20 Na_2SiO_3 treatment is enhancing bond quality.

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22 Setting accelerators are widely-used as the application is easy to accomplish,
23 pressing and clamping time are reduced (Simatupang et al. 1990) and additionally
24 bond quality between wood and cement is enhanced and thereby the mechanical
25 properties of CBCs are improved.

26
27 Several substances are suitable to accelerate cement setting, e.g., MgCl_2 , CaCl_2
28 and NH_4Cl , but because of the corrosive action of chlorous substances, the
29 application of these boards is limited, hence the use of Na_2SiO_3 (Schubert et al.
30 1990a) or non-chlorous accelerators is preferable. The results of the accelerated
31 samples are most likely explained by the reduced setting time, which prevents
32 extractives to be washed out of the wood (Bietz and Uschmann 1984; Simatupang
33 et al. 1990). But also the pH-value has big influence on cement setting. The use of
34 less alkali cement, or the addition of acidic substances, reduces the alkali
35 degradation of hemicelluloses which is called peeling reaction. These degradation
36 products, especially saccharinic acids, which arise from monomer and oligomer
37 sugars, as well as polysaccharides (cellulose, hemicelluloses), have similar
38 inhibitory effects on hydration like water soluble monosaccharides (Wienhaus
39 1979; Schubert et al. 1990b, a) whereas degradation products, e.g., saccharinic

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3 acids, are much more effective in inhibiting hydration of cement (Govin et al.
4 2005). Concerning this case Wienhaus (1979) has mentioned the impregnation of
5 wood particles with acidic-hydrolysing salts (CaCl_2 , MgCl_2 , $\text{Al}_2(\text{SO}_4)_3$, FeSO_4).
6 These salts delay the formation of an alkali milieu around wood particles, thus
7 promoting hydration by suppressing the development of saccharinic acids.
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10 During preparation of the accelerated samples, a liquidation of the cement water
11 slurry could be observed. This lower viscosity could possibly have lead to a better
12 contact between wood and cement and furthermore to an improved impregnation
13 of the strands. Also Eusebio et al. (2000) relate this improvement to a better fibre
14 to fibre contact when CaCl_2 was used as an accelerator. A negative side effect of
15 using setting accelerators, which was noticed by Hermawan et al. (2002), is a
16 decrease in dimensional stability of CBCs. A quite important result of this study is
17 the fact that wet embedded strands (~90% MC) showed more or less the same
18 pull-out strength like the dry strands which were embedded in cement where
19 accelerator was added. This shows that additives are not stringently needed for
20 spruce to enhance bonding strength between wood and cement matrix. A
21 beneficial side effect of this elevated MC is that simultaneously some extraction is
22 taking place when strands are stored in water. Nevertheless, to achieve this
23 secondary goal the strands have to be extracted for more than 10 minutes like it
24 was done for this study. Own unpublished research showed that pull-out strength
25 is improved by hot water extraction at 60°C for 24 h. But also after 6 h a slight
26 increase in pull-out strength was observed.
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28 This high bonding strength could be explained by an undisturbed cement setting.
29 This was also observed by Dewitz et al. (1984) when they measured mass
30 transport of minerals into sapwood of pine. By using dry wood, substances which
31 are essential for setting are withdrawn from the cement. Wood is indeed
32 mineralised but this is neither contributing to the strength of the matrix nor to the
33 development of bonding strength between matrix and wood. By contrast if wet
34 wood (>90% MC) was used transport of minerals was delayed for a couple of
35 hours and minimized in intensity. Tamba et al. (2001) relate this effect to the
36 hydrophilic nature of wood, which affects the water cement ratio and thereby
37 limiting the water available for hydration.
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39 The highest bonding strength could be achieved with wet strands which were
40 embedded in cement with added accelerator. This could be related to faster setting
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3 times (Bietz and Uschmann 1984; Simatupang et al. 1990), as mentioned before
4 and additionally to the reduced transport of minerals when wet wood is used
5 (Dewitz et al. 1984).
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8 During pull-out testing embrittlement of the strands could be observed on some of
9 the samples, which manifested in brittle failure near the embedment zone.
10 Embrittlement is known to be caused by the alkaline environment provided by the
11 cement (Youngquist 1999) but could partly also be caused by the mineralization
12 of the wood surface. Cziesielski (1975) has already reported that wood surfaces
13 which are in direct contact to cement experience mineralization. Concerning this
14 fact further studies have to be done to clearly determine the influence of
15 embrittlement on the strength of wood particles.
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18 Most of the samples showed discoloration on the wood surface. This can be
19 attributed to the reaction of alkali chemicals of cement with wood. It is assumed
20 that discoloration is mostly caused by water soluble phenolic components but also
21 by lignin (Hon and Shiraishi 2001). Especially the untreated samples with added
22 accelerator, as well as the NaOH treated samples showed increased discoloration
23 up to 30 mm above the embedment zone while the wet ones, also the wet ones
24 with added accelerator, did not show an apparent discoloration. Due to the
25 elevated moisture content of the strands additional water absorption could not take
26 place. Thus no alkali substances could penetrate into the strands and therefore no
27 discolouration occurred.
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30 The results of the thick samples (800 μm) showed that geometry of the strands, in
31 this case thickness, has great influence on the development of bond strength
32 (Badejo 1988). That is why no significant difference between the untreated and
33 even the Na_2SiO_3 treated strands could be observed (Fig. 4). It can be assumed
34 that bonding strength at the wood-cement interface was significantly reduced by
35 shrinkage of the strands during the time the cement cured. Due to shrinkage of the
36 strands cross tension and shear forces are induced which cause de-bonding at the
37 wood-cement interface.
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40 NaOH treatment does just barely enhance bonding strength although it is
41 described as being able to enhance compatibility by removing inhibitory
42 substances (Moslemi et al. 1983). However, this may just be the case for highly
43 incompatible species like larch but not for spruce, as it is described as a low
44 inhibitory species (Schubert et al. 1990a), thus the difference is not that
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3 conspicuous. Anyway, treatment of particles with diluted NaOH (0.5%, 2h) is
4 cited as being able to reduce thickness swelling of CBCs (Kavvouras 1987),
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6 which could be confirmed by our own research.
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9 The data obtained in this study suggests that using wet spruce (MC~90%) as
10 reinforcement enhances bonding strength compared to dry wood (12%). On the
11 other hand, addition of 2% NH₄Cl as accelerator will generate even better results
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13 for untreated wet spruce.
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16 17 **5 Conclusion**

18
19 As spruce causes marginal compatibility problems, there is no necessary need for
20 extraction. Nevertheless, a slight increase in bonding strength could be measured
21 when using hot water or diluted NaOH extraction which results from removal of
22 several polysaccharides. However, a more effective and economic method to
23 enhance mechanical properties is by using wooden material with an elevated MC.
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25 At 20% a slight enhancement took place, while at around 90% MC the pull-out
26 strength nearly doubled, compared to 12% MC.
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30 The application of Na₂SiO₃ onto the wood particles is beneficial and therefore a
31 conventional method for enhancing mechanical properties of CBCs. Compared to
32 strands embedded in accelerated cement this method is more sophisticated to
33 accomplish as strands have to be treated prior to mixing with cement.
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37 The addition of accelerators, in this case NH₄Cl, enhances mechanical properties,
38 though by reducing setting time at the same time. Using accelerators may be much
39 more uncomplicated for the industrial process, as the additive is just admixed to
40 the neat cement powder. Both untreated (12%) and wet (~90%) strands achieved
41 superior bonding strength, whereas wet strands produced highest bonding
42 strength.
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46 Thin, but also long particles have to be preferred when mechanical properties, as
47 well as low thickness swelling are the desired key properties for CBCs.
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For Peer Review

Table 1 Description of the different treatments of the specimens.

Tabelle 1 Beschreibung der unterschiedlichen Behandlungen der Probekörper.

Name	Treatment
none	conditioned 12% ¹
wet	10 min in H ₂ O (~92%) ²
NaOH (sodium hydroxide solution)	1% dilution - 1½ h
Na ₂ SiO ₃ (sodium silicate solution)	2% dilution – 1½ h
none + accelerator	conditioned 12% ¹ - 2% of NH ₄ Cl based on cement weight
wet + accelerator	10 min in H ₂ O (~92%) ² - 2% of NH ₄ Cl based on cement weight

¹ The strands were stored in a climate room (20°C, 65% RH) for one week.² The strands, which were stored in the climate room, were dipped in water at room temperature for 10 min.

Table 2 Results of the pull out test, n = number of samples, τ = pull-out or shear strength, s = standard deviation.

Tabelle 2 Ergebnisse des Auszugstests, n = Probenanzahl, τ = Auszugs- bzw. Scherfestigkeit, s = Standardabweichung.

Treatment	planned embedment depth (mm)	n	pull-out strength (N/mm ²)	
			τ	s
12%	15	9	0.29	0.066
20%	15	11	0.34	0.126
NaOH	15	11	0.35	0.086
wet	15	10	0.44	0.166
12%	10	14	0.36	0.0718
Na ₂ SiO ₃	10	14	0.47	0.079
12% + NH ₄ Cl	10	13	0.57	0.096
wet	10	11	0.59	0.103
wet + NH ₄ Cl	10	8	0.73	0.076

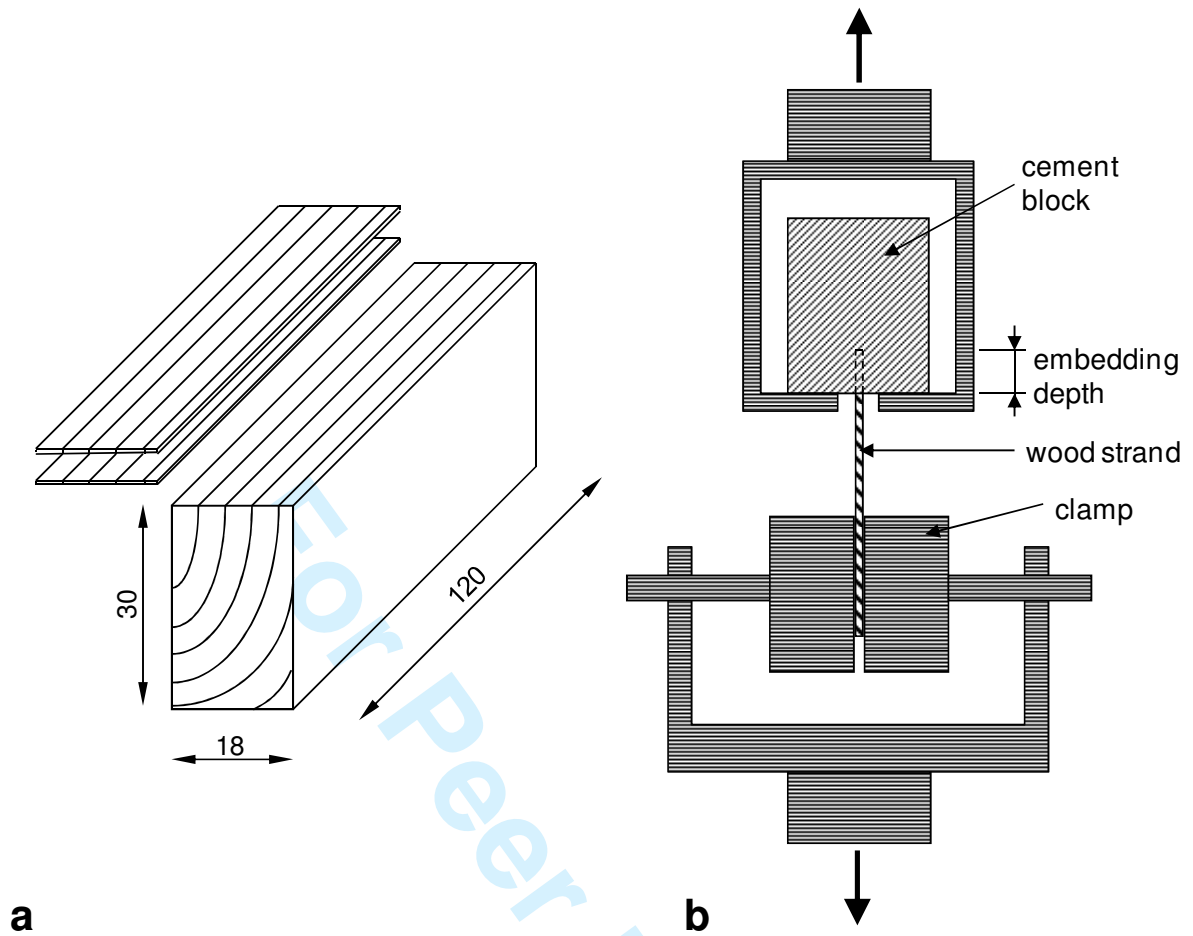


Fig. 1 a Schematic illustration of strand preparation, dimensions in mm. b Clamped specimen during pull-out test.

Abb. 1 a Schematische Darstellung der Strand-Herstellung, Abmessungen in mm. b eingespannte Probe im Auszugstest.

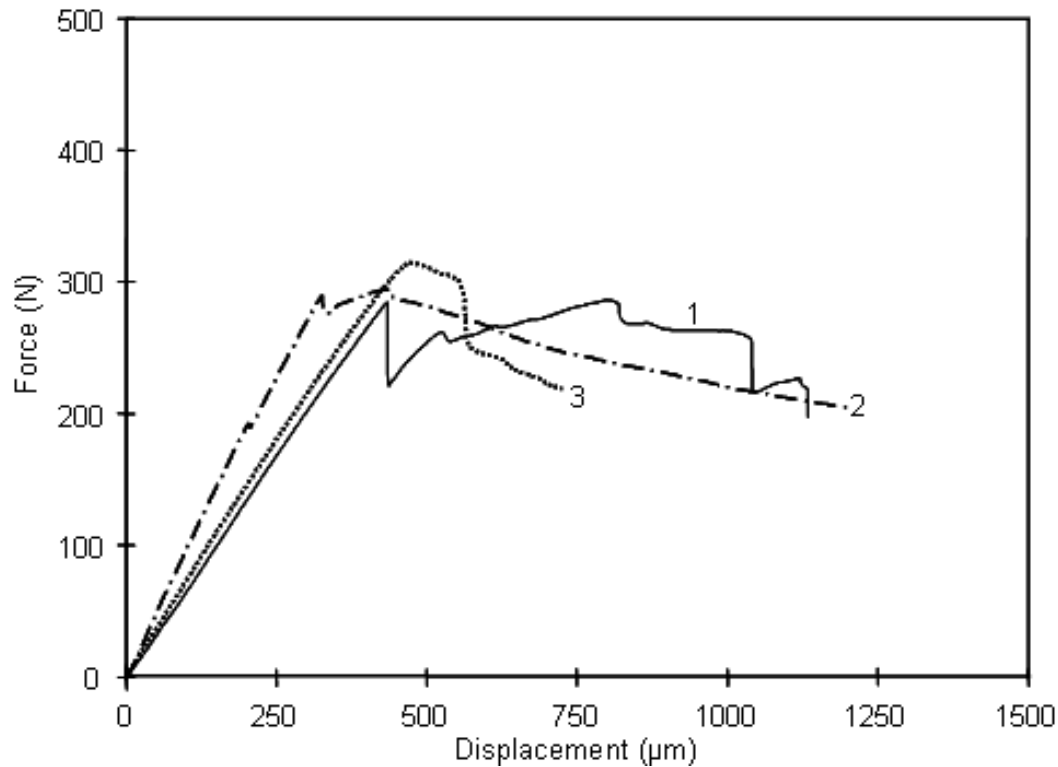


Fig. 2 Examples of different load displacement curves of the pull-out test: 1 saw tooth pattern, 2 debonding followed by a slight load increase and subsequent nearly linear load decrease, 3 debonding followed by a force decline.

Abb. 2 Beispiele für verschiedene Formen des Kraft-Weg-Diagramms der Auszugsprüfung: 1 Sägezahnmuster, langsamer Abfall des Auszugswiderstandes, 2 Ablösung gefolgt von einem kurzen Anstieg und anschließendem fast linearem Kraftabfall, 3 Ablösung gefolgt von einem Kraftabfall.

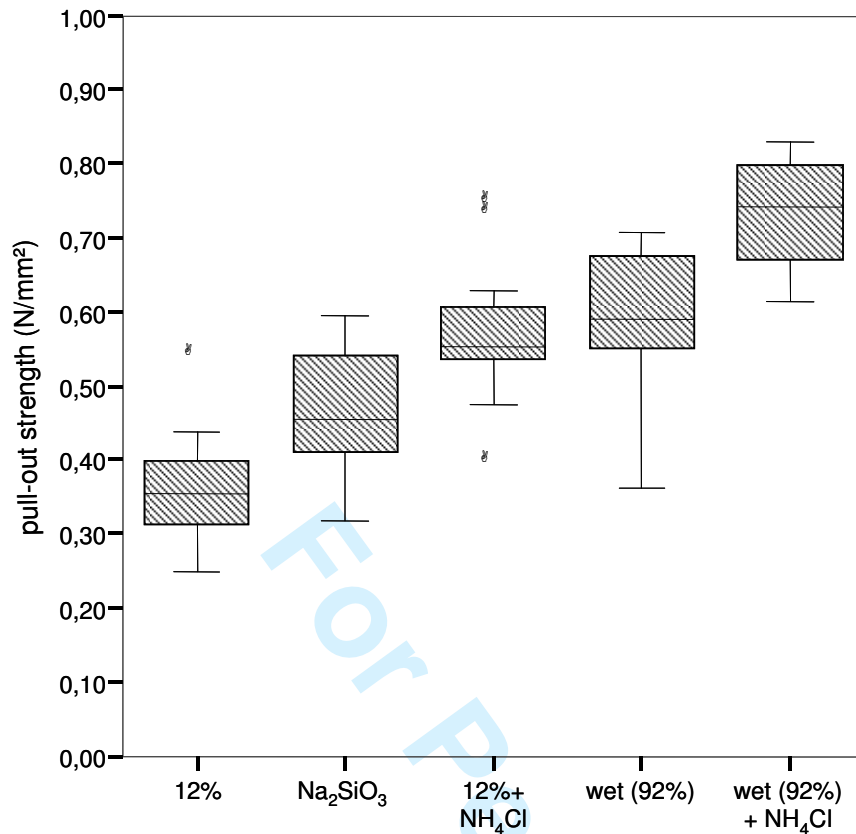


Fig. 3 Pull-out strength plotted over the different strand treatments (none, wet and sodium silicate solution), with or without added accelerator (NH_4Cl 2% based on cement weight), strand thickness 400 μm , embedment depth 10 mm.

Abb. 3 Auszugsfestigkeit gegenüber den unterschiedlichen Behandlungen der Strands, unbehandelt (none), feucht (wet) und Wasserglas (Na_2SiO_3), mit und ohne Zugabe eines Beschleunigers (NH_4Cl 2% bezogen auf Zementgewicht), Stranddicke 400 μm , Einbettungstiefe 10 mm.

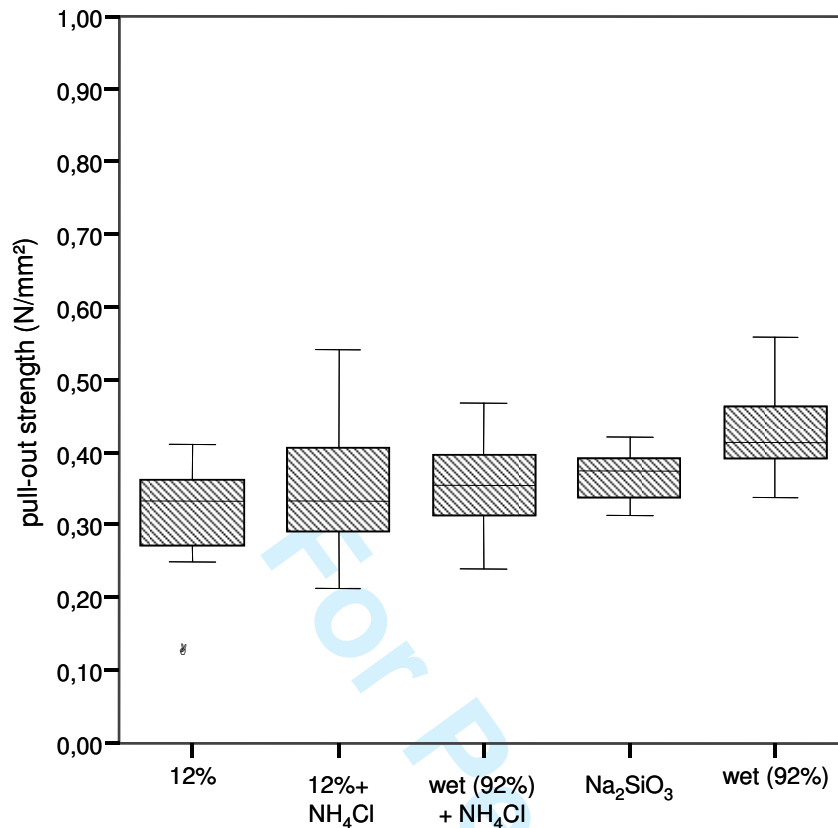


Fig. 4 Pull-out strength of a previous study plotted over the different strand treatments, no treatment (12%), no treatment with added accelerator, wet with added accelerator, sodium silicate solution, and wet, strand thickness 800 μm , embedment depth 15 mm.

Abb. 4 Auszugsfestigkeit gegenüber den unterschiedlichen Behandlungen der Strands, unbehandelt (12%), unbehandelt mit Zugabe eines Beschleunigers (12% + NH₄Cl), feucht mit Zugabe eines Beschleunigers (wet% + NH₄Cl), Wasserglas (Na₂SiO₃) und nass (92%), Stranddicke 800 μm , Einbettungstiefe 15 mm.