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The Effect of Water Absorption of Cross-Laminated Timber and Glue-Laminated Timber on Concrete Physical and Mechanical Properties

Mantas Širvinskas, Svajūnas Juočiūnas, Mindaugas Daukšys*

Kaunas University of Technology, Faculty of Civil Engineering and Architecture,
Studentu st. 48, LT-51367 Kaunas, Lithuania

*Corresponding author: **mindaugas.dauksys@ktu.lt**

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Abstract

This study examines the potential of coating the surfaces of cross-laminated timber (CLT) and glue-laminated timber (GLT) to evaluate the impact of moisture on the physical and mechanical properties of concrete in a timber-concrete composite slab. The C30/37 strength-class concrete was poured to simulate a timber-concrete composite slab on top of CLT and GLT samples. Natural oil (NO) and a flexible two-component waterproofing slurry (WPS) were applied to the timber surface to investigate the effects of water absorption and compare them with those of uncoated timber elements. The density, strength, and surface moisture of hardened concrete were measured in the laboratory after 3, 7, 14, and 28 days. Surface moisture and moisture at a 10 mm depth in the timber were also assessed at the same intervals. Prior to pouring the concrete, the timber surface was sprayed with water to simulate rain during on-site construction. The findings revealed that, among all surface treatments tested, the WPS coating was the most effective in limiting moisture migration, reducing water ingress by approximately 2.5 times in CLT and 2.4 times in GLT after three days. This demonstrates that WPS forms a significantly more effective moisture barrier than the alternative treatments. This reduction directly enhances concrete performance: strength increased by 9.4% (CLT) and 7.8% (GLT) compared to uncoated samples. The proposed solution offers practical benefits in overcoming many challenges related to precipitation and water ingress during construction. The study provides concrete evidence that moisture management strategies are essential for the wider adoption of timber–concrete composite systems in sustainable structural design.

Keywords: cross-laminated timber; glue-laminated timber; timber-concrete composite slabs; low-carbon construction; moisture absorption; compressive strength.

Introduction

The Ministry of the Environment of the Republic of Lithuania (2024), by Order No. D1-359 approved the methodology for the use of wood and other organic materials in public buildings. It states that, from 1st of November 2024, at least 50% of wood and other organic materials derived from renewable natural resources must be used in the construction of new buildings. To promote climate- and environment-friendly transformation of the construction sector and its products, selecting green building materials is essential to designing sustainable structures. Composite beams, combined with composite slabs, reduce CO_2 emissions by minimising the amount of concrete required for the slab and by producing steel beams from recycled steel. The combination of

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steel, wood, and concrete is well-regarded because it offers better fire resistance, allows for larger spans between columns, provides more open space, results in lighter structures, and creates a sense of warmth and closeness to nature – delivering an innovative structural solution in terms of sustainability, aesthetics, and interior flexibility.

Today, the variety of mass wood products is wide, including Cross-Laminated Timber (CLT), Glulam (Glue-Laminated Timber), Nail-Laminated Timber (NLT), Dowel-Laminated Timber (DLT), and Structural Composite Lumber (SCL). One of the most widely used mass timber products, CLT, is made by layering dimension lumber at right angles and bonding them together to create structural panels that offer high strength, dimensional stability, and rigidity (reThink Wood, 2020; Ahmed & Arocho, 2020). In comparison, GLT consists of individual wood laminations (dimension lumber) that are selected and arranged according to their performance properties, then bonded with strong, moisture-resistant adhesives (Kordziel, 2018). CLT panels are primarily applied in structural elements such as walls, roofs, and floor slabs, whereas GLT panels are mainly used for floor and roof decking (Kordziel et al., 2019; reThink Wood, 2020).

CLT panels are a relatively new wood product, developed in Austria and Germany in the 1980s, but have only been widely used for about 20 years (Karacabeyli & Douglas, 2013). Approximately 90% (800,000 m^3) of CLT panels produced worldwide originate from Europe, with the majority being produced in the Alpine region, where the technology was first developed (Fink et al., 2018). Most of these panels have similar parameters; for example, the most commonly used wood is Norway spruce (Picea abies), the raw lumber corresponds to class C24 or T14 according to EN 338:2016 "Structural timber - Strength classes", and the layers are glued together with flat surfaces (Fink et al., 2018). Layers of timber are glued together with polyurethane, melamine, and phenolic-based adhesives (Kordziel, 2018). In Europe, the production of CLT panels is described in the standard EN 16351:2016 "Timber structures - Cross-laminated timber - Requirements". These panels are composed of at least three separate layers of lamellas, each layer rotated 90 degrees relative to the previous one. This type of bonding allows the panel to carry loads in two directions, similar to concrete floor slabs (Brandner et al., 2016). Each lamella varied in width from 40 to 300 mm and in height from 6 to 47 mm. The overall dimensions of the product are usually limited only by transport capabilities, with a maximum length of 16 m, a width of 3.6 m (to fit upright stacking in a 4-meter-high truck), and a height of up to 500 mm (per EN 16351:2016). According to EN 16351:2016, three classes of adhesives can be used: phenolic and aminoplastic (MF, MUF, PRF), polyurethane (PUR) or emulsion polymer isocyanate (EPI) adhesives, but some countries (e.g. Sweden) limit the amount of formaldehyde in products, so in Europe, PUR-based adhesives are most often used. The wood used in production must have a moisture content of 12 ± 2%, and the finished product must not exceed 15%.

CLT constructions, including joints, connections, and attachment points, can be affected by precipitation during construction. According to the author's research (Olsson, 2020), it is difficult or impossible to prevent microbial growth in CLT during construction without weather protection. Thanks to their bonding method, CLT panels are highly dimensionally stable in width and length; however, when exposed to water, these panels change in height. This is an undesirable effect, and if the panel deforms sufficiently, it can become challenging to assemble joints, and even finished structures may lose their joint strength, posing a risk to the building's structural stability. A study by Wang (2020) showed that CLT absorbs considerably less water than oriented strand board (OSB) or plywood panels. Nevertheless, even small amounts of water exposure can negatively affect the wood. After inspecting 10 objects built with or containing CLT products, 6 exhibited fungal damage, and in 1, the fungus had destroyed the wood to a depth of 20 mm (Austigard & Mattsson, 2020). A study (Kalbe et al., 2022) indicated that the primary pathway for moisture absorption into the panel was through the end-grain edges, rather than the longitudinal surfaces. Moreover, moisture content above 25% persisted for many months until specific heating or drying treatments were applied. The findings highlight that CLT end-grain edges are vulnerable to moisture, and further research is needed to develop cost-effective, efficient strategies for comprehensive CLT moisture management.

Often, moisture enters the wood through the end-grain edges during construction, and the CLT panels are then covered with waterproof materials, sealing the moisture inside the panels. In this case, even after many months of construction completion, the moisture content remains too high, leading to the growth of mould and fungi (Brandstätter, Kalbe, Autengruber, et al., 2023). Although the EN 16351:2016 standard defines CLT production, it does not address water absorption at the end-grain edges, and each builder handles this problem differently. It is recommended on a construction site to wrap (six-face) CLT panel packs completely and place them on wood skids to protect them from standing water during storage on site (Karacabeyli & Douglas, 2013). CLT panel manufacturers always recommend constructing in a dry environment to prevent water from affecting the wood products. For example, in Scandinavia, tents are used to provide full weather protection for buildings after CLT is installed (Kalbe et al., 2022). Still, this practice requires installing structures to support the tent, which entails additional labour and time costs. When carrying out construction without weather protection, it is crucial to complete the installation of the building's wood structures as quickly as possible, thereby minimising the wood's exposure to precipitation (Olsson, 2020). Studies (Austigard & Mattsson, 2020) show that even during rapid assembly, timber can be exposed to between 18 and 300 mm of rainfall [20]. This issue is less relevant in southern regions, where precipitation is infrequent and scarce. Still, it becomes a critical concern in areas with high rainfall and construction activities outside the summer season.

CLT panels absorb water mainly through their end-grain edges, which means the main problem is the panel ends and joints. Although it may seem logical at first glance to waterproof the ends as much as possible, studies have shown that the panels tend to dry out through the ends. For this reason, the ends should be covered with a material that acts as a diffusion film, which will prevent water from entering the panels, but if it does, it will allow water to drain away more quickly. It has also been observed that panels that dry too quickly can crack or even delaminate (Schmidt, Riggio, Barbosa, & Mugabo, 2019). For this reason, it is essential to control the drying process, as cracks that form not only weaken the structure but also allow moisture to enter the panels during building operations. Authors (Kalbe, Kukk, & Kalamees, 2020) recommend applying a liquid-applied membrane coating to the cut edges of CLT panels to protect the end grain. They also suggest covering horizontal CLT panels with self-adhesive membranes and vertical CLT panels with temporary clear weather protection films. It was concluded that the use of self-adhesive membranes is impractical, as the membrane peels off, becomes mechanically damaged, and fails to perform its function. In his study, Olsson (2021) examined various methods to ensure moisture safety. These methods included using tape, covering joints or openings with plywood boards, protecting the edges of floor structures with plastic or felt paper, and isolating wood pillars or cross-laminated timber (CLT) walls from the floor structures. This was achieved by placing them on steel stands, plastic blocks, or sound-and-vibration pads. The study revealed that, despite the measures employed, wood products were still affected by moisture. It means that for high-quality waterproofing, a sealant should be used that is elastic enough to prevent cracking as the wood deforms and to allow application to hard-to-reach areas, such as connections and attachment points. Although considerable research has been conducted, it remains unclear which solution is most effective for managing moisture effects in construction without weather protection.

Today, engineers often choose mass timber systems alongside wood-frame and post-and-beam construction. Most of these products can be transformed into a wood-concrete composite by applying a concrete topping, allowing both materials to act as one. A timber–concrete composite slab can be constructed using two primary methods: a) pouring fresh concrete into a CLT in situ, b) erecting in situ the prefabricated timber-concrete composite slab manufactured at the factory (Jiang & Crocetti, 2019). The primary method is the most commonly used, a wet construction method. Using this method, CLT is considered a porous material and can absorb some of the water used in concrete mixing. It means the wood's moisture content can increase. Additionally, moisture migration from concrete to CLT can affect the curing conditions of the concrete and its physical and mechanical properties. Losses in water used for mixture preparation can affect the water-to-cement ratio of concrete, leading to reduced concrete strength, increased concrete cracks, and the occurrence of the creep phenomenon (Song, Baek, Lee, & Hong, 2021; Kolias, Georgiou, & Tsiatis, 2005; Piasta & Zarzycki, 2017). The ongoing loss of moisture without proper curing will lead to permanent weakness of concrete due to incomplete cement hydration (Ait-Aider, Hannachi, & Mouret, 2007). Differences in moisture and temperature between the concrete surface and the subgrade can cause concrete curling (Lim, Jeong, & Zollinger, 2009). Authors Song, Baek, Lee, & Hong (2021) concluded that mechanical shear connections between CLT panels and concrete are unprotected areas where moisture can penetrate from the concrete during the production of timber-concrete composite slabs. It was observed that moisture migration from concrete to CLT caused degradation and delamination of the wood structure. To prevent moisture penetration from the concrete to the CLT during the concrete curing period, the shear bonding method was used, using an epoxy adhesive between the CLT and the concrete. The method used minimised the impact of moisture on both components, allowing concrete to retain its compressive strength after hardening and preventing delamination in CLT slabs.

Previous research has shown that CLT and GLT absorb water differently depending on grain orientation, adhesive type, and exposure conditions, and that excessive moisture can cause dimensional instability, fungal growth, and deterioration of mechanical properties. Although moisture-related issues are well recognised, most existing studies focus either on long-term environmental exposure or on individual timber products in isolation. However, there are gaps in the literature regarding comparative studies that examine CLT and GLT under the same short-term wetting conditions relevant to construction sites, evidence linking the moisture absorbed by timber to measurable changes in the physical and mechanical properties of the concrete layer, and limited evaluation of surface treatments aimed at reducing moisture ingress at the timber-concrete interface.

The study provides a comparative analysis of two timber surface treatments: a natural oil treatment and a flexible two-component waterproofing slurry applied to both CLT and GLT under simulated rainfall conditions before concrete casting. It offers quantitative evidence of how the choice of surface treatment affects early-stage moisture transfer between wood and concrete and, consequently, influences the physical and mechanical properties of concrete at the timber-concrete interface. This highlights the sensitivity of concrete hardening conditions to the moisture content of CLT and GLT elements during construction. The findings deliver new practical guidelines for selecting surface treatments in timber-concrete composite construction, where early-stage moisture is crucial.

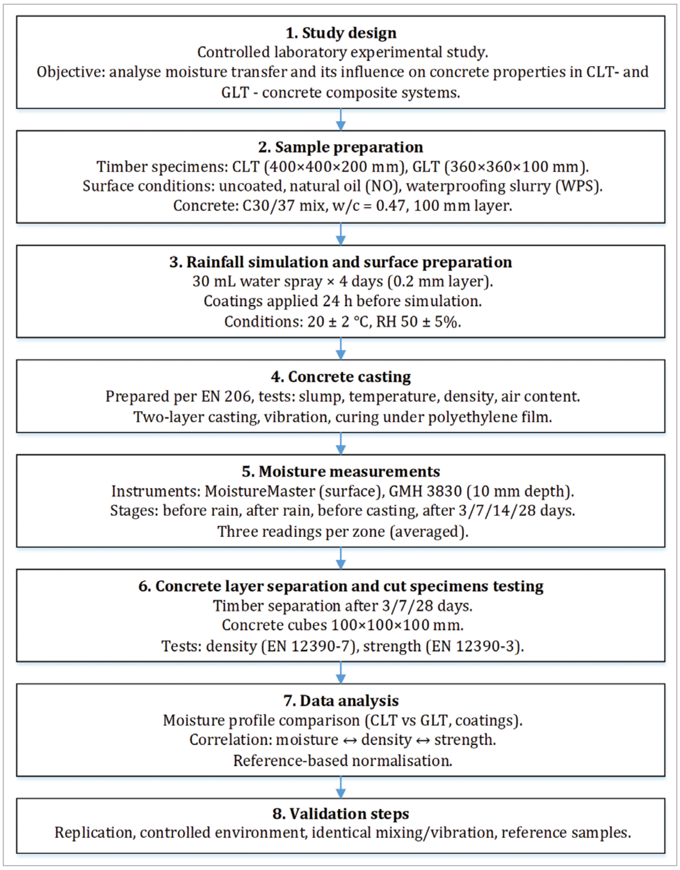
Materials and testing methods

An experimental study was conducted in KTU's controlled laboratory. This empirical research, involving physical testing and quantitative measurements, followed the experimental workflow diagram illustrated in Fig. 1.

Timber specimens and coating application. A total of seven composite specimens were prepared: four CLT-concrete composite specimens and three GLT-concrete composite specimens, each with three surface conditions: (1) uncoated reference, (2) coated with natural oil (NO), and (3) coated with waterproofing slurry (WPS). The timber specimen characteristics were as follows: CLT specimens - 400×400×200 mm spruce panels (see Fig. 2a) with outer lamella C24 (Mayr-Melnhof

Holz, 2024) and GLT specimens - 360×360×100 mm spruce panels (see **Fig. 2b**) of GL24h class (Jūrės medis, 2024).

Based on a literature review, two treatments for timber surfaces that had not been investigated previously were selected for the research: natural oil (NO) for wood treatment and a flexible two-component waterproofing slurry (WPS). NO's technical data state that it is based on white mineral oil and is non-toxic, solvent-free, colourless, and odourless. Application: used to protect wood against moisture, drying out, cracking, and splitting. WPS's technical data are as follows: it is based on compound A (a mixture of cement with mineral fillers) and compound B (a dispersion of



1. Study design
Controlled laboratory experimental study.
Objective: analyse moisture transfer and its influence on concrete properties in CLT- and GLT - concrete composite systems.

2. Sample preparation
Timber specimens: CLT (400×400×200 mm), GLT (360×360×100 mm).
Surface conditions: uncoated, natural oil (NO), waterproofing slurry (WPS).
Concrete: C30/37 mix, w/c = 0.47, 100 mm layer.

3. Rainfall simulation and surface preparation
30 mL water spray × 4 days (0.2 mm layer).
Coatings applied 24 h before simulation.
Conditions: 20 ± 2 °C, RH 50 ± 5%.

4. Concrete casting
Prepared per EN 206, tests: slump, temperature, density, air content.
Two-layer casting, vibration, curing under polyethylene film.

5. Moisture measurements
Instruments: MoistureMaster (surface), GMH 3830 (10 mm depth).
Stages: before rain, after rain, before casting, after 3/7/14/28 days.
Three readings per zone (averaged).

6. Concrete layer separation and cut specimens testing
Timber separation after 3/7/28 days.
Concrete cubes 100×100×100 mm.
Tests: density (EN 12390-7), strength (EN 12390-3).

7. Data analysis
Moisture profile comparison (CLT vs GLT, coatings).
Correlation: moisture ↔ density ↔ strength.
Reference-based normalisation.

8. Validation steps
Replication, controlled environment, identical mixing/vibration, reference samples.

Fig. 1
Diagram of the experimental workflow

a) Cross-laminated timber (CLT) specimens

b) Glue-laminated timber (GLT) specimens

Fig. 2
View of glued timber specimens

polymers in water); the density of the mixed product is approximately 1.48 kg/m^3; the mixing ratio for brush application is 24 kg of compound A per 8 litres of compound B; application temperature: from +5°C to +25°C; crack bridging ability is ≥ 0.5 mm according to ZUAT-15/IV.13/2002. Application: it is designed for waterproofing and damp-proofing on deformable and non-deformable mineral substrates. The surfaces of the CLT (**Fig. 3a**) and GLT (**Fig. 3b**) specimens were divided into three parts: one was left uncoated (reference), the second was coated with NO, and the third was coated with WPS.

NO and WPS were applied to the surface of the CLT and GLT specimens one day before the rain simulation test. Before the test, the WPS was manually mixed from compounds A and B at an 8:1 mixing ratio, while NO was already prepared for use by the manufacturer. The coatings were applied uniformly in a continuous layer across the entire exposed surface, with special attention given to the edges and corners to ensure full coverage. In this case, the NO and WPS coatings were applied in two layers using a brush. The first layer was applied horizontally to the surfaces of the test specimens, while the second was applied perpendicular to them. Care was taken to avoid excess material buildup, too. After the application, the specimens were left to cure under laboratory conditions.

Fig. 3

A view of timber specimens with applied coatings on their surface: WPS, NO, and without coating (order is presented from top to bottom)

a) CLT test specimens with coatings

b) GLT test specimens with coatings

Concrete mixture composition and preparation. The concrete mix components necessary for the research were delivered from the concrete mixing plant UAB Kauno gelžbetonis in Lithuania (2023). An ordinary concrete (OC) of C30/37 strength class and S3 slump class, typically used for on-site monolithic concrete slab concreting, was chosen for this research. Its composition was similar to that of the concrete mixing plant. Portland-limestone cement CEM II/A-LL 42.5 R, satisfying the requirements of EN 197-1:2011, was used as a binder for OC. The physical and mechanical properties of the cement were as follows: water demand for standard consistency (Vicat method) was 29.9%, initial setting time was 130 minutes, and compressive strength after 2/28 days was 30/51 MPa, respectively. Sand with a fraction of 0/4 from the Zatyšių query was used as a fine aggregate. It has the following characteristics: dry bulk density of 1587 kg/m^3, specific gravity of approximately 2.65, fineness modulus of 3.1, and moisture content of 5.1%. Gravel of fraction 4/16 and crushed gravel of fraction 4/16 from the Zatyšių query were used as a coarse aggregate. The physical properties of the gravel and crushed gravel were as follows: dry bulk density of 1585 kg/m^3 and 1385 kg/m^3, respectively; specific gravity of approximately 2.79, respectively. The particle size distributions of both fine and coarse aggregates met the requirements of standard EN 12620:2002+A1:2008. A superplasticising admixture, Dynamon NRG-400 (Mapei AS), based on a modified acrylic polymer blend, was used. It has the following technical characteristics: an amber liquid, a density of approximately 1.07 kg/L, a dry solids content of approximately 30.0%, a pH of approximately 6, and a viscosity of approximately 30 mPa.s. The dosage of admixture was 0.6% of the cement mass. A viscosity-modifying admixture, Sika Stabiliser-4 R (Sika AS), was used to enhance the stability and cohesiveness of the concrete mix, based on a modified starch complex. It has the following technical characteristics: a violet liquid, a density of approximately 1.07 kg/l, and a pH value of approximately 7.5. The admixture dosage was 0.2% of the cement mass.

The amounts of materials (in kilograms) per cubic meter of the mix were as follows: 360 kg of Portland-limestone cement, 886 kg of sand in the 0/4 mm fraction, 460 kg of gravel and 470 kg of crushed gravel, both in the 4/16 mm fractions, 2.16 kg of superplasticiser, and 0.72 kg viscosity-modifying admixture. The water-to-cement ratio was 0.47. The fresh concrete was prepared in the laboratory in accordance with standard EN 206:2013+A2:2021. The concrete mixtures were prepared using dry materials and a Zyklos rotating pan mixer, model ZZ 50 HE, from Pemat. The mixing was done according to the following stages (Fig. 4):

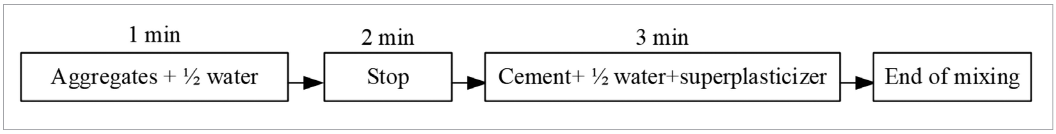


Fig. 4

The stages of mixture preparation

Fresh concrete properties. After the concrete was prepared, the following fresh concrete properties were assessed: the temperature of the fresh concrete was measured according to the standard EN 12350-1:2019; the slump test was conducted in accordance with EN 12350-2:2019; the density was determined following EN 12350-6:2019; and the air content of the compacted fresh concrete was measured as per EN 12350-7:2019.

Table 1

Determined fresh concrete properties

Marking	Temperature, °C	Slump, mm	Density, kg/m3	Air content, %	Ambient temperature, °C	Ambient relative humidity, %
C-0 (ref.)	18.6	250	2380	2.9	21.0	53.1
C-1	21.7	260	2300	5.4	21.5	51.6
C-2	21.1	250	2370	2.1	21.5	51.6

Table 1 shows the properties of fresh concrete for each batch, with data presented as the average of test results. The mean values of the properties of the fresh concrete mixture were as follows: the mixture temperature was approximately 20.5 °C, the slump was approximately 250 mm, the air content was approximately 3.5%, and the density was approximately 2350 kg/m^3.

Timber-concrete test specimens' preparation. The CLT and GLT concrete composite specimens were cast in parallel with the cubes. In this case, CLT (Fig. 5a) and GLT (Fig. 5b) specimens with surface coatings were used to prepare the moulds. Vertical elements made from 18-mm-thick film-faced plywood surrounded the timber specimens. These vertical mould parts were coated with a water-soluble emulsion about 60 minutes before casting in each test. The gap between the CLT and GLT specimens and the formwork was sealed using a hermetic sealant. During the concreting stage, a scenario in this research was employed in which the surfaces of the CLT (Fig. 5c) and GLT (Fig. 5d) test specimens were wetted to simulate rainy conditions at a construction site. Moisture absorption into the CLT specimen should occur through the longitudinal surfaces, while for the GLT specimen, it should occur through the end-grain edges.

Rainfall simulation. The rain simulation procedure was as follows: the surfaces of the timber specimens, with and without coatings, were sprayed with water for 4 days, using 30 mL per spray. In this case, a 0.2 mm layer of water should form on the surface of the timber specimens with coatings. Specimens were stored under laboratory conditions at 20±2 °C and 50±5 % relative humidity.

In both cases, a 100mm-thick layer of concrete was formed over the timber specimen. Sixteen litres of fresh mix were required for a single specimen to form a 100mm-thick concrete over the timber specimen in the case of CLT-concrete composite specimens. Four specimens were cast. In comparison, approximately 13 litres of fresh mix were required to form a 100 mm-thick concrete layer over the timber specimen in GLT-concrete composite specimens. Three specimens were cast. Each test specimen was cast in two layers, consuming an 8-litre and a 6.5-litre load bucket for each layer, respectively. The fresh concrete was manually placed into the moulds (**Fig. 6a**). After the first layer was poured, the second layer was poured immediately. To compact fresh concrete, a portable electric concrete vibrator, the ENAR Dingo, was used, with the following technical specifications: 13.750 vibrations per minute, 230 V (50 Hz), and a flexible shaft. The vibration began when the 25 mm-diameter poker head was inserted into the fresh concrete. The vibration time was measured using a digital stopwatch. Each time, the optimal vibration time was close to 15–20 seconds (**Fig. 6b**).

Fig. 5

A view of timber specimens prepared for concreting


a) CLT test specimen with a dry surface
b) CLT test specimen with a wet surface
c) GLT test specimen with a dry surface
d) GLT test specimen with a wet surface

Fig. 6

A moment of the CLT-concrete composite specimens' preparation


a) poured fresh concrete
b) compacted fresh concrete
c) hardened concrete

Curing, separation, and test-specimen cube preparation. After casting, the CLT and GLT-concrete composite specimens were stored in laboratory conditions at a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5% (**Fig. 6c**). During the curing period, a polythene film was applied to the top of the specimens to prevent water evaporation from the concrete. After 3, 7, and 28 days, the CLT and GLT (**Fig. 7a**) specimens with NO and WPS coatings were separated from the surface of the hardened concrete layer (**Fig. 7b**). After the separation process, the concrete specimens were cut into cubes of 100×100×100 mm (**Fig. 7c**) using a Cedima CTS-200 table saw with a diamond saw blade to assess the density and compressive strength of hardened concrete after 3, 7, and 28 days of curing.

Disassembly of the CLT-concrete composite specimen

Disassembly of the GLT-concrete composite specimen

a) view of timber surface with coatings

b) view of the concrete layer surface

c) view of cut cubes from a concrete block for testing

Fig. 7

A moment of the test specimens' cube preparation

a) Laserliner MoistureMaster device

b) Greisinger GMH 3830 moisture meter

Fig. 8

A moment of the moisture measurement

Moisture measurements. To evaluate the effectiveness of each coating in reducing moisture ingress into the timber and its transfer into the concrete layer, moisture levels at the timber surface and at a 10 mm depth were measured during the research. For the surface moisture measurements, the portable Laserliner MoistureMaster device was employed (Fig. 8a). The surface moisture of CLT and GLT specimens was measured during and after rain simulation, before the concreting process, and after 3, 7, 14 and 28 days of concrete curing when the concrete layer was separated from the timber specimen. The technical specifications were as follows: the measurement principle was capacitive, using integrated rubber electrodes, and the measurement range/accuracy were as follows: for concrete, 0... 5%/±0.5%, and for wood (spruce), 0... 60%/±2%. Moisture was measured in three randomly selected areas of the specimen without coating, with NO coating, and with WPS coating, as well as in the concrete layer. The final result was presented as an average value.

In comparison, the Greisinger GMH 3830 moisture meter was used to measure the moisture content of timber specimens at a depth of 10 mm (**Fig. 8b**). Measurements were carried out during and after rain simulation, before the concreting process, and after 3, 7, 14 and 28 days of concrete curing when the concrete layer was separated from the timber specimen. The measurement was done using appropriate electrodes and cables. The technical specifications were as follows: accuracy (wood) ±0.2%, measurement Range (wood) 0-100%. Photos were taken using a digital camera after the concrete specimens were removed from the moulds, which were stored under laboratory conditions. Moisture was measured in three randomly selected areas of the specimen without coating, with NO, and with WPS coatings, and the final result was presented as the average.

The density and compressive strength. To assess how moisture conditions in timber influenced the development of these properties in concrete, both parameters were analysed over time for all specimen types: concrete in contact with untreated timber, concrete in contact with NO, and concrete in contact with WPS, and all samples were compared to reference concrete cured under standard conditions. Tests on hardened concrete were conducted in accordance with EN 12390-7:2019 and EN 12390-3:2019 standards, respectively. The Toni Technik 2020 load frame, designed for compressive strength testing with a maximum load of 600 kN, was used in the study. Additionally, after measuring the properties of fresh concrete, test specimens, cubes measuring 100×100×100 mm, were cast in metal moulds following standard EN 12390-2:2019. The fresh concrete in the moulds was compacted using a vibrating table, with an optimal vibration time of approximately 15–20 seconds. These specimens were then used to determine the reference density and compressive strength of the hardened concrete after curing periods of 3, 7, 14, and 28 days under standard conditions.

Methodological rigour was maintained through: replicating measurements (three per region), using standard curing reference samples, taking repeated moisture readings with two instruments, controlling environmental conditions, applying identical mixing and vibration procedures to all concrete batches, and comparing results with established hydration behaviour described in literature. These procedures ensure reproducibility, internal consistency, and validation of observed effects.

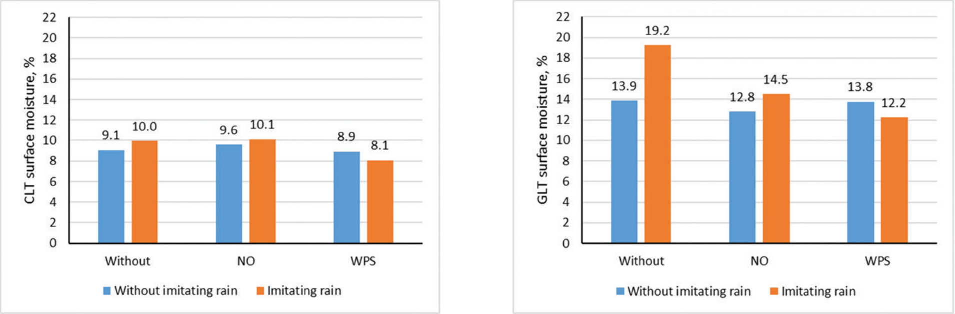
Results and discussion

This chapter compares moisture profiles, examines correlations between moisture and concrete strength, and normalises data against the reference analysis. It also investigates relationships between surface moisture and moisture at a 10 mm depth in timber, which in turn influence concrete density and compressive strength at corresponding time points, establishing a mechanistic link between moisture transfer and concrete performance.

Rain-simulation impact on moisture-content variations of timber specimens

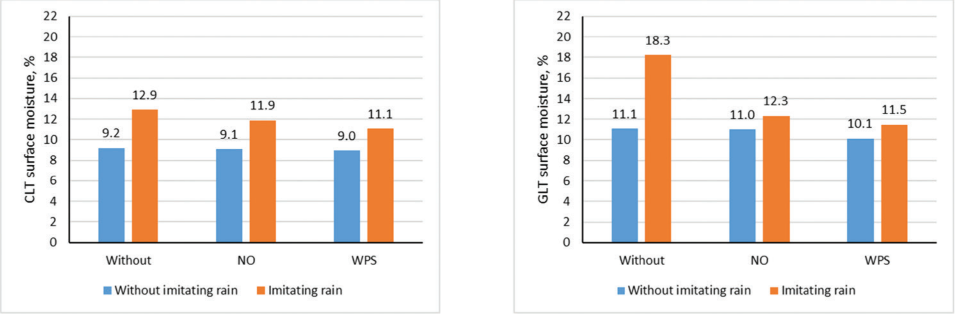
This chapter analyses the effect of short-term rainfall conditions on uncoated CLT and GLT specimens' moisture absorption. These findings can indicate whether tested timber types are susceptible to moisture uptake before concrete is cast.

From Fig. 9a, it is clear that the surface moisture measurements of CLT surfaces with and without coatings were similar, at approximately 9%, when rain was not simulated. 9% presents the initial moisture content of the CLT specimens' surface. The longitudinal surface moisture of the CLT specimens was quite similar for the surface without any coatings (10%) and for the surface coated with NO (around 10.1%), simulating rain, while the surface covered with WPS coating showed a slight decrease in surface moisture from about 9% to 8%. In contrast, the surface moisture measurements of the GLT specimens showed increased moisture when simulating rain on surfaces without a coating (from 14% to 19%) and on those coated with NO (from 13% to 15%). This is logical because the GLT specimens expose the wood's end-grain surface and its porosity. The water absorption of CLT panels decreased when the surface was covered with WPS coating, specifically from 14% to 12%. The initial surface moisture content of the GLT end-grain ranged from 12.8 to 13.9%.



a) Surface moisture measurements of the CLT specimen

c) Surface moisture measurements of the GLT specimen



b) Moisture measurements of the CLT specimen at a 10 mm depth

d) Moisture measurements of the GLT specimen at a 10 mm depth

Fig. 9

Moisture content variations of test specimens before the concreting process

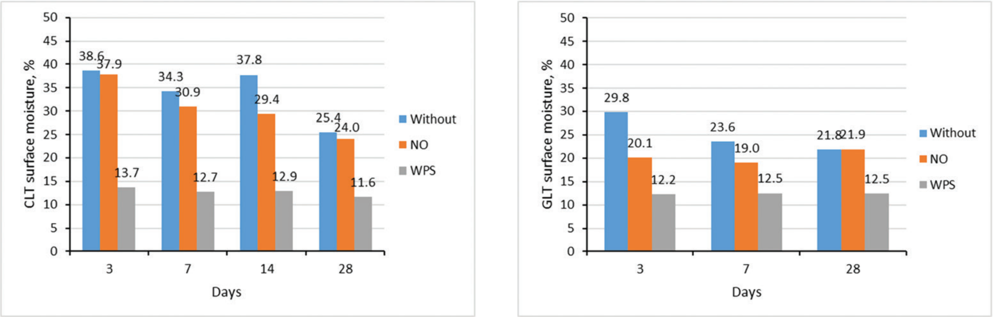
After conducting the surface moisture measurements, additional readings were taken at a depth of 10 mm in the timber. This aimed to determine whether the timber can absorb water through the coating. The graph in Fig. 9b indicates that the highest moisture content at a depth of 10 mm was observed in the CLT specimen without any coating, reaching 13%. For timber coated with NO, the percentage was 12%, and for wood coated with WPS, it was approximately 11%. Moreover, the moisture levels at this depth in CLT specimens, whether coated or not, were similar, around 9%, when rain was not simulated. In the case of GLT specimens, the highest moisture content at 10 mm was observed in the uncoated surface, at 18.3%, under simulated rain conditions. Lower moisture contents were recorded for surfaces coated with NO (about 12%) and WPS (about 11.5%), respectively. When rain was not simulated, the moisture levels at this depth in GLT specimens, whether coated or not, varied from 10% to 11%. The results show that the flexible two-component waterproofing slurry (WPS) coating can reduce water absorption into the wood in both CLT and GLT specimens during rain simulation.

Under the short-term rainfall conditions tested, both uncoated CLT and GLT absorbed more moisture than samples not exposed to rain simulation. Notably, CLT exhibited a greater moisture accumulation at a depth of 10 mm than GLT. This difference can be attributed to the wood grain structure and its porosity. These findings suggest that both types of timber are susceptible to moisture uptake before concrete is cast, but the extent and depth of absorption vary with the wood's specific properties.

It should be noted that, due to the limited number of GLT specimens, it was not possible to follow the same data-collection schedule as for the CLT test series at 3, 7, 14, and 28 days of curing without affecting the integrity of the experimental plan. Consequently, GLT measurements were performed only after 3, 7, and 28 days of curing, while the 14-day measurement was omitted. Therefore, the results corresponding to the 14-day curing period are not presented in Figures 10, 11, and 12.

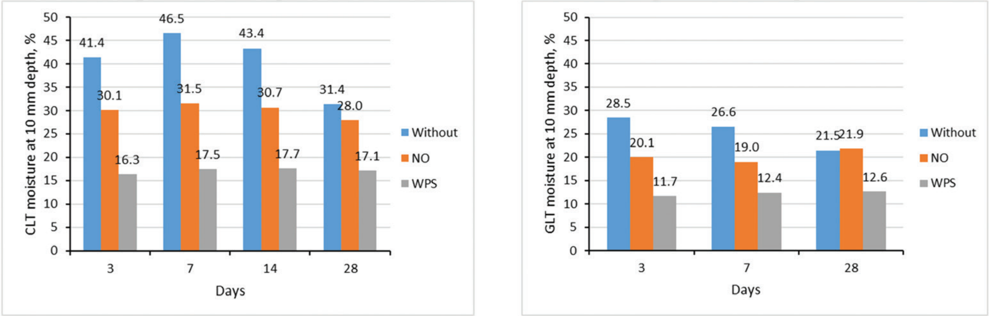
Fig. 10

Moisture measurement of test specimens when timber was separated from concrete



a) Surface moisture measurements of the separated CLT specimen

c) Surface moisture measurements of the separated GLT specimen



b) Moisture measurements of the separated CLT specimen at a 10 mm depth

d) Moisture measurements of the separated GLT specimen at a 10 mm depth

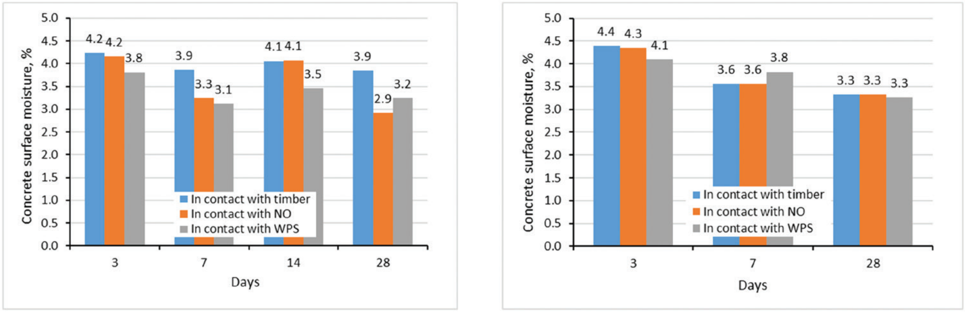
The coatings' impact on moisture migration and the concrete strength

This chapter analyses the hypothesis that WPS coating should produce the lowest moisture migration and the highest resulting concrete strength. This aligns with the case study, which shows that WPS coating most effectively reduces moisture transfer, creating a significantly more impermeable interface at the construction site.

As expected, the most significant variation in moisture content of the longitudinal timber surface of CLT was observed on the side in contact with the concrete layer, where the timber surface was uncoated (**Fig. 10a**). After 3 days of concrete curing, the average surface moisture content was 38.6%; after 28 days, it decreased to 25.4%. A reduction in moisture content in CLT from 38.6% to 25.4% (approximately 34%) indicates active moisture exchange between timber and concrete (**see Fig. 10a**). This decreases coincided with a 12% increase in concrete strength (**see Fig. 12b**), implying a mechanistic relationship: higher early moisture levels inhibit hydration, while drying stabilises the curing environment. For the GLT specimens, the average surface moisture content after 3 days reached 29.8%, and after 28 days, it declined to 21.8%. As a result, concrete over GLT shows smaller strength (**see Fig. 12d**) loss (compared to CLT), likely because moisture flux is more uniform and does not excessively increase the local w/c ratio. Lower surface moisture levels were found on the timber surface coated with the NO coating for both CLT and GLT specimens. The natural oil on the timber surface likely forms a film that limits water penetration into the timber. The most notable reduction in surface moisture was observed on CLT and GLT surfaces coated with the flexible two-component waterproofing slurry (WPS). After 28 days of curing, the moisture content decreased by approximately 1.8 times relative to the uncoated surface of the CLT specimen at the same curing stage. In the case of the GLT specimen, the reduction in surface moisture content was about 1.7 times compared to the uncoated surface. Measurements of surface moisture content showed a decline as curing time increased.

For this research, moisture readings at a 10 mm depth in timber are essential to determine whether the wood can absorb water through the coating. The moisture levels in the CLT and GLT specimens, separated from the concrete layer, at a depth of 10 mm, are shown in **Fig. 10b** and **10d**, respectively. For CLT specimens, the uncoated timber surface in contact with concrete had the highest moisture levels at this depth (**Fig. 10b**). After 3 days of concrete curing, the average surface moisture content was 41.4%, increasing slightly to 46.5% after 7 days, then decreasing to 46.5% after 14 days, and further to 43.4% after 28 days. Specimens with the highest moisture content at a depth of 10 mm showed the lowest compressive strength. This inverse relationship remains consistent across all curing stages, indicating that internal timber moisture influences concrete hydration kinetics. In contrast, the CLT specimens coated with NO and WPS that were in contact with the concrete layer had lower timber moisture values at a 10 mm depth during the curing period. The NO coating reduced the timber moisture values at this depth by approximately 1.37 times after 3 days and 1.12 times after 28 days, compared to the uncoated timber surface. The WPS coating was the most effective in reducing water penetration into the timber. Compared to the uncoated timber surface, the timber moisture content at a 10 mm depth decreased by about 2.5 times after 3 days and by about 1.8 times after 28 days of curing. This reduction corresponds to a 6–10% improvement in 28-day strength (**see Fig. 12b**), indicating that WPS not only protects timber but also provides more favourable hydration conditions for concrete. The WPS coating reduced moisture absorption into the panel, and the moisture content (17.1%) returned to its original level, similar to that (11.1%) before the CLT concrete specimen concreting procedures. The authors (Song, Baek, Lee, & Hong, 2021) considered that CLT moisture can be dried by the sharp temperature rise in the concrete due to the hydration reaction that occurs immediately after the concrete is poured. This effect can reduce moisture content in CLT and GLT specimens.

Similar patterns in water moisture reduction were observed when measuring timber moisture content at a 10 mm depth in the case of the GLT specimens with and without coatings (**Fig. 10d**). However, the values determined were lower compared to those for the CLT specimen (**Fig. 10b**). The uncoated timber moisture content ranged from 28.5% to 21.5% over 28 days of concrete curing. The moisture likely transfers between concrete and timber during the 28-day curing period. According to Kalbe et al. (2022), the main pathway for moisture absorption into the CLT panel occurs through the end-grain edges. This suggests that end-grain edges and the porosity of GLT could facilitate water migration. When the GLT specimens were coated with NO, the timber moisture content at a 10 mm depth decreased by about 1.4 times after 3 days of curing, and after 28 days, it was very similar to that of the uncoated timber surface. The most significant reduction in timber moisture content at this depth was achieved by applying WPS coating to the surface of the GLT specimen. The graph in Fig. 10d shows that the timber moisture content at this depth decreased by approximately 2.4 times after 3 days of curing and by approximately 1.7 times after 28 days, compared to the uncoated timber surface. These results demonstrate that the flexible two-component waterproofing slurry (WPS) can effectively reduce moisture transfer from the concrete to the timber in the contact zone between the two materials.



a) CLT-concrete composite

b) GLT-concrete composite

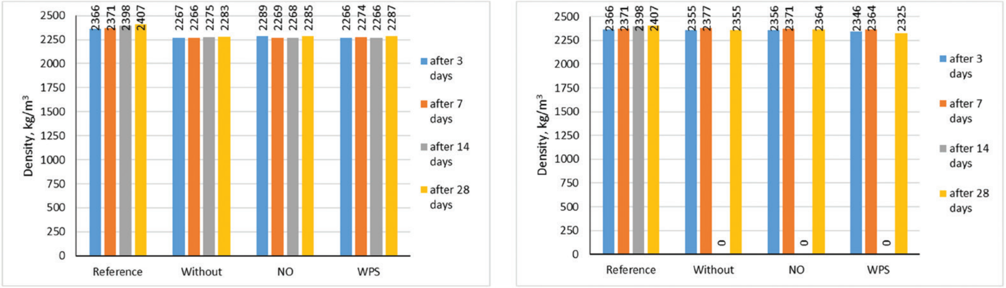
Fig. 11

Surface moisture measurement of the separated concrete layer

The variation in surface moisture within the separated concrete layer of the CLT and GLT specimens is shown in the graphs in **Fig. 11a** and **11 b**, respectively. From **Fig. 11a**, it is clear that surface moisture fluctuations are quite similar over the 28 days of concrete curing; that is, concrete in contact with uncoated CLT timber exhibits the highest values, which slightly decrease when in contact with the NO coating, and moisture levels drop further when in contact with the WPS coating. In the case of the GLT specimen, the concrete surface moisture in contact with the uncoated timber surface shows the highest content; it decreases when the NO coating covers the timber surface, and it continues to drop when the WPS coating is applied (**Fig. 11b**). During the initial hydration stage of cementitious materials, free water quickly interacts with these materials, leading to the formation of chemically bonded water. As hydration progresses, the amount of free water decreases while the quantity of chemically bonded water increases (Kong et al., 2020). The moisture content of concrete can decrease during curing because some water is chemically bound in hydration products, some is lost to evaporation, and some is redistributed or consumed internally due to self-desiccation.

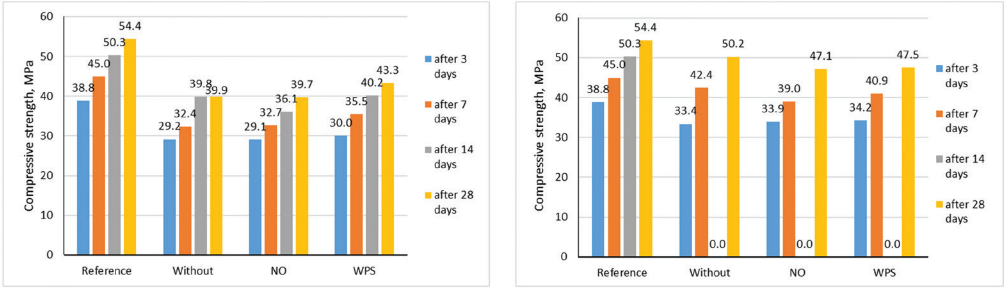
Fig. 12

Density and compressive strength of hardened concrete layer separated from timber specimens and cut into cubes 100×100×100 mm in size



a) Density of hardened concrete separated from the CLT specimen

c) Density of hardened concrete separated from the GLT specimen



b) Compressive strength of hardened concrete separated from the CLT specimen

d) Compressive strength of hardened concrete separated from the GLT specimen

Determined surface moisture on concrete, showing higher and lower values (**Fig. 11**), is likely linked to the density and compressive strength of the hardened concrete (**Fig. 12**). Authors (Lim, Jeong, & Zollinger, 2009) concluded that moisture loss in concrete results from both autogenous drying and conventional external drying. Autogenous drying, or self-desiccation, depends on the degree of hydration, which is expressed as the strength ratio derived from the maturity-strength relationship. During the curing of timber-concrete specimens, a polythene film was placed on top to prevent water evaporation, while the laboratory maintained an ambient temperature of 20 ± 2 °C and relative humidity of 50 ± 5%. The moisture at the timber-concrete interface maintains a wet condition, which can provide better curing conditions for the concrete. The variation in density and compressive strength of the hardened concrete, separated from the CLT and GLT specimens, is shown in the graphs in **Fig. 12**. These graphs illustrate the density and strength of 100×100×100 mm cubes cut from the separate concrete layer. The values obtained were compared with those of reference concrete cubes cured under standard conditions, i.e., in water at 20 ± 2 °C.

Whether the reference is concrete or concrete that was in contact with NO or WPS coating, it exhibits the same tendency: the density and strength of hardened concrete increase during the 28-day curing period, with properties related to increased cement hydration (Kumar Nair et al., 2021). The density of hardened concrete from reference specimens is higher than that of the concrete in contact with CLT and GLT timber. After 28 days of curing, the density of the concrete separated from the CLT specimen in contact with NO and WPS coatings decreases by approximately 1.05 times (see Fig. 12a), while that from the GLT specimen in contact with NO and WPS coatings decreases by about 1.02 to 1.04 times, respectively (see Fig. 12c), compared to the reference concrete. These lower density values are likely due to higher air entrainment in the fresh mixture. From Table 1, it is evident that mixture batch C-0 used for reference cubes contains 2.9% entrained air, while batch C-1 used for CLT-concrete specimens contains 5.4%, and the batch used for GLT-concrete specimens contains 2.1%. Fig. 12b demonstrates that hardened concrete in contact with the CLT specimen coated with NO and WPS coatings has lower compressive strength compared to both the reference concrete and the concrete in contact with the GLT specimen coated with the same coatings (Fig. 12d). According to the Federal Highway Administration (2020), a 1% increase in air content within concrete can cause about a 3 to 5% reduction in its 28-day compressive strength. This suggests that an increase in air content likely contributed to the reduction in concrete strength. However, even if a 3-5% decrease is estimated, it is evident that fluctuations in moisture content also contributed to the reduction in concrete's compressive strength. For the CLT specimens, the lowest compressive strength of concrete was observed when it was in contact with the uncoated wood surface during 28-day curing period, compared to the highest values achieved when in contact with the WPS coating (Fig. 12b). When the uncoated wood surface contacted the concrete, it exhibited the highest moisture content at a depth of 10 mm (Fig. 10b), whereas the values decreased when in contact with the WPS coating. A somewhat different situation was seen with the GLT concrete specimens. The compressive strength of concrete in contact with uncoated wood, NO, and WPS coatings was higher compared to the strength of concrete in contact with the CLT specimen, regardless of whether it had coatings. Results show that the concrete separated from the CLT specimen exhibited higher strength when in contact with coatings, but these values were lower than those of the reference concrete. In the case of GLT- concrete specimens, the concrete separated from the CLT specimen exhibited higher strength in contact with timber without coating, compared to the contact with NO and WPS coatings.

Among all investigated surface treatments, the WPS coating showed the highest effectiveness in limiting moisture migration, decreasing water ingress by about 2.5 times in CLT and 2.4 times in GLT after three days. This result indicates that WPS creates a significantly more effective moisture-barrier interface than the alternative treatments. This reduction is directly linked to improved concrete performance: strength increased by 9.4% (CLT) and 7.8% (GLT) relative to uncoated samples. These findings support the hypothesis that controlling moisture at the timber–concrete interface helps stabilise the early-age hydration process, reduces porosity development, and enhances compressive strength.

An experimental scenario was used in which the surfaces of the CLT and GLT test specimens were wetted to simulate rainy conditions at a construction site. By identifying surface treatments that regulate moisture absorption without adversely affecting material compatibility, it becomes possible to extend the service life of timber-concrete composite structures, improve construction reliability, and minimise material waste during both construction and operation. This research advances knowledge of sustainable hybrid structural systems that integrate bio-based materials with mineral components to reduce embodied carbon and improve resource efficiency.

Timber-concrete composites are increasingly recognised worldwide as a key solution for low and mid-rise buildings, retrofits, and long-span floor systems. This is especially important at the national level after the entry into force of the Ministry of the Environment of the Republic of Lithuania (2024), by Order No. D1-359 states that from 1st of November 2024, at least 50% of wood and other organic materials derived from renewable natural resources must be used in the construction of new buildings.

Based on the research results, designers should explicitly consider construction-stage moisture exposure when developing structural details and material specifications for timber–concrete composite systems. This includes anticipating short-term wetting from rainfall, construction delays, or temporary storage conditions, and reflecting these scenarios in the selection of timber products, surface treatments, and interface detailing. At the construction level, contractors should adopt transparent, standardised on-site protocols for timber surface preparation prior to concrete placement. These protocols should address temporary weather protection measures, such as covering exposed timber elements, controlled pre-wetting or drying procedures, and visual or instrumental checks of surface moisture content before casting. Such measures reduce variability in concrete curing conditions and help ensure consistent mechanical performance across the composite slab. Additionally, the selection of timber surface treatments should not be driven solely by adhesion requirements or ease of application. Instead, surface treatments should be evaluated based on their ability to regulate moisture exchange at the timber-concrete interface during early-age concrete curing, when both materials are susceptible to moisture effects. Treatments that effectively limit excessive moisture uptake by timber can stabilise the curing environment of the concrete, reduce strength variability, and mitigate risks of long-term degradation or differential movement. Incorporating these considerations into design guidelines and construction specifications can significantly improve the robustness, durability, and sustainability of timber-concrete composite structures.

Conclusions

1. Under the applied short-term rainfall conditions, uncoated CLT and GLT absorbed more moisture compared to those without rain simulation. CLT showed greater moisture accumulation at a 10 mm depth than GLT, due to the wood's grain exposure and its porosity. These observations indicate that both timber types are susceptible to moisture uptake before concrete casting, but the extent and depth of absorption depend on the wood's specific properties.
2. NO and WPS surface coatings reduced moisture ingress to some degree, but WPS demonstrated substantially higher effectiveness. After 3 days of concrete curing, the moisture at a 10 mm depth was reduced by approximately 2.5 times in CLT and 2.4 times in GLT compared to uncoated specimens.
3. Concrete cast directly on uncoated timber showed lower density and decreased compressive strength compared to reference concrete. This decline is linked to higher moisture levels at the timber–concrete interface, indicating that excessive early-age moisture hinders hydration and diminishes mechanical performance. In all cases, concrete in contact with WPS-coated timber achieved greater strength than concrete cast on uncoated timber, suggesting that reducing moisture transfer can enhance curing conditions.
4. The findings suggest that managing short-term moisture exposure during construction can help maintain more consistent concrete curing conditions and reduce performance variability. These implications are specific to the CLT and GLT products, coating systems, and environmental boundary conditions examined in this study. This study emphasises early-age moisture dynamics under controlled laboratory conditions and does not address long-term moisture behaviour, cyclic wetting and drying, or other construction scenarios. Further research is needed to investigate long-term behaviour, different wood species, adhesive systems, and alternative coating materials.

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About the authors

MANTAS ŠIRVINSKAS

Master's student at the Faculty of Civil Engineering and Architecture

Kaunas University of Technology, Faculty of Civil Engineering and Architecture

Main research area

Civil engineering

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
E-mail: mantas.sirv@gmail.com

SVAJŪNAS JUOČIŪNAS

Lecturer at the Faculty of Civil Engineering and Architecture

Kaunas University of Technology, Faculty of Civil Engineering and Architecture

Main research area

Civil engineering, construction technology

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
E-mail:
svajunas.juociunas@ktu.lt

MINDAUGAS DAUKŠYS

PhD at the Faculty of Civil Engineering and Architecture

Kaunas University of Technology, Faculty of Civil Engineering and Architecture

Main research area

Civil engineering, construction technology

Address

Studentu str. 48, LT-51367
Kaunas, Lithuania
E-mail:
mindaugas.dauksys@ktu.lt