Architectural Design from Upcycled Formwork Wood:

Perspectives on New Physical and Aesthetic Qualities of Salvaged Formwork Wood, Computer Vision and Algorithm-Assisted Façade Design

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Abstract

In Finland and many other countries worldwide, standard-quality wood is used as a building material in countless ways, from permanent to temporary uses as auxiliary construction and formwork. Unfortunately, formwork is difficult to clean after its use, which is why the construction industry considers it contaminated, no longer usable and, therefore, waste, and usually sends it to energy recovery. However, the remaining concrete on the formwork wood can be considered a process that can give the boards physical and aesthetic properties not previously considered. The research investigates how salvaged formwork wood performs compared to rough-sawn wood under natural weather conditions based on concrete coverage percentage. It assesses mechanical properties, ageing, and color changes, aiming to find the best fit for each board in new architectural applications such as facades while enhancing durability, and predicting future appearance for sustainability and design values. Our research employs a comprehensive approach that combines quantitative and qualitative methods, as well as architectural design techniques, to investigate the characteristics and behavior of used concrete formwork wood, considering both untreated and oil-treated variants. The properties of salvaged wood material are experimentally investigated. We (i) photographically scan each wood board to determine concrete coverage using image processing and computer vision, and (ii) conduct combined sun and water absorption tests to understand the performance and color changes of the individual boards. We show that sun exposure enhances water repellency for natural boards and both types of formwork wood, untreated and oil-treated, but comparably, formwork wood exhibits significantly lower water absorption rates. Our results identify oil-treated boards as the most water-repellent but with increased water absorption for elevated temperatures, often associated with sun exposure. These findings are used as input data to create algorithm-assisted customized architectural designs using a color gradient system. This method is a valuable tool for forecasting the surface color and its evolution over time that inversely also refers back to the identified performance of the board. We showcase façade designs on two scales, featuring a realized demonstrator using salvaged formwork wood and a façade study for the CE building at Aalto University, Espoo, Finland, both of them include ageing color gradient-based simulations alongside actual weather and climate data.

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Keywords: Formwork wood; Computer Vision; Upcycle; Timber Façade, Sustainability, Architecture.

Wooden formworks are traditionally single-use in the construction industry; how can we develop new solutions to recycle this material in new fields using AI to analyze the surface properties and design generated façades?

Introduction

It is well known, our planet is amongst other issues running out of resources, and we need to find new alternatives to raw virgin materials. Simultaneously, the construction industry is one of the main contributors to climate change, and in 2018, the building and construction sector was responsible for 36% of the global energy use and 39% of energy and process-related carbon dioxide emissions worldwide ('2019 Global Status Report for Buildings and Construction', 2019). Moreover, these numbers are increasing yearly. Studies show that in the US, the quantities of construction and demolition (C&D) waste grew ten times faster from 2005-2018 than between 1990-2005 (US EPA, 2017). By 2025 2,2 billion tons of construction waste annually will be generated worldwide (*Construction Waste Market*, no date). Up to 30% of the on-site materials of a new building end up as waste (Osmani, 2011), and according to EPA 2020 (EPA, 2020), more than 75% of the generated waste (wood, drywall, asphalt shingles, bricks and clay tiles) are sent to landfill. With a growth rate of 4,4% per year, wood is becoming increasingly popular in construction and it is mainly used for formwork (Adhikari and Ozarska, 2018). Formwork wood is low-priced, lightweight, thermally resistant, and easy to process and adapt to customized shapes, contrary to steel formwork, which is more expensive and usually has fixed dimensions. However, wooden formwork is used once or twice only in construction for several reasons including costs for surface cleaning, logistics, storage, and extraction of nails and screws before reuse. These economically driven decisions result in a significant negative ecological impact. It is known that wooden formwork generates 20 to 30% of the total construction waste (Hao *et al.*, 2018) due to explained short service life despite its remaining good quality as a material (Ruan, Filz and Fink, 2022d). Even though it could be upcycled for different functions or recycled for material utilization in products this wood is often sent to energy recovery (Sommerhuber, Welling and Krause, 2015). Besides the attempt to reduce material consumption, strategies and concepts are nowadays developed to reuse and prolong (Niu et al., 2021), cascade (Sakaguchi et al., 2017) or even upcycle this material for new products and uses including new architectural designs (Harjani, 2020; Nicolas and Filz, 2022). The research tries to rethink such approaches and offers a novel proposal.

From waste to resource to application

In Finland in 2021, 9% of the total dry wood mass used was bound in paperboard and 8% in paper, pulp accounted for 10%, wood-based panels accounted for 2%, and sawn wood accounted for 12% (Luke, 2022). According to the Natural Resources Institute Finland (Luke), the total consumption of wood dry was 40.4 million tons - the largest amount in the history of the statistics, with 4.387 million tons accounted for by sawn wood products. Without giving exact numbers, (Puuinfo, 2020) mentions concrete moulds as one of the most common uses for quality classes VI and VII of sawn wood. However, even in the absence of exact numbers from the industry, one can imagine the amount of formwork wood consumed as a single use.

Interchangeability of used terms for formwork wood

In this research, we are usually referring to wood that has previously been used as temporary structures in which concrete has been poured to shape it as it sets. Depending on the context, we may also interchangeably use terms such as "concrete moulds", "moulds", "formwork", "timber boards" etc., instead of exclusively the term "formwork wood" for better readability purposes.

Overview of this paper and guiding questions

This research is at the threshold of architecture and civil engineering. It is in the light of sustainability and responsible use of limited resources, and it aims to link studies of the modified material and surface properties and experiments with architectural, visual, and aesthetic aspects.

This paper opens with a short introduction to pressing aspects of material use and waste in the building sector with an emphasis on formwork wood. Hereafter, we provide an overview of our hypothesis and consequently present 3 summarized research questions. The aims, but also the limitations are explained before providing an overview of quantitative, qualitative and architectural methods for observation and evaluation of the wooden formwork boards as well as architectural design methods for simulation and demonstration of applicability. The investigations of this paper are then split into the following main chapters;

- “Wooden boards from concrete moulds”, explains the collecting, categorizing and preparing of the wooden boards before analyzing their concrete coverage ratio, as well as providing an overview of the results of this chapter;
- “Salvaged formwork wood in weathering conditions: suntests, color change evaluation, and water absorption tests”, gives insights into the performed tests as well as providing an overview of the results of this chapter;

The chapter “A combined interpretation of test results: generating data for the “best fit” and color predictability”, provides a more holistic view of the aforementioned chapters and their individual results. The chapter “Façade design and demonstrator with salvaged formwork wood” shows how the gained results are implemented and transformed into a full-scale demonstrator. The last chapter “Application on large-scale buildings: Helsinki”, applies the insights and workflow within the framework of a so-called speculative design study, aiming to find emergent visual performance by applying longer- simulations for a specific façade design. Finally, the chapter “Discussion, Conclusion and Outlook” discusses the gained results, and reflects on possibly new material and design perception in the framework of salvaged material, before sketching future research and expected economic, environmental and societal impact of proposed approaches.

Hypothesis and research questions

New concepts and ideas often come from looking at the same thing in a creative (Deo, Hölttä-Otto and Filz, 2020), novel and different angle (Filz, 2020; Ruan, Filz and Fink, 2022, 2022b, 2022c). During use, the formwork wood was exposed to concrete, and its traditional components of water, sand, and cement. In this sense, we look at formwork wood as a (modified) material that possibly has gained value through its use, instead of being at the end of its life after use.

As a central aspect, this work proposes to recognize formwork wood as a new material source with modified and hypothetically upgraded properties compared to the virgin material. In this context, the overarching research questions are:

1. What are the new (surface) properties of wooden boards from concrete formwork?
2. When used as façade panels and exposed to natural weather conditions, how do they perform compared to untreated, sawn wooden boards of the same species?
3. And what will be the visual appearance of such facades from reclaimed formwork wood?

Aims

The aim of our research is to investigate how salvaged oiled or unoiled formwork wood used for concrete formwork, compared to rough-sawn formwork wood, performs under natural weather conditions such as rain and sun, depending on the percentage of concrete coverage of the boards´ surface. This research aims not only to examine and compare the mechanical material properties but also to assess the ageing behavior and associated color changes. With this approach, the ultimate objective is to computationally find the "best fit", exemplified for facade applications, for each individual wooden board, thereby increasing the durability of the application. Simultaneously, by simulating long-term color changes, this research seeks to predict the future visual appearance of the facade. Overall, the aim is to purposefully utilize formwork wood as a material resource, contributing to sustainability in terms of material consumption as well as aesthetics and design values.

Overview of used methods

Our research employs a comprehensive approach that combines quantitative and qualitative methods, as well as architectural design techniques, to investigate the characteristics and behavior of used concrete formwork wood, considering both untreated and oil-treated variants. As a reference, we compare these findings with natural, sawn wooden boards, particularly Spruce, which is the dominant species for this application in Finland. This holistic approach allows us to gain valuable insights into the boards` material properties and its potential applications.

In the quantitative aspect of our research, we undertake manual processes to collect and categorize wooden formwork boards from construction sites. This process provides us with a comprehensive overview of how these boards have been used and whether they have undergone pretreatment with or without oil. To further enhance our understanding, we document weather data at the time of collection, including exposure to sunlight, temperature fluctuations, and wet/dry weather conditions.

In our qualitative evaluation, we utilize standardized methods for suntests and water absorption tests, both as separate and combined studies. Additionally, we employ a digital image processing technique developed by the authors to assess board surfaces, concrete coverage ratios and monitor color gradients over time. These methods allow us to delve deeper into the boards´ mechanical and visual response to environmental factors such as UV (Ultraviolet) exposure and moisture.

Based on the results and insights gained from quantitative and qualitative analyses, we explore speculative façade design concepts that emphasize the wood's color changes over time through computational simulations. We developed algorithms that assign the individual wooden board in stock in a best-fit logic to a specific location on a façade. Our case studies and a physical demonstrator in Espoo, Finland, serve as practical demonstrations of our approach, highlighting its workflow, feasibility, and reliability. These real-world applications complement the architectural methods and viewpoints. Finally, a large-scale speculative façade design concept aims to predict the wood's color changes over time and is computationally explored.

Limitations

- We focus on wooden boards (Finnish Spruce), which typically come in cross-sectional dimensions of about 10 x 2.5 cm and 4m length. This is the predominant species used as formwork wood in Finland and other European countries. Other wood species and wood products such as plywood are not considered in our study for now.
- Presently, we assume the wooden boards for façade applications. In this sense, the boards will be exposed only to natural weather conditions. This way, further mechanical, physical or chemical influences as they would

happen in the case of wooden flooring, wooden decks, or structural use are excluded.
- For now, we have not performed separate studies for different mixtures of concrete or specific sorts of formwork oil.
- The process of curing including its thermal effect and the pressure of the self-weight on the formwork as well as the weather conditions may have an impact on the surface of the formwork wood, but for now, they were not considered in the presented study.

Wooden boards from concrete moulds

In Finland and many other countries, sawn wooden boards in addition to other wooden products are used as formwork for concrete moulds. Mostly the boards are from quality classes VI and VII, but often we find higher class boards, when the concrete surface is supposed to meet specific visual standards and requirements. Such qualities are used for exposed concrete surfaces in architecture, civil structures such as concrete bridges, and many other applications.

The wooden formwork boards are used both ways untreated and as oiled boards. Oiled boards are used for easier de-moulding to facilitate the peeling-off process after curing. Only the surface exposed to concrete is usually oiled. However, if high demands are made on the surface quality, and stains must be avoided, untreated, natural bards are used, to have the wooden boards' surface pattern as a print on the later concrete surface, referred to as exposed concrete or béton brut (Gargiani and Rosellini, 2014; Günther H. Filz *et al.*, 2020) in modern architecture.
As mentioned, for this paper, we limited our investigation on sawn, wooden boards from Finnish spruce, which typically come in cross-sectional dimensions of about 10 x 2.5 cm and 4 m length. So, we have three categories of wooden boards:

1. W is the category of natural wooden board, the virgin material. These boards are unused and not oiled, but can also be the backside of categories CW and CWo. Our investigations and experiments are always compared to this category. W-type boards are our benchmark.
2. CW represents concrete exposed, wooden boards from formwork.
3. CWo is the category of concrete exposed, wooden board from formwork, which were oiled before use.

Collecting, Categorizing and Preparing Wooden Boards and Samples from Concrete Formwork

On March 9th, 2022, 200 wooden boards from concrete formwork were collected from a building construction site on the Otaniemi campus, Aalto University, Espoo, Finland. The wooden boards had been used in a traditional way for the formwork of walls and floor slaps of future office and lab buildings. The collected wooden boards were used in both untreated (CW) and oil-treated (CWo) ways as follows:

30% of collected boards are CW. They were used as a mould without any surface treatment to have the surface pattern as a print on the later exposed concrete surface. After its formwork use, the wooden boards were roughly cleaned by removing the concrete by tapping but without the use of brushes, chemicals or similar. Finally, the formwork wood was stored outside for several weeks, fully exposed to Finnish winter weather conditions. The exact time when the formwork wood was exposed outside is unknown; it varies from being casted and collected the same day to being stored outside for a couple of weeks. As we can observe from Figures 1 and 2 provided by (Cedar Lake Ventures, Inc., 2023), the temperatures, to which the wooden boards were exposed, were in the range of +5°C to -20°C during the months of November 2021 to March 2022. Precipitation was predominantly in the form of snow, as periods above 5°C were mostly low in precipitation. This observation is also relevant for the later drying process.

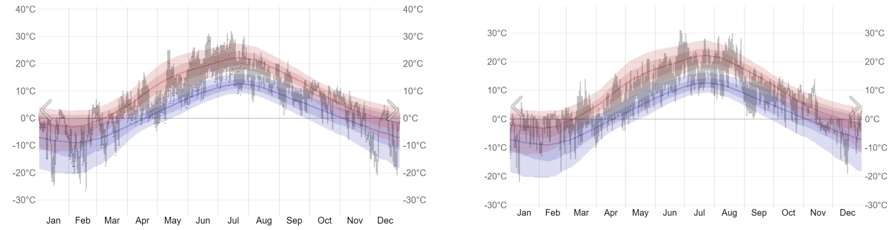


Figure 1. Espoo Temperature History 2021 (left) and 2022 (right). The daily range of reported temperatures (grey bars) and 24-hour highs (red ticks) and lows (blue ticks), placed over the daily average high (faint red line) and low (faint blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. Graphs provided by WeatherSpark.com

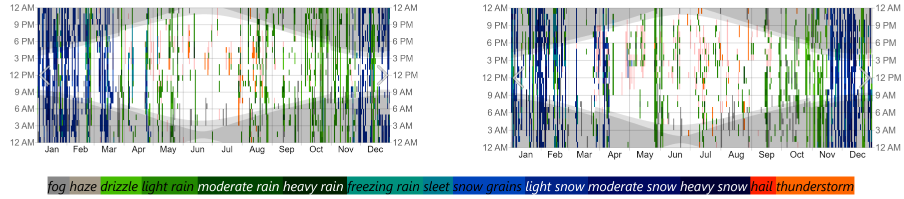


Figure 2. Observed Weather in Espoo in 2021 (left) and 2022 (right). The hourly observed weather, color coded by category (in order of severity). Graphs provided by WeatherSpark.com

70% of the collected boards are CWo. These boards were used to build an elevator shaft. Since there is no specific visual requirement such as exposed concrete, oil was applied as a surface treatment to decrease sticking to the concrete. The formwork wood was collected directly after its use, respectively curing. So, it was not exposed to weather conditions such as sun, rain and snow during a storage period.

Figure 3. Natural formwork wood collected in March on a construction site on Otaniemi campus

Figure 4. Formwork wood stock of approximately 200 boards

As it is necessary for the later applied water absorption test, which is explained in detail below, a drying process was implemented for the formwork wood boards to ensure that the concrete on the boards´ surfaces and the wooden boards were at a controlled humidity before testing the boards´ physical properties and before taking and analyzing the images from formwork wood.

The first period of drying was done by interior storage and natural ventilation. After three weeks, a change of color was observed on the CW samples. The concrete remains on CWo samples were significantly darker, but our measurements showed a range of 11 to 17% of relative humidity. Techniques such as creating airflow, using a plastic tarp, and adding a dehumidifier, fan, and heater were used to accelerate and control the drying process. The relative humidity of the wooden boards was constantly measured until all wooden boards were in a controlled range of 8 to 10 % of relative humidity at an average temperature of 23°C.

Additionally, some smaller samples of formwork wood were dried in an oven at 65°C for 24 hours to study the color changes, especially of the concrete remains. We observed that the surface did not change color or texture. So, we can assume the boards characteristics “static” in this regard.

Methods for Analyzing the Concrete Coverage Ratio on Wooden Boards from Concrete Formwork

The later performance of the wooden boards as façade application is depending if oil-treated or not and to what extend the surface is covered with concrete. So, it is necessary to analyze the salvaged wooden boards and to determine the percentage of concrete on the surface of formwork wood. For this purpose, the surfaces of the whole wooden boards (10 x 400 cm) were examined.

To be relevant as an industrial application, the process of analysis is supposed to be highly automated. In the case of using salvaged formwork wood, such automated processes may include tasks such as quality control and defect detection identifying knots, cracks, and other imperfections. Together with digital resource management, labelling and supply chain optimization, predictive material performance can assist both the industry and the designers in making informed decisions (Saleh Tabari, Khojastehmehr and Filz, 2022) decreasing the environmental impact while increasing quality and lifespan of buildings.

In this light, we explored two methods; (i) artificial intelligence and machine learning, and (ii) image processing. As the first method is based on a large dataset, which is far beyond the 200 samples that we collected, the second method was more suitable for our purposes. Therefore, the first method is explained in brief only and the image processing in more detail. However, the results can serve as valuable training data for future AI approaches.

Artificial Intelligence and Machine Learning

Initially an approach by using artificial intelligence and machine learning was prioritized, as it seemed to be more flexible for later increase of included parameters and features. The focus was on properties, such as concrete coverage but simultaneously knots, grain density, cracks and color.

For the AI and machine learning approach, we created a dataset of the formwork wood images and utilized the open-source library Tensorflow (TensorFlow, 2022), which is based on deep neural networks for image classification. However, to achieve an accuracy of more than 80% a training-dataset of minimum 500 images was necessary. Due to computational costs and time required for training data generation, this approach was not considered suitable at this stage of the investigation.

Image Processing with Photoshop and Automation Tools

Image Processing by use of the commercial software Adobe Photoshop (Adobe Inc., 2022) is an efficient, semi-automated process that delivers precise and reliable results.

In a nutshell, the software converts the input image into black and white and a colored background, where in our case the white color corresponds to the wood and black corresponds to the concrete, see Figures 5 and 6. However, photos with sufficient size and resolution are a prerequisite for smooth and successful processing. We used the Canon EOS 5DS R camera, generating images with a resolution of 8688 x 5792. The lighting conditions must be the same for all images, means that glare, reflections and shadows must be avoided. Finally, the image is analyzed by the software and the color ranges of wood and concrete are assigned to black and white as mentioned above. The background is replaced by any color different to the ones assigned to the boards to avoid confusion in the evaluation. Then the black and white pixels are counted and put into a ratio. All pixels from the background and in case pixels from blurry edges are excluded from the count. For this reason, it is essential to keep the image size and resolution constant throughout the whole process.

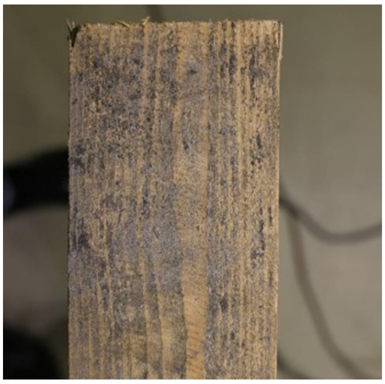


Figure 5. CW Formwork wood – original image

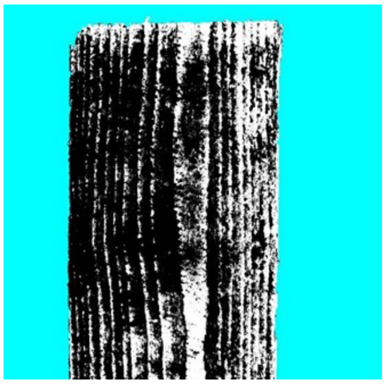


Figure 6. CW Formwork wood - processed image

The percentage of concrete coverage can be calculated in two ways, (i) using Python and OpenCV by determining the number of pixels of each color, or (ii) using the "histogram" window in Photoshop. The second option indicates the total number of pixels for the image respectively each layer. So, in this case the step of separating the image into different layers is necessary to obtain the information on the number of pixels as explained above. The main difference between the two options is calculating pixels according to RGB-color codes (black (0,0,0), white (255,255,255)) versus counting pixels per layer. We tested both options and received the same output results, which means that the procedures and results are validated.

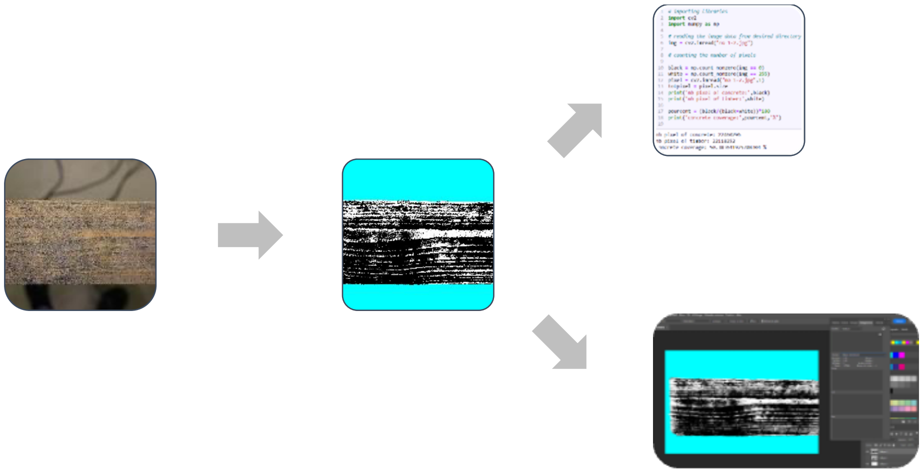


Figure 7. Options for image processing

In any case, the coverage ratio of concrete with C as the total number of image pixels for the concrete layer, and T as the total number of image pixels for the wood layer, is calculated as follows:

$$\% \text{ concrete} = \frac{\mathrm{C}}{\mathrm{C}+\mathrm{T}}$$

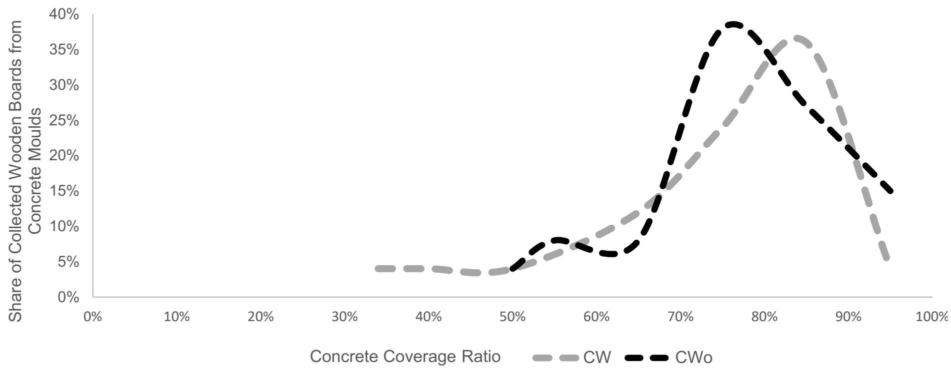
The desired output from computer vision is the percentage of concrete on the wood surface. Having established a reliable process, this workflow can be automated for each single or sets of images, ensuring consistent and efficient image processing.

Results from the Classification of Wooden Boards from Concrete Moulds

In this study, 200 wooden boards were collected from a building construction site located on the Otaniemi campus at Aalto University in Espoo, Finland. These wooden boards were originally part of concrete formwork used in the construction process. The environmental conditions to which these wooden boards were exposed varied, with temperatures ranging from +5°C to -20°C during the months of November 2021 to March 2022. Precipitation primarily occurred in the form of snow. Of the boards collected, 30% were categorized as CW and 70% as CWo. The wooden boards underwent a preliminary cleaning process, although roughly, and then dried at an average temperature of 23 ° C in a range of 8 % to 10 % of relative humidity over a period of around 3 weeks.

Based on these data and applying the above-described automated, computational methods described above for analyzing the concrete coverage ratio on the wooden boards, we received distributions as shown in Graph 1. Consequently, the data analysis shows that:

- Overall, more than 50% of boards fell within the concrete coverage range of 70-90%.
- Generally, in the CW category, the majority of boards indicate an 85% concrete coverage ratio, while the oiled surface of the CWo category shows a lower concrete coverage ratio of 75%.
- Independently from the category, no board had a concrete coverage ratio below 34%, and no board had a concrete coverage ratio exceeding 95%.



Graph 1. Share of Type CW and CWo Wooden Boards from Concrete Moulds (200 samples) over identified Concrete Coverage Ratio

Salvaged formwork wood in weathering conditions: suntests, color change evaluation, and water absorption tests

With the help of fully automated image processing, we can classify the formwork boards as described above and evaluate them in terms of concrete coverage. As sun and precipitation are the two most influential factors in the ageing and decay of wood (Herrera et al., 2018) the following methods and tests were utilized to study, under controlled laboratory conditions, the influence of such weather conditions on the properties and visual changes of the formwork boards.

We equally tested wooden boards of all categories, namely W, CW and CWo, means natural wood, boards from concrete formwork and boards from concrete formwork that were previously oiled. The boards were tested in dry state as above-described, at a range of 8 % to 10 % of relative humidity.

The suntests were conducted using a Suntest CPS+ device as described below. For the color change evaluation, we used CIELab to document the impact of sun radiation over time and in dependence of the concrete coverage ratio of each individual board. We adopted the Standard Test Method for Determination of Liquid Water Absorption of Coated Wood and Wood Based Products Via “Cobb Ring” Apparatus (D01 Committee, 2016), which provides a simple but efficient water absorption test method. Both the CIELab evaluation and the water absorption test were done before, during, and after the suntest.

The test results were examined, compared, and ultimately serve as a dataset regarding the performance of each individual formwork board. These insights and combinations mentioned thus form the basis for computational, algorithm-assisted design.

Suntests and Color Change Evaluation

The test is conducted using a Suntest CPS+ device. Each board is exposed for a duration of 96 hours. The temperature and irradiance are set to 40°C and 760 W/m2, respectively. Figures 8 and 9 show the device, which has a 30 x 20 cm surface area. The formwork wood samples measure 10 x 10 cm, so only five can fit inside the machine at once. The ageing of wood is determined by observing the surface color change. Using the annual global radiation in Helsinki, the sun exposure equivalence of the suntest is determined in comparison to the sun exposure outdoors (Haukkala, 2015).

Helsinki's annual global solar radiation is 1175 kWh/m² (Pirinen, 2012). The experiment was run for 96 hours at 760 W/ m^2. First, the irradiance (Ee) is converted into solar radiation following this formula:

$$solar\ radiation = \frac{\mathrm{Ee} \times \mathrm{h}}{1000} = \frac{760 \times 96}{1000} = 73{,}44\ \frac{kWh}{m^2}$$

Figure 8. Suntest CPS+ device

To determine the equivalence in days for a specific place, we divide the solar radiation of the suntest by the daily solar radiation, in our case for the city of Helsinki, Finland.

Outdoor exposure in days results:

$$Helsinki = \frac{73{,}44}{\frac{1175}{365}} \frac{kWh/m^2}{\frac{kWh/m^2}{days}} = 23\ days$$

According to above calculation the 96h-suntests are equivalent to 23 days of sun exposure in Helsinki. In the context of the suntest and the associated color changes of the samples it is assumed that there is no effect of the test temperature on the samples and results.

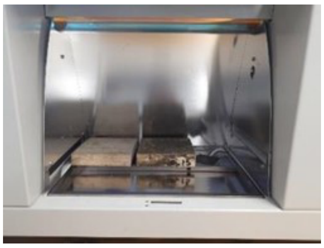


Figure 9. Suntest CPS+ device - suntest with two formwork wood samples

Before each suntest experiment, photographs with consistent lighting are taken to evaluate the color change of the boards. The average color is then measured using Photoshop. The image is first converted to CIE lab mode (image<mode<lab), and then the average is calculated using the filter<blur<average tool as shown in table 1.

Table 2. Suntest results - surface changes before and after the suntest

	Before suntest	*Averaged color*	*After suntest*	*Averaged color*
CW with a concrete coverage ratio of 80 %				
CWo with a concrete coverage ratio of 73%				

CIELAB is a color space defined by the International Commission on Illumination (CIE) (*CIELab | Color tool based on human perception*, no date). It is a three-dimensional space where the coordinates "L" indicate the white-black spectrum, "a" the green-red spectrum, and "b" the blue and yellow one. This color space is based on the opponent color model of human vision. Each letter, L, a, and b, corresponds to an opponent. CIELAB is used in research for its precision in determining a color difference.
The difference ΔE of color from the wooden surface after the suntest is calculated by measuring the Euclidean distance between two colors:

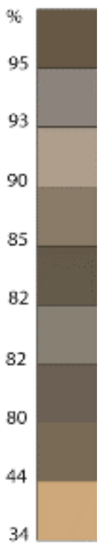
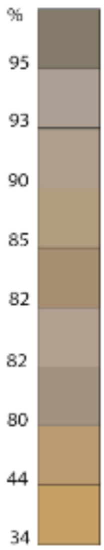
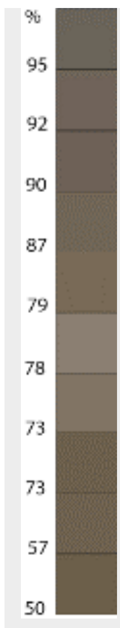
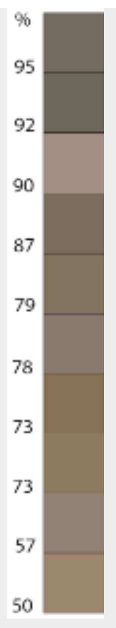
$$\Delta \mathrm{E} = \sqrt{\Delta \mathrm{L}^2 + \Delta a^2 + \Delta b^2}$$

Results from the Suntests and the associated Color Change Evaluation

Using a Suntest CPS+ device, ten types of CWo, nine types of CW, and ten type W wooden board samples were exposed to 760 W/m2 at 40 ° C for a duration of 96 hours. Generally speaking, for both, CW-type and CWo-type formwork wood, it needs to be mentioned that the boards were exposed for an indefinite time outside before being collected. Some of the boards were outside for one month, others were removed from the casting on the day of their collection. In other words, sun and other environmental influences on the individual boards, cannot be precisely tracked back in time. That is also why they were also at various stages of the drying process. Therefore, the average color of the boards before the suntest does not follow a strict gradient logic. However, due to the magnitude of samples we can observe general color trends. It may be also noted that cured concrete usually turns very light grey to white. Therefore, all type CW and type CWo boards show this surface color nuance depending on the concrete coverage ratio. For the CWo formwork, we observed that this result occurred infrequently.

The averaged color of the boards before and after the suntest is displayed in Table 2. It reveals that the average color of each board follows a color gradient based on the concrete coverage. As a result of suntests and the associated color change evaluation, the color of the CW formwork wood's surface changes more while exposed to the sun and test temperature. Their surfaces are mostly lighter in color (beige, grey) than CWo boards. The CWo formwork also brightens up but comparably stays darker. An overview of color changes of all tested boards can be seen in Appendix 1 and Appendix 2.

Table 2. Color analysis based on the concrete coverage ratio - before and after suntest

CW				CWo			
board	*concrete coverage ratio %*	*averaged color before suntest*	*averaged color after suntest*	*board*	*concrete coverage ratio %*	*averaged color before suntest*	*averaged color after suntest*
2	95			3	95		
7	93			15	92		
1	90			12	90		
3	85			17	87		
9	82			16	79		
10	82			8	78		
8	80			5	73		
6	44			19	73		
4	34			6	57		
				4	50		

Suntest results and color change of CW-type formwork wood (Table 2):

- Prior to the suntest, a slight gradient of color was observed. In the case of the CW formwork, the concrete settled at a faster rate compared to the CWo formwork. The surface color difference is attributed to the fact that each board

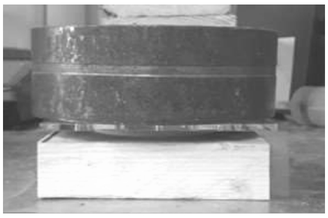


Figure 90. Water absorption test with a weight to seal the system

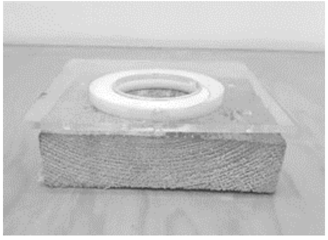


Figure 11. Joint and acrylic plate to define

was at a different stage in the concrete drying process. As such, we cannot define a clear logic for the color range of samples before the sun exposure test.
- After the suntest: A gradient of color is now clearly present. The average shade is greyer after 80% of the concrete coverage, which makes sense because drying concrete turns to whitish/grey color.

Suntest results and color change of CWo-type formwork wood (Table 2):
- Before the suntest, there is no discernible gradient between the percentage of concrete coverage and the average color of each board. The formwork wood with a percentage coverage between 73% and 78% stands out from the other range. Before the sun test, the concrete has begun to settle on these boards, causing them to appear greyer.
- After the suntest, a gradient of color is present depending on the percentage of concrete coverage. For example, the formwork range of 50% is lighter and beige. The one with a coverage of 95 % is darker and greyish.

Water Absorption Tests

(Pakkala, 2016) demonstrates that wind-driven rain significantly impacts concrete degradation mechanisms in Finland, particularly on facades. The research also examines its potential increase due to climate change in coastal regions and southern Finland. Assumingly, the same applies to wooden facades. In this sense, also for wooden facades, it is crucial to understand the surface's water repellency in order to evaluate its resistance to humidity and rain. Performance water testing is focused on the absorption of liquid and its movement on a surface of and/or through a material. The rain/water tests measure resistance to or repellency of water on a surface. Other tests for water absorbency, repellency, and resistance are standards developed for example by the American Association of Textile Chemists and Colorists (AATCC, 2023).

For our purposes, we used water absorption tests, since in accordance with EN 1062-3 (Österreichisches Normungsinstitut Austrian Standards Institute, 2008) evidence of how well coatings applied outdoors are likely to withstand rain. Water absorption such as described in (D01 Committee, 2016; D07 Committee, 2019; Österreichisches Normungsinstitut Austrian Standards Institute, 2008; Xu, Winistorfer and Moschler, 1996) are used to determine the amount of water absorbed under specified conditions. Factors affecting water absorption include: type of material, additives used, temperature and length of exposure. The data shed light on the performance of the materials in water or humid environments. Usually, for the water absorption test, the specimens are dried in an oven for a specified time and temperature and immediately upon cooling the specimens are weighed. The material is then emerged in water at agreed upon conditions, often 23°C for 24 hours or until equilibrium. Specimens are removed, patted dry with a lint free cloth, and weighed. Water absorption (A) is expressed as increase in weight percent. In the case of our investigations, we used the same board for both, the water absorption test before the suntest, which delivers A1 and the water absorption test after the suntest, which delivers A2. Between the experiments the samples were dried to exactly the same humidity as above described.

We adopted the Standard Test Method for Determination of Liquid Water Absorption of Coated Wood and Wood Based Products Via “Cobb Ring” Apparatus (D01 Committee, 2016), which provides a simple quantitative measure of water absorption. The water absorbance is determined by measuring the weight of the samples before and after immerging. The sample is placed horizontally, and the test is performed on a controlled surface within a circle with 2 cm radius (1256,6 mm²) and a time of 5 minutes. The time and immersion depth are kept constant. In order to conduct the experiment, a foam joint is placed in the center to delimit the water-contacting surface. An acrylic plate is placed on top of the joint with a weight guaranteeing the system's water tightness, as shown in figure 10 and 11.

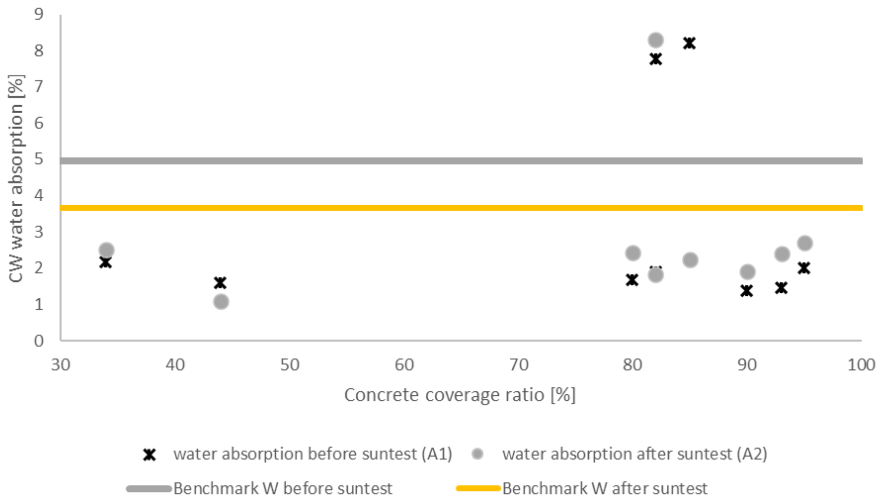
The percentage of water absorption (A) is determined by measuring the weight [g] of the wood sample before (W1) and after the absorption test (W2). This indicates the percentage of water absorption, which is a measure of how much moisture the wooden boards can absorb. It is expressed as a percentage of the initial weight of the board. The absorption is computed using the following formula:

$$A = \frac{W2-W1}{W2} \times 100\ [\%]$$

Results from the Water Absorption Tests

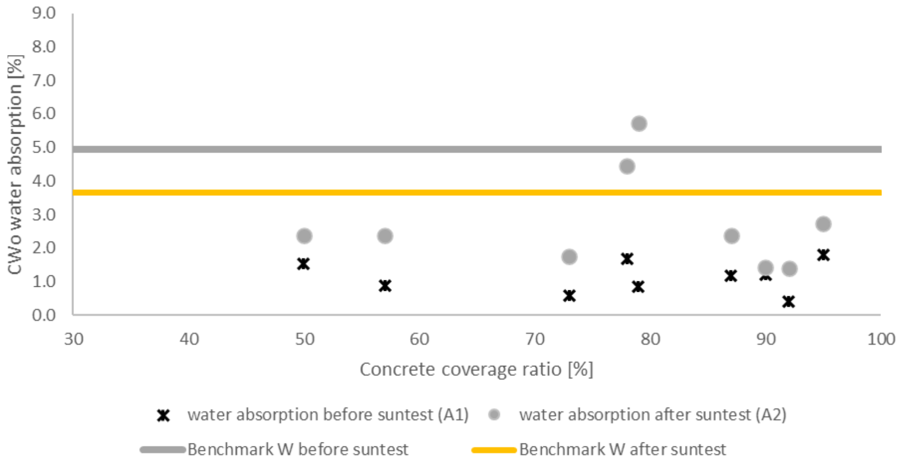
The provided tables and graphs display water absorption percentages for different types of wooden boards (W, CW, and CWo) before and after undergoing a suntest. Type W Wooden boards had a water absorption percentage of 4.95% before the suntest. After the suntest, their water absorption percentage decreased to 3.66%, implying that the suntest may have led to improved water resistance characteristics for these boards (Table 3). Graphs 2 and 3 and Table 3 depict the water absorption of CW and CWo before and after the suntest in dependence of concrete coverage ratio, where A1 is water absorption rate before the suntest and A2 the water absorption rate after the suntest.

Graph 2 shows that the water absorption of CW formwork wood before and after the suntest are in a similar range, whereas A2 is mostly higher than A1. Some minor exceptions could be identified. For example, formwork wood sample with 44% and 82% of concrete coverage ratio slightly increase water absorption after suntest, and the sample with 85% concrete coverage ratio significantly increase water absorption after suntest. We observed that due to the grain density or the temperature during the suntest and resulting surface modifications such as cracks the water absorption test procedure delivered such singularities. However, such cases are very singular, and as a general result there are no significant differences in water absorption before and after the sun test for the vast majority CW boards. In general, before and after the sun test, the differences in water absorption range between 0.3% and 0.7%.



Graph 2. Water absorption of CW formwork wood before and after the suntest in dependence of concrete coverage ratio

Graph 3 displays that the water absorption of CWo formwork wood before and after the suntest are significantly different, and in opposite to CW results, here A2 is always higher than A1. Again, similar to explained above, some minor exceptions could be identified; for example, in the case of formwork wood sample with 78% and 79% of concrete coverage ratio where the water absorption difference exceed 2,5%. Before and after the sun test, the difference in water absorption usually ranges from 0.8% to 1.4%, which is roughly double the percentage compared to CW formwork values.



Graph 3. Water absorption of CWo formwork wood before and after the suntest in dependence of concrete coverage ratio

Table 3 illustrates averaged water absorption percentages before and after suntests for W, CW, and CWo types of wooden boards. This overview provides insight into the significant effects of wood that has been previously used for concrete formwork compared to natural boards. Most significantly it is shown that sun radiation and temperature - the suntest was conducted at 40°C - play a balancing but also major role in the water absorption of the wooden boards.

Table 3. Water absorption A in % before and after suntest

Water absorption A in %	*before suntest (A1)*	*after suntest (A2)*
W	4,95	3,66
CW	3,29	3,06
CWo	1,42	2,79

- Type W wooden boards serve as benchmark for water absorption with an average of 4.95% before the suntest, which decreases to 3.66% after the suntest. So, sun and temperature have led to improved water resistance characteristics for these boards by 35% in average.
- Before the suntest, CW boards have an average water absorption percentage of 3.29%, indicating that they absorb approximately 3.29% of their initial weight in water. After the suntest, this absorption percentage decreases by approximately 8% to 3.06%.
- In contrast to CW boards, CWo boards exhibit a water absorption percentage of 1.42% before the suntest, which counterintuitively increases by 96% to 2.79% after the suntest.

Comparing water absorption of CW (Graph 2) and of CWo (Graph 3) formwork wood to type W wooden boards (average of 4.95% before and 3.66% after the suntest) it is obvious that

- sun radiation decreases water absorption of type W boards (natural wood).
- concerning type W and CW after exposure to sun radiation, its water absorption decreases, respectively its resistance to rain increases, and for CWo it is the exact opposite.
- both types, CW (3,29/3,06) and CWo (1,42/2,79) formwork wood show significantly lower water absorption rates than W (4.95/3.66).
- type CWo is more water-repellent than CW and W, and even though its water absorption rates increase after suntest, these values are lower than CW and W values.
- Before and after suntest, the CWo has a higher water resistance than W and CW.
- high temperatures, which usually come with sun exposure, increase the water absorption rates of CWo formwork wood, and its relative resistance to rain decreases.

A combined interpretation of test results: generating data for the “best fit” and color predictability

“best-fit” - Determination

With the above-described fully automated image processing method, it is possible to classify the formwork boards, to analyze them in terms of concrete coverage ratio, and to individually label each single wooden board. As an overall insight, we observe that the prior use as formwork for concrete results in a significant positive effect in terms of water absorption, means the boards are more water repellent. Additionally, it can be observed that sunlight radiation has a further positive effect on the water-repellent properties of the boards for W and CW. Temperatures, especially high temperatures as easily attainable in facade applications, can significantly impact the water absorption rate, as evidenced in the case of oiled formwork boards. The surface color resulting from the natural color of the rough-sawn formwork boards and their contact with concrete, which is altered by sunlight exposure, also influences the expected surface temperatures. Facade with a dark-colored surface can easily reach temperatures of 70°C and beyond (Bishara, Kramberger-Kaplan and Ptatschek, 2017). However, these factors, along with the influence of natural weathering due to rain, are not currently the main focus of this study.

Assigned properties, learned from sun and water absorption tests, create individual 'fingerprints' for each pre-labeled wooden board, defining its specific performance. Presently, the combined data generates a multi-objective “best fit” for each board with respect to its application as a façade. According to the water absorption test results, the dark-colored type CWo boards seem more suitable for faces less exposed to sun radiation and heat, which usually are north-facing facades. Additionally, the pre-moulding oil treatment enhances the surface's weather and water resistance. For this reason keeping the CWo wood protected from the direct sunlight radiation, will help preserve the water resistance properties that bring the oil treatment. Consequently, CW boards are better suited for sun-exposed surfaces where the facade can reach high temperatures. Additionally, untreated formwork wood becomes more water-repellent after sun exposure, and the light color of the boards covered with concrete may help mitigate the effects of overheating. This logic is simulated, applied, and verified in the full-scale demonstrator shown below.

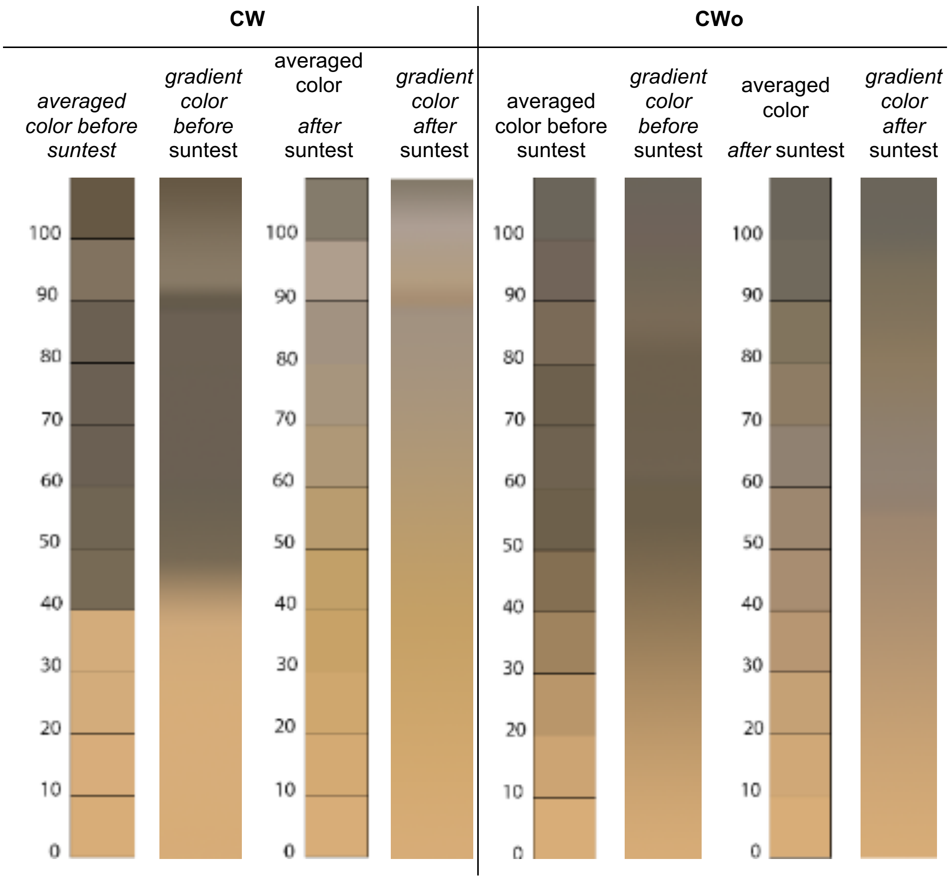
Prediction of Color Gradients

Mentioned logic for the “best-fit” placement of boards on a specific facade also results in a visual and architectural logic. When analyzing the average color of the wood samples before and after the sun test and categorizing them based on the concrete coverage ratio, we observed a color gradient.

We used the gradient editor tool in Photoshop to predict the average color of the wood based on the percentage of concrete coverage on the surface. Each color was positioned at a specific point on the gradient scale. For instance, for a sample had 90% concrete coverage ratio, the corresponding color is placed at the 90% position on the gradient scale. Results that significantly deviated in terms of shade from the others were excluded from the gradient. For example, samples CW 10 and CWo 82 were omitted from their respective gradients due to their dissimilar results. Such results were not included in the color gradient, as the color difference to the other results was unusually large. The reasons for the hue variance include uncertainties attributed to the formwork wood's exposure state prior to collection.

The ability to predict the color of the formwork wood in a façade design using this method is a valuable tool for forecasting the surface color and its evolution over time. The color gradients can also be inversely used to predict the performance of the board. The gradients can be found in Table 4.

Table 4. Color prediction- gradients



Façade design and demonstrator with salvaged formwork wood

To test the proposed approach and workflow, to apply the insights of our investigations, and to finally demonstrate the reusability of the formwork wood, a prototype was designed and constructed based on the weathering resilience of each board type and the amount of concrete coverage.

The demonstration prototype is designed for outdoor display at Aalto University, Otaniemi campus. The design considers the effects of weather; thus, a climatic analysis was conducted beforehand. The façade design of the demonstrator was realized using our stock of collected the type CW and CWo material, which simulates a real-world scenario.

Best-fit selection of the boards based on site specifics

The prototype is a circular facade with a diameter of 1.2 meters, assembled from 39 formwork boards from the same stock as the experiments. The circular shape was selected to generate a 360° orientation of the object. So, it is necessary and possible to find the “best-fit” for each individual position according to its availability from stock. The design of the prototype was initially generated using Grasshopper and Rhinoceros software, parametric design tools, allowing to explore multiple diameters and settings. The length of the formwork wood was maintained during construction, resulting in boards with non-uniform dimensions. Mimicking a real-world scenario in which every board is unique, in Grasshopper, random board lengths were generated to further imitate this scenario.

Two site specific, micro-climatic variables were investigated: the effect of sun exposure on the surface and wind speed at the specific site in Espoo, 60°11'15.7"N 24°49'55.4"E.

Exposure to sun. The hourly sun exposure of the cylindrical surface of the prototype is generated by Grasshopper software and the Ladybug plug-in as shown in Figure 12. Based on this information, the position of the boards is first determined according the number of hours the boards` surfaces are exposed to direct sunlight. As we know, the CW type formwork is comparably more resistant to sun exposure exceeding 1,800 hours per year. Therefore, the CW boards are positioned in the southern surfaces (ESE-S-WSW) as they receive the most sunlight, shown in Figure 12. The CWo formwork wood is placed in the northern zone (WNW-N-ENE) as they are most water-repellent and best suited for humid and wet conditions. However, the effectiveness of the oil treatment decreases when exposed to sunlight and high temperatures.

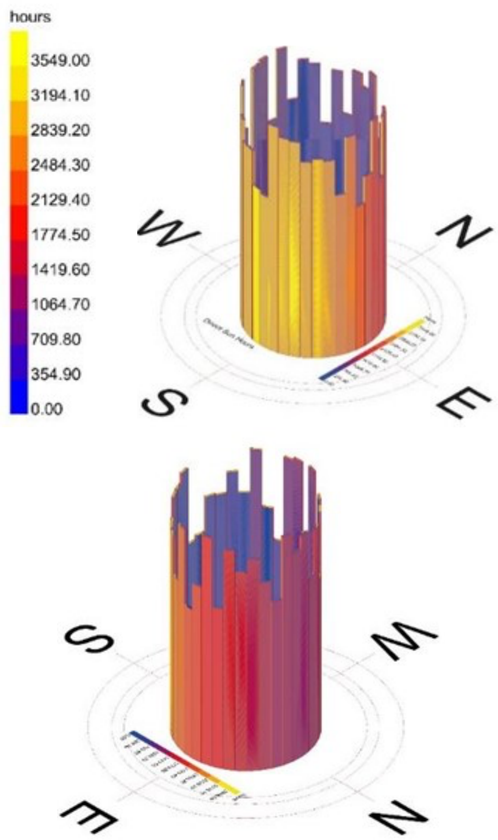


Figure 12. Sun exposure of the surface of the prototype – generated with Grasshopper/Ladybug software

The wind direction can indicate the areas most exposed to precipitation, making it a key factor in determining board placement. To establish a logical order for weather-related board arrangements, we begin by analyzing wind patterns at the building's location and identifying wind direction and intensity. Based on the wind intensity, the boards are arranged in order of highest to lowest resistance to weather conditions. Having previously defined CW and CWo zones, the concrete coverage is evaluated, considering the severity of rainfall, which is directly proportional to the wind direction and speed. The associated CW or CWo type and the varying concrete coverage ratio for each board in stock are determined using image processing techniques, as described in the previous chapter.

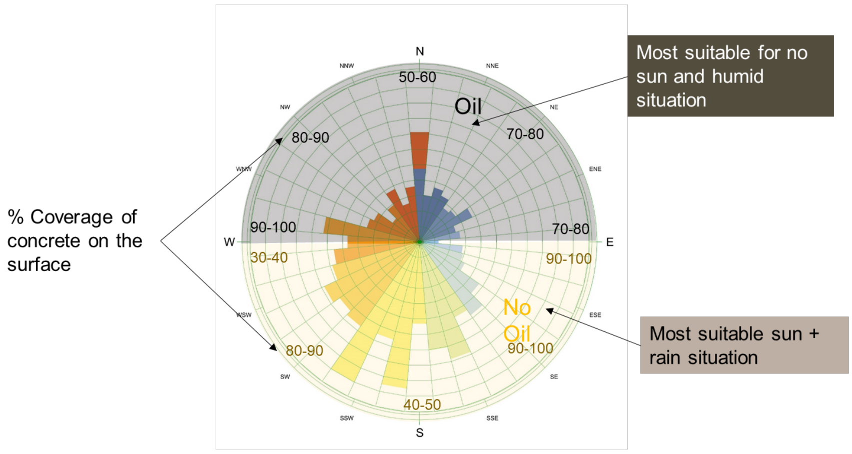
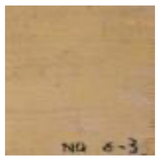


Figure 13. Graph of wind directions and magnitudes paired with sun exposure generated with Grasshopper / Ladybug software and logic of positioning the boards on the prototypical demonstrator facade

Having assessed the appropriateness of each type of formwork wood (CW or CWo + concrete coverage) for different scenarios, we computationally initiate the assignment process, selecting and placing the most suitable boards from available stock. This process hierarchically progresses zone by zone, starting with the most critical exposure and continuing until boards have been assigned to all parts of the façade surface. For instance, one of the most critical conditions are found in the southern, more specifically in SSW direction. According to the location and weather data a high level of radiation paired with higher temperatures and high wind speeds can be expected (Figure 13). In our example, 50 boards with individual fingerprints are on stock, and according to this analysis and the board evaluation, the most suitable board on stock is a CW type formwork wood with a 44% concrete coverage on the surface as shown in Table 5.

Table 5. Suntest results and color changes for CW with a concrete coverage ratio of 44 %

	Before suntest	*After suntest*	*Average color*	*Averaged color*
CW with a concrete coverage ratio of 44 %				

For the demonstrator, 39 of the 50 boards with individual fingerprints on stock are used, as they are deemed the most suitable for the designed facade. The assembly process of the full-scale demonstrator uses the computationally found list of "best-fit" boards, which can be easily found on stock by their individual fingerprints. Figure 14 shows the prototype immediately after construction on June 20, 2022 and after four months of exposure to outdoor conditions on October 19, 2022. It is noteworthy to observe the initial color difference between the CW boards (on the south side) and the CWo boards (on the north side). As previously described, CW boards have a light grey shade, whereas CWo boards have a dark brownish shade of color. After four months, the surface has already undergone significant changes. The CW boards are becoming lighter, while the CWo boards are also acquiring lighter surface colors. This is because the oil acts as a retardant in the concrete's setting process, thus the surface transformation of CWo boards is taking longer. However, the process of design, assignment of boards and their real-life performance show matching results as we can observe by comparing Table 5 with Figure 14. As the prototype was set up outdoors, different weather conditions prevailed at the time of photo documentation. This means that the lighting conditions cannot be controlled and adjusted in the same way as in the laboratory, which can consequently affect the lighting of the image and the colors displayed. However, our photo documentation shows a clear color change on the wood surfaces, which was visually verified on site and is consistent with the results of the suntests.

Figure 14. Comparisons of the south and north view of the full scale demonstrator at Aalto University, Otaniemi Campus, Espoo, 60°11'15.7"N 24°49'55.4"E - before and after 4 months of exposure to natural environment June to October 2022.

Application on large-scale buildings: Helsinki

In the previous chapter, a realized prototype with a diameter of 1.2 meters was presented. This chapter explores larger-scale applications by conducting a simulation on an existing building, the civil engineering building at Aalto University located at Rakentajanaukio 4. The goal is to determine the potential outcome if the facade is covered with the formwork wood studied in this research and to predict the aesthetic surface of the exterior.

Case Study: The Civil Engineering Building at Aalto University, Espoo, Finland

The civil engineering building at Aalto University has a U-shaped geometry consisting of multiple volumes that create a complex form. Figures 15 and 16 show the building's geometry in its surrounding context. The complex geometry and surrounding trees result in many shadows on the building, even on the facades facing south. The sunniest parts of the building are the large southwest facade and the south facades of the annexes on the right side of the U-shaped volume. The direct sun exposure hours can be observed in Figures 17 and 18.

As previously established through the experiment results, CW formwork wood is more efficient in high sun exposure. Therefore, the CW boards are placed on the facades with direct sun exposure hours of over 1800 h/year. Once the location of the CWo and CW boards on the volume has been determined, the formwork wood boards can be arranged according to their concrete coverage on the surface. The boards will then be arranged in order of highest to lowest resistance to weather conditions based on the wind intensity. As the wind intensity changes by zone, the concrete coverage also alters to suit the associated weather conditions. The color of the facade created with formwork wood is determined by replacing each type of board with a specific concrete coverage with its corresponding predicted color. Furthermore, the facade's outcome is predicted and demonstrated in Figure 19 and 20 by creating a gradient with the corresponding color for each indicated concrete coverage. Two cases are studied for the facade's color prediction: one at the initial state when the boards are fixed on the building (Figure 19 and 20), and one after approximately one month of exposure to the weather conditions (Figure 21 and 22).

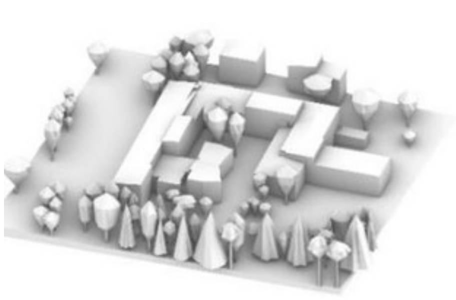


Figure 15: Aalto Civil Engineering Building: South-East view

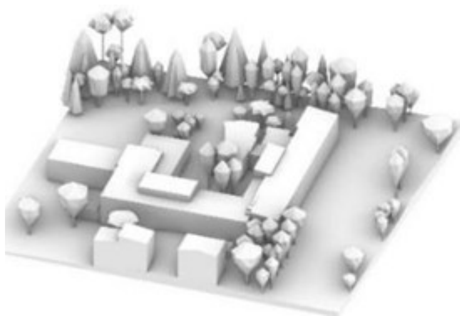


Figure 16: Aalto- Civil Engineer Building: Northwest view

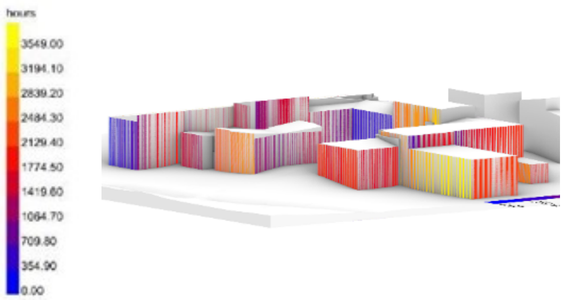


Figure 17. Aalto Civil Engineering Building: annual sun exposure; South-East view

Figure 18: Aalto Civil Engineering Building: annual sun exposure; Northwest view

The complex geometry of the building and surrounding vegetation results in shadow zones on the facades. Therefore, the CWo formwork wood is mainly used to cover the shadowed facades, as the boards has a higher resistance in zones less exposed to the sun and therefore less prone to overheating. The CWo formwork wood is noticeable by its darker color compared to the CW formwork wood. On the southeast view, the use of different materials creates an interesting gradient of color. Especially in the case of the wooden boards being exposed for one month outside (figures 21 and 22), we observed a gradual change from dark to light brown. This color transition follows the change in direct sun hours exposure. The light color shade represents the CW formwork wood, which is located on the most exposed facades to the sun.

The 3D simulation predicted the general overview and aesthetic of the application of formwork wood on the civil engineering facade at Aalto University. By zooming in on the southeast corner of the left annexes, as shown in Figure 23, we can go into more detail and replace the color spots with images of the corresponding formwork wood from our stock studied for this research. The results are as follows:

- Left from the corner: CW boards 30% concrete coverage. In stock: CW with 44% and 34% of concrete coverage ratio.

- Right from the corner: CWo boards with 80% concrete coverage. In stock: CWo with 87% and 79% of concrete coverage ratio. By disposing some of the formwork wood boards on a strategic corner of the building facade, it gives a realistic overview for the simulation.

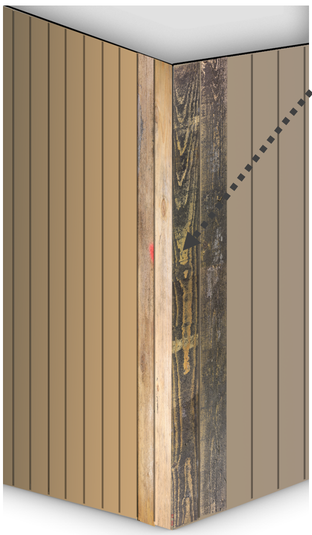


Figure 103: close-up view of the Aalto Civil Engineering Building

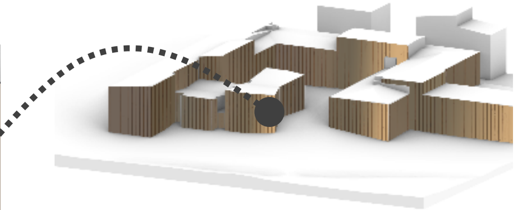


Figure 19. Aalto Civil Engineering Building: predicted color gradient – South-East View initial state

Figure 21. Aalto Civil Engineering Building: South-East View predicted color gradient- after being exposed to one month outside

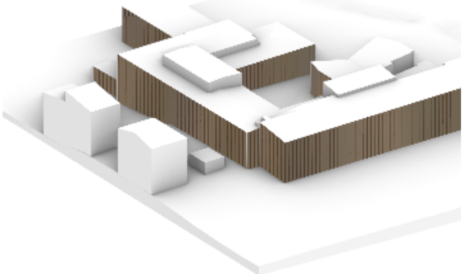


Figure 20. Aalto Civil Engineering Building: predicted color gradient – Northwest view initial state

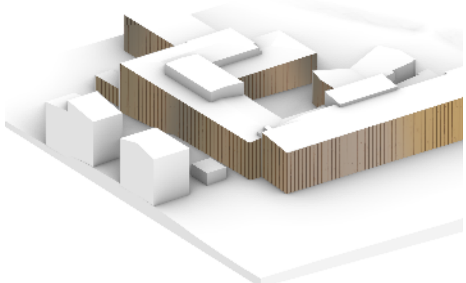


Figure 22. Aalto Civil Engineering Building: Northwest view predicted color gradient- after being exposed to one month outside

Discussion, Conclusion and Outlook

After the formwork, the wooden boards become a new material with new properties.

Our research proposes to consider formwork wood instead of waste material as a material with new properties, which we study and present as the influence of concrete on the CW and CWo formwork wood. To make use of this new source of material, we cover two main aspects with our investigations. First, analytically, we look into the formwork boards and its new properties after having been used as formwork wood to understand its behavior and performance. Second, we are interested in the aesthetic architectural aspect of the boards including its ageing and the associated color changing process. Both aspects are supported by computer vision techniques. Consequently, in an algorithm-assisted design process, the best fit for every single board on stock can be found for a potential application such as the demonstrated façade designs, simultaneously maximizing their lifetime. A predictive simulation is based on a color gradient system, and allows for estimating the visual appearance of the façade in future including color changes and natural ageing effects. Our realized prototype showcased both, the process and the performance in the long-term test. All these aspects were fundamental to finding new strategies for reuse and opening up new avenues for architectural design, as explained in more detail and critically reflected below.

The surface color changes with time, giving a new perception of beauty.

Results from experimental testing and their effects

For this stage of the investigation, the most effective method for determining the concrete coverage on the surface of formwork wood is through the use of Photoshop software for image processing and calculation of the percentage of concrete. However, machine learning techniques are more efficient when dealing with larger datasets. Presently, our data set is based on 200 collected formwork boards. Even though the quantitative analysis and classification is processed semi-automated, this time-consuming task should be covered by fully (for example robotically) automated procedures for capturing and sorting and labelling. Linked to machine learning procedures the data would be increasingly robust and reliable. The effects of different climate conditions are simulated on wood samples using a sun-test CPS+ device and through the performance of water absorption tests. Also, this testing is presently highly time-consuming (96h of sun test per sample) due to manual work, and therefore cut from machine learning advantages. As previously stated CWo boards exhibit a low water absorption rate before the suntest, which counterintuitively increases after the suntest. However, the oil treatment on the surface improves the weather and water resistance of the CWo formwork wood and makes it more suitable for use on north-facing facades. In this use it is less exposed to sunlight and associated heat, which seems to cause the above-mentioned increase of water absorption. In this regard further (long-term) studies regarding the oil and different sorts of formwork-oil are necessary. On the other hand, CW formwork wood is more suitable for sunlit surfaces where the façade reaches high temperatures. As the CW formwork wood becomes more water-repellent after exposure to sunlight, the light color of the boards´ surfaces covered with concrete may also reduce overheating effects. As noted, we did not perform separate studies for different concrete mixtures. The ratio of cement and other ingredients may have their effect on the wood surface and future performance. The process of curing including its thermal effect and the pressure of the self-weight on the formwork as well as the weather conditions during pouring and curing may also have their impact on the surface of the formwork wood and worth a study. However, based on our findings, facades can be designed to maximize the potential of each formwork wood board. In conclusion, we have shown that with this approach formwork wood can be upcycled for facade design and that the use applied computer vision procedures re essential tools for maximizing the potential reuse of the formwork boards.

We design based on the unique properties of the formwork boards. We don’t choose the boards based on the design.

New Material and Design Perception

The concrete coverage on the surface of each formwork wood board is unique, and by understanding the surface properties when exposed to sun and/or rain, an optimization of reuse of the formwork boards can be achieved. This approach represents a novel method of design, as the wooden boards are not sourced directly from the industry but rather is derived from its use as formwork. However, the properties of the formwork wood are little known and described in literature, and thus, require intensive analysis and study. It is acknowledged that each formwork wood board represents a unique new material with distinct properties, which we aim to analyze in real time by scanning and computer vision. While traditionally, facade design with wooden boards ends with drawings of the layout and pattern this study employed an inverse method. It is neither random nor an individual's decision which panel is placed where on the façade, but the formwork boards are collected, analyzed, and the facade design is developed according to the unique properties of each formwork wood board. So, the whole process follows a clear logic based on expected material performance, and its application is informed by weather data and exposure. This logic will also be represented by a visual effect as boards with similar history and treatment as formwork wood will have similar properties such as color and water absorption rates. The designed facades will reflect this as an overall visual appearance. Additionally, it is acknowledged that the surface properties of the wood will change over time, and through weather simulation, these changes can be predicted. This hands-off approach to design may also allow the boards to evolve in unconventional ways, leading to a re-evaluation of conventional perceptions of beauty.

Limitations and Further Research

Even though our investigation enters new terrain, it encompasses various fields such as machine learning, wood sciences and algorithmic/parametric design, which are complex and require a significant amount of time to investigate and analyze. From this perspective, specific aspects such as performance under sun exposure, water absorption and color changes were given priority for now. As the methodologies and testing had to be developed and adjusted in parallel the number of boards, data and tests were limited to a level following the Pareto principle. The demand to approach this topic in a multidisciplinary way – from material testing, to material science to computer science to creative design studies – would equally increase complexity and enrich the research work, and gives rise to questions that would need to be developed in detail in future research:

- Machine learning. The use of computer vision and Photoshop technologies were effective for initial investigations and a limited number of boards and data. To further improve efficiency, it is important to explore and develop machine learning methods and algorithms that can analyze more detailed and numerous surface properties of formwork wood, such as concrete coverage, knot position, grain direction, and density. This approach will be particularly useful when dealing with a larger material stock and automating the system in the future. Even though the training in the machine learning process is time-consuming the benefit will be that once a smooth workflow is developed, it can be reused for other projects and adapted to materials other than formwork wood.

- Material properties. Obtaining a comprehensive understanding of the boards´ material properties requires a significant increase of samples from different seasons and locations. The current testing process, utilizing the suntest machine, which can only accommodate a limited number of samples at a time, resulted in a testing duration of over two months for shown wood samples, including formwork wood as well as natural untreated wooden boards. As a result, the available data needs to be complemented to establish a more precise and reliable correlation between the level of concrete coverage on the surface and the wood's resistance to weathering. The simulated climate conditions during testing were limited to the suntest and water absorption tests. Furthermore, the water absorption qualities of the formwork wood were examined rather than its drying capabilities. We estimate that the thin coating of concrete has a retarding but insignificant effect on the drying process based on observations from the samples' overall drying process. In order to gain a more robust understanding of the boards´ properties and to achieve more accurate results, future research should incorporate additional testing such as prolonging the suntest duration to predict wood ageing over a longer period and increasing the number of formwork wood samples tested.

- Prototype. A prototype façade was constructed to demonstrate the potential for upcycling formwork wood. The prototype is on display in the outdoor environment at the Otaniemi campus, and we observed predicted color changes during the first months of being exposed to natural weather conditions. The changes in the boards over the course of one year as it is exposed to various seasons will further inform and verify the simulations. We expect potential changes that include changes in the color and surface appearance of the wood due to exposure to sunlight and weathering; changes in the mechanical properties of the wood, such as changes in strength, stiffness, and durability; changes in the overall durability of the wood and its ability to withstand weathering; signs of degradation, cracking or rotting. Such long-term testing can provide several material-related, architectural and economic key insights such as durability and longevity, ageing, maintenance and cost-effectiveness. By evaluating the boards´ performance over a longer period, it will be possible to determine whether the benefits of using formwork wood outweigh the costs of obtaining, processing, and maintaining it, which is a crucial indicator for future real-life applications.

- Material upcycling for other architectural and structural designs. The formwork wood was studied and analyzed for its potential reuse as a façade material in outdoor conditions. The method presented in this paper can be adapted to upcycle the formwork boards in a variety of architectural or structural applications. Depending on the intended application, the weather resistance and mechanical properties of the boards, as well as other surface parameters such as knot position and grain density, color changes over time, and haptic or energetic aspects can be studied in greater detail. In conclusion, the method developed in this paper can be adapted for different purposes and for different materials.

Future Impact

Altogether, the proposed research on using formwork wood as a building material has the potential to have a positive impact on architecture, society, and the environment.

The proposed strategies offer an innovative approach to the problem of construction waste, a major contributor to environmental degradation. By Finding new uses for formwork wood, it could help to conserve natural resources, reduce the amount of waste sent to landfills and decrease the environmental impact of the construction industry. Additionally, a reduction in energy consumption associated with the production and transportation of building materials can be assumed.

The use of computer vision and algorithms to assign specific wooden boards to specific locations on a façade based on environmental requirements could improve the performance and the overall carbon footprint of the building by ensuring that the boards used are well suited to their intended location and weather conditions.

In architecture, it could provide a new and innovative approach to re-use and upcycle construction materials, leading to unique aesthetics and more diverse and visually interesting buildings that stand out from traditional building materials (Popovic Larsen and Filz, 2023). The surface of formwork wood is modified by its exposure to concrete, which can give it an unconventional texture and appearance. As formwork wood is often low-priced and readily available, it could also provide a cost-effective alternative to virgin materials - making building, construction and housing more affordable for a wider range of people, and more sustainable communities.

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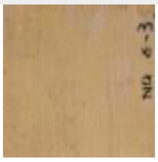
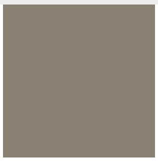
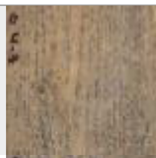
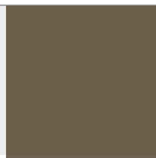
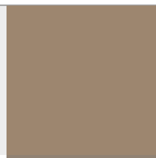
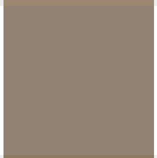
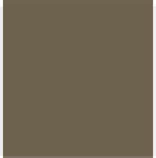
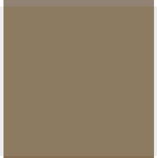
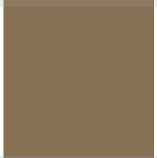
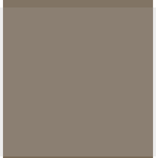
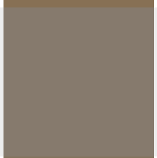
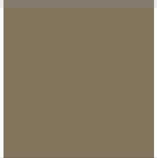
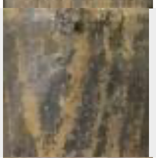
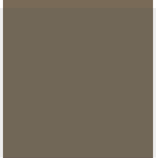
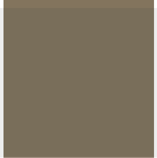
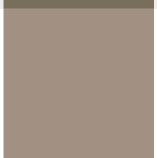
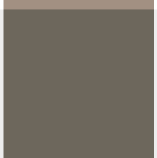
Appendices

Appendix 1. surface color changes before and after the suntest – CW

Board number	*%Concrete*	*Image before suntest*	*Image after suntest*	*Average color before suntest*	*Average color after suntest*
NO 4	34				
NO 6	44				
NO 8	80				
NO 10	82				
NO 9	82				
NO 3	85				
NO 1	90				
NO 7	93				
NO 2	95				

Appendix 2. Surface color changes before and after the suntest- CWo

Board number	*%Concrete*	*Image before suntest*	*Image after suntest*	*Average color before suntest*	*Average color after suntest*
Oil 4	50				
Oil 6	57				
Oil 19	73				
Oil 5	73				
Oil 8	78				
Oil 16	79				
Oil 17	87				
Oil 12	90				
Oil 15	92				
Oil 3	95