U.PORTO

FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

WATER PROOFING APPROACHES ON WOODEN ELEMENTS

DIOGO JAIME CARNEIRO DA COSTA E BRANCO

Dissertação submetida para satisfação parcial dos requisitos do grau de

MESTRE EM ENGENHARIA CIVIL — ESPECIALIZAÇÃO EM CONSTRUÇÕES

Orientador: Professor José Manuel Marques Amorim de A. Faria

Coorientador: Professora Maria Stefanidou, AUTH, Greece

JULHO DE 2018

MESTRADO INTEGRADO EM ENGENHARIA CIVIL 2017/2018

DEPARTAMENTO DE ENGENHARIA CIVIL

Tel. +351-22-508 1901

Fax +351-22-508 1446

✉ miec@fe.up.pt

Editado por

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rua Dr. Roberto Frias

4200-465 PORTO

Portugal

Tel. +351-22-508 1400

Fax +351-22-508 1440

✉ feup@fe.up.pt

http://www.fe.up.pt

ACKNOWLEDGEMENTS

I would like to express the deepest appreciation to my coordinator Professor José Amorim Faria, who continually and convincingly conveyed a spirit of responsability and an excitement in regard to accomplish this dissertation. Without his guidance, persistent help and his full availability this dissertation would not have been possible.

I would like to thank my coorientator Professor Maria Stefanisou, from AUTH, Thessaloniki, Greece, whose knowledge and guidance in my internship was indispensable to develop my resarch on the dissertation subject. I would also like to thank her for all the help provided after my return to Portugal. In addiction a thank you to the PhD students working with me in the Laboratory of Building Materials, AUTH.

A special thank you to my parents, who supported me during all this time, and always helped me to overcome the obstacles that have been appearing throughout life. I would also like to thank them for making me the person i am today.

A thank you to all my friends that supported me and have been in my life during all this time.

ABSTRACT

The use of wood in construction is becoming more frequent, both in Portugal and abroad. This use is increasing because of the mechanical properties as well as the aesthetic properties and qualities present in the wood.
It´s used in several stages of construction, as in the structural part, and in the finishes of many construction elements. However, wood is a very sensitive material and it is normally being submitted to several setbacks, such as events related with humidity, and that can seriously damage the wood material or decrease its properties. For this reason, it is necessary to protect the material, coating it with some product, normally liquid, so the properties do not fall away, or at least last the longer period possible.

In this work it was intended to evaluate the performance of small samples of Greek oak under durability and mechanical resistance tests after applying protective products.
In the durability tests, 3 different types of tests were performed (Water Cycles, Freeze-Thaw Cycles and Water Drop Analysis). A limited number of tests was done using "clean samples" and samples treated with two solutions (a basic solution, designated as A and a solution B, that resulted from the addition of a nanomaterial to solution A).
The basic objective of this dissertation may therefore be defined as performing a set of resistance and durability tests that may be used to understand what is the effect of using nanomaterials as additions to common finishing coatings of timber elements.

The laboratory work presented on this dissertation was realized in the Laboratory of Building Materials, in Faculty of Civil Engineering in Aristotle University, in Thessaloniki, Greece.
The first step was to perform mechanical resistance tests, in 6 cubes of Greek oak wood. After being properly numbered, they were weighted and measured. 2 of these specimens were placed inside water during 24h, in room environment, about 20ºC, while the other 4 specimens were placed inside an oven at 40ºC, for the same period. The load was applied both in parallel and vertical to the wood veins. The maximum loads and deformations were recorded, and the specimen´s dimensions were measured again. In this way the influence of heat and humidity on the compressive strength was recorded.
Then, 12 prisms of Greek oak wood specimens were used. After numbered, each specimen from 1 to 12, the dimensions and weights were measured. The division of the specimens performed in the following way, Group 1: specimens 1, 2, 3 and 10; Group 2: specimens 4, 5, 6 and 11; Group 3: specimens 7, 8, 9 and 12. The last group of samples was not submitted to any appliance of coating, so it was in the natural state and was used as "base of comparison" with the other two groups.
In the first group, a basic coating was applied and designated as solution A. In the second group, a coating using solution A + a nanomaterial (designated solution B) was applied. One specimen of each group, applied with the respective solution, was submitted to aging cycles, such as Freeze-Thaw Cycles and Water Cycle. These cycles lasted for approximately 10 days. Every specimen of each group was also subjected to extra tests, Water Drop Analysis.
Lastly, it was possible to observe under stereoscope, microscopically and macroscopically, the difference in the specimens concerning the level of degradation, after the cycles.

It was possible to conclude that the absence of coating in wood samples originates circumstances that may damage the material in a very wide form. Both coatings applied (Solutions A and B) had a positive response to the Water Cycles tests, although coating B (which incorporates the nanomaterial) had a more effective performance.
All the samples submitted to the Freeze-Thaw Cycles tests suffered a similar increase of volume. Also a bigger volume variation was verified, when comparing with the Water Cycles tests results.
When no coating was applied to the samples (samples 7, 8, 9 and 12 – clean samples - BASE) the results were very variable and difficult to explain.

KEY-WORDS: Timber, Coatings, Nanomaterials, Experimental Research, Greek oak

RESUMO

A utilização de madeira na construção tem vindo a tornar-se cada vez mais frequente, tanto em Portugal como no estrangeiro. Este crescimento deve-se as qualidades presentes na madeira, assim como as suas propriedades mecânicas e estéticas.
É usada em diversas etapas da construção, como a parte estrutural e acabamentos de inúmeros elementos de construção. No entanto, a madeira é um material bastante sensível e que é diversas vezes submetido a adversidades, como por exemplo humidade, e que podem afetar drasticamente o material ou as suas propriedades. Por esta razão, é necessário proteger o material, revestindo-o com algum tipo de produto, normalmente líquido, para que as suas propriedades não se percam, ou para que pelo menos duram o maior período de tempo possível.

Neste trabalho experimental pretendeu-se avaliar a performance de pequenos exemplares de madeira de carvalho Grego através de testes de durabilidade e resistência após a aplicação de produtos de proteção. Em relação aos testes de durabilidade, 3 diferentes tipos de testes foram realizados (Water Cycles, Freeze-Thaw Cycles e Water Drop Analysis). Um conjunto de testes foi realizado usando "exemplares crus" e exemplares revestidos com dois tipos de soluções (uma solução básica, designada por A e uma solução B, que resultou da adição de nanomateriais à solução A).
O objetivo desta dissertação pode ser definido como a realização de uma sequência de testes de resistência e de durabilidade que podem ser usados para perceber qual o efeito da utilização de nanomateriais como adição a comuns revestimentos usados no acabamento de elementos de madeira.

O trabalho laboratorial presente nesta dissertação foi realizado no Laboratório de Materiais de Construção, da Faculdade de Engenharia Civil da Universidade de Aristóteles, em Salónica, Grécia.
A primeira etapa do trabalho consistiu em submeter 6 cubos de madeira de carvalho Grego a testes de resistência mecânica. 2 dos espécimes foram colocados em água durante 24h, em temperatura ambiente, cerca de 20ºC, enquanto que os outros 4 espécimes foram colocados dentro de um forno a 40ºC, durante o mesmo período. Em seguida, foram realizados os testes de compressão. As cargas foram aplicadas nas direções paralela e perpendicular às fibras da madeira. As cargas máximas e as deformações foram registadas, e as dimensões dos espécimes foram medidas de novo. Foi então registada a influência do calor e da humidade na força de compressão.
Em seguida, foram usados os 12 prismas de madeira de carvalho Grego. Após serem numerados, cada prisma foi numerado de 1 a 12 e foram medidas as respetivas dimensões e pesos. Grupo 1: prismas 1, 2, 3 e 10; Grupo 2: prismas 4, 5, 6 e 11; Grupo 3: prismas 7, 8, 9 e 12. O último grupo de espécimes não foi submetido à aplicação de qualquer tipo de revestimento, sendo utilizados no seu estado natural e sendo assim considerados como "base de comparação" para com os restantes grupos.
No primeiro grupo, uma solução básica foi aplicada e designada como solução A. No segundo grupo, um revestimento composto pela solução A + nanomaterial (designado solução B) foi aplicado. Um espécime de cada grupo, revestido com a respetiva solução, foi submetido a testes de envelhecimento, como *Freeze-Thaw Cycles e Water Cycles*. Os testes foram realizados durante aproximadamente 10 dias. Todos os espécimes de cada grupo foram ainda submetidos a testes extras, Water Drop Analysis.
Por último, foi possível observar através de microscópio, microscopicamente e macroscopicamente, a diferença do nível de degradação em cada espécime, após os ciclos.

Foi possível concluir que a ausência de revestimento da madeira originou situações que podem danificar o material. Ambos os revestimentos aplicados (Solução A e B) tiveram uma resposta positiva aos *Water Cycles*, enquanto que a solução B (incorporação de nanomateriais) obteve a performance mais efetiva.
Todos os exemplares submetidos aos *Freeze-Thaw Cycles* sofreram idêntico aumento de volume, superior ao aumento sofrido nos *Water Cycles.*

PALAVRAS-CHAVE: Madeira de Construção, Revestimentos, Nanomateriais, Pesquisa Experimental, Carvalho Grego

Περίληψη

Η χρήση ξύλου στην κατασκευή γίνεται όλο και πιο κοινή, τόσο στην Πορτογαλία όσο και στο εξωτερικό. Η χρήση αυτή αυξάνεται λόγω των μηχανικών ιδιοτήτων, των αισθητικών χαρακτηριστικών καθώς και λόγω της ποικιλίας που παρουσιάζει το ξύλο.
Το ξύλο χρησιμοποιείται σε διάφορα στάδια κατασκευής, όπως στο δομικό μέρος και στα τελειώματα πολλών δομικών στοιχείων. Ωστόσο, είναι ένα πολύ ευαίσθητο υλικό και συνήθως παρουσιάζει προβλήματα που σχετίζονται με την υγρασία, τα οποία μπορούν να προκαλέσουν σοβαρή βλάβη στο ξύλο ή να υποβαθμίσουν τις ιδιότητές του. Για το λόγο αυτό, είναι απαραίτητο να προστατεύσετε επικαλύπτοντάς το με κάποιο προϊόν, συνήθως υγρό, έτσι ώστε οι ιδιότητες να διατηρούνται ή τουλάχιστον να διαρκούν όσο το δυνατόν περισσότερο.

Η παρούσα έρευνα έχει σκοπό να αξιολογήσει την απόδοση μικρών δειγμάτων ξύλου από Ελληνική δρύ σε δοκιμές ανθεκτικότητας και μηχανικής αντοχής μετά από επεξεργασία με προστατευτικά υλικά. Στις δοκιμές ανθεκτικότητας πραγματοποιήθηκαν 3 διαφορετικοί τύποι δοκιμών (κύκλοι ύγρανσης-ξήρανσης, κύκλοι ψύξης-απόψυξης και απορρόφηση σταγόνας). Ένας περιορισμένος αριθμός δοκιμών χρησιμοποιήθηκε ως υλικό αναφοράς ενώ άλλα δείγματα επεξεργάστηκαν με δύο διαλύματα Α και Β. Το διάλυμα Β προέκυψε από την προσθήκη νανοσωματιδίων στο διάλυμα Α.
Ο βασικός στόχος της παρούσας διατριβής μπορεί ως εκ τούτου να οριστεί ως η εκτέλεση ενός συνόλου δοκιμών αντίστασης και ανθεκτικότητας που μπορούν να χρησιμοποιηθούν για να γίνει κατανοητή η επίδραση της χρήσης νανοϋλικών ως προσθήκη σε κοινά προστατευτικά υλικά ξύλινων στοιχείων.

Το εργαστηριακό έργο που παρουσιάστηκε σε αυτή τη διατριβή πραγματοποιήθηκε στο Εργαστήριο Δομικών Υλικών, Τμήμα Πολιτικών Μηχανικών, Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης.
Το πρώτο βήμα ήταν να πραγματοποιηθούν δοκιμές μηχανικής αντοχής σε 6 κύβους ξύλου ελληνικής οξιάς. Αφού αριθμήθηκαν, ζυγίστηκαν και διαστασιολογήθηκαν. 2 από αυτά τα δείγματα τοποθετήθηκαν μέσα στο νερό για 24 ώρες και σε περιβάλλον δωματίου, περίπου στους 20ºC, ενώ τα άλλα 4 δείγματα τοποθετήθηκαν μέσα σε ένα φούρνο στους 40ºC για την ίδια περίοδο ώστε να είναι στεγνά. Το φορτίο ασκήθηκε τόσο παράλληλα όσο και κάθετα στις φλέβες. Καταγράφηκε το μέγιστο φορτίο και η παραμόρφωση ενώ στο τέλος του πειράματος ξαναμετρήθηκαν οι διαστάσεις των δοκιμίων. Με αυτό τον τρόπο μετρήθηκε η επίδραση της υγρασίας στη θλιπτική αντοχή.
Στη συνέχεια, χρησιμοποιήθηκαν 12 πρίσματα από το ίδιο ξύλο. Αριθμήθηκαν από το 1 μέχρι το 12 μετρήθηκαν και ζυγίστηκαν. Ο διαχωρισμός των δειγμάτων έγινε όπως φαίνεται παρακάτω: Ομάδα 1: δείγματα 1, 2, 3 και 10, Ομάδα 2: δείγματα 4, 5, 6 και 11. Ομάδα 3: δείγματα 7, 8, 9 και 12. Η τελευταία ομάδα δειγμάτων δεν υποβλήθηκε σε καμία επεξεργασία (δείγματα αναφοράς), έτσι ήταν στη φυσική κατάσταση και χρησιμοποιήθηκε ως "βάση σύγκρισης" με τις άλλες δύο ομάδες.
Στην πρώτη ομάδα εφαρμόστηκε επικάλυψη και προσδιορίστηκε ως διάλυμα Α. Στηδεύτερη ομάδα εφαρμόστηκε επικάλυψη χρησιμοποιώντας διάλυμα Α + και νανοϋλικό (προσδιορισμένο ως διάλυμα Β). Ένα δείγμα κάθε ομάδας υποβλήθηκε σε κύκλους γήρανσης, όπως κύκλοι ψύξης-απόψυξης και κύκλοι ύγρανσης-ξήρανσης. Οι κύκλοι αυτοί διήρκεσαν περίπου 10 ημέρες. Ένα δείγμα από κάθε ομάδα υποβλήθηκε επίσης σε πρόσθετη δοκιμή αυτή της απορρόφησης σταγόνων νερού.

Τέλος, ήταν δυνατή η οπτική παρατήρηση, με χρήση στερεοσκοπίου και μακροσκοπικά με σκοπό τον έλεγχο της φθοράς της επικάλυψης μετά τους κύκλους.
Από τα αποτελέσματα φαίνεται ότι η απουσία επικάλυψης στα ξύλινα δείγματα προκαλεί εκτενείς φθορές. Η χρήση και των δύο των διαλυμάτων (Α και Β) είχαν θετική επίδραση στην απορρόφηση σταγόνας αλλά το διάλυμα Β (που περιείχε νανοσωματίδια) είχε καλύτερη απόδοση.
Όλα τα δείγματα που ελέγχθηκαν σε ψύξη- απόψυξη παρουσίασαν την ίδια μεταβολή όγκου. Η μεταβολή αυτή ήταν μεγαλύτερη σε σχέση με τον έλεγχο της σταγόνας.
Στα δοκίμια αναφοράς όπου δεν εφαρμόστηκε επικάλυψη (δείγματα 7, 8, 9 και 12), τα αποτελέσματα ήταν μπερδεμένα και δύσκολο να εξηγηθούν.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Ξυλεία, Επίστρωση, Νανοϋλικά, Πειραματική Έρευνα, Ελληνική δρυς

INDEX

INDEX OF FIGURES TABLES

INDEX OF TABLES

INDEX OF FORMULAS

SYMBOLS, ACRONYMS AND ABBREVIATIONS

E – Modulus of Elasticity

EL – Modulus of Elasticity along the longitudinal axis of wood

EN – European Normative

ER – Modulus of Elasticity along the radial axis of wood

ET – Modulus of Elasticity aliong the tangencial axis of wood

FEUP – Faculdade de Engenharia da Universidade do Porto (Faculty of Engineering og University of Porto)

G – Modulus of Rigitdity

GLR – Modulus of rigidity based on shear strain in the *LR* plane and shear stresses in the *LT* and *RT* planes

GLT – Modulus of rigidity based on shear strain in the *LT* plane and shear stresses in the *LR* and *RT* planes

GRT – Modulus of rigidity based on shear strain in the *RT* plane and shear stresses in the *LR* and *LT* planes

H – Humidity

KN – Kilo Newton

kPa – Kilo Pascal

L – Longitudinal axis

MPa/s – Mega Pascal per second

Mp – Moisture contente at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of the strength–moisture content relationship for dry wood

N – Strenght

n – Empirically determined constant

No. – Number

P – Strenght parallel to grain (Formula 2.2)

P – Property at moisture content (%) (Formula 2.3)

P12 – Property at moisture content 12%

Pg – Property at moisture contente for green wood

Q – Strenght perpendicular to grain

R – Radial axis

U. PORTO – Universidade do Porto (University of Porto)

T – Tangencial Axis

Wa – Work of adhesion or bonding energy (Formula 5.1)

γLV – Surface tension of the liquid

μ - Poisson´s ratio

μLR – Poisson´s ratio for deformation along the radial axis caused by stress along the longidutinal axis

μLT – Poisson´s ratio for deformation along thetangencial axis caused by stress along the longidutinal axis

μRL – Poisson´s ratio for deformation along the longidutinal axis caused by stress along the radial axis

μRT – Poisson´s ratio for deformation along the tangencial axis caused by stress along the radial axis

μTL – Poisson´s ratio for deformation along the longidutinal axis caused by stress along the tangencial axis

μTR – Poisson´s ratio for deformation along the radial axis caused by stress along the tangencial axis

^{o}C – Celsius degree

^{o}F – Fahrenheit degree

θ – Angle of fibre direction

Θ – Water Drop Angle

1
INTRODUCTION

1.1. FRAMEWORK

The coatings of wood in construction, have always been an effective procedure to conserve the wooden properties that are expected to last for long periods of time, along with the building life, where these wood elements are present.

These wooden elements are often subjected to extreme environmental conditions, whether they are in “inside” or in “outside” conditions. It is important to refer that “inside” conditions, is referred as in the different conditions that can be presented inside the building. “Outside” conditions, is considered when the wooden elements are subjected to weather phenomena and actions.

In any of these situations, the wooden specimens are subjected to aggressive conditions. The more important effect to discuss is humidity. Humidity is the main responsible for affecting the wooden elements, once its presence can cause the detachment of wood covers in structural elements and the deterioration of wooden materials, that results in a loss of properties and consequently in a loss of performance.

It is also important to understand the different performances of wood when subjected to different environments and conditions. As moisture is the most critical phenomenon that wood can be subjected to, and that causes taunting, swelling or shrinkage, it is extremely important the use of the correct coating, depending on the conditions the material will be exposed to.

A lot of aspects must be considered, for the choice of the correct coating. The type of environmental condition the material will be exposed, the type of performance pretended for the material/technical global solution and also the financial aspect.

There are also some functional requirements related with the appliance of coatings:

- to ensure the physical integrity of the occupants of the space where this coating his applied in order to safeguard the security requirements;

- to ensure the comfort conditions that guarantee the habitability of the space;

- to safeguard the maintenance of the properties of the coating, and therefore ensuring the durability of the pieces. [1]

1.2. OBJECTIVES OF THE WORK

The present work intends to evaluate the performance of different types of coating on oak wood samples, in order to find out the most effective procedures to protect wood when exposed to long periods

of humidity. The influence of humidity on the dimensional stability and strength of wooden elements is tested on some samples.

The coatings used on the tests include common commercial products, and mixtures of those products mixed with a small incorporation of a nano-modified powder. The tests performed on the samples include the testing of properties related with the hydric behaviour such as porosity, water absorption, capillarity and also a water drop analysis to measure the surface absorption of the samples.

The same properties were analysed after subjecting other samples to the water and the freeze-thaw cycles.

In order to accomplish the proposed objectives, some shores and partial objectives were settled:

- Understand the performance of the wooden elements when exposed to long periods in humidity conditions and observe the consequences;

- Enumerate the current waterproofing approaches on wood elements, as their advantages and disadvantages;

- Define and apply the more efficient procedures to evaluate the loss of wooden properties when exposed to long periods in humidity conditions;

- Analyse and comment the results, comparing the procedures realized in order to determine the most effective, or which group of procedures were the most effective;

- Determine which coating presented more effective results, in order to preserve the properties of the wooden samples, after being subjected to the testing procedures;

- Determine the eventual advantages of incorporating nanomaterials in coating products;

- Determine if the most effective coating, is viable to be applied in a current construction situation – outside conditions.

1.3. WORK STRUCTURE

The present work is divided into 6 chapters:

- Chapter 1 introduces the topic, framing it into the context and referring the main objectives. It also describes the organization and the structure of the work developed;

- Chapter 2 presents a synthesis of the general concepts about wood mechanics and physics. Here, the mechanical properties of wooden elements are described. Physical consequences and the decreasing of the mechanical properties, are the main topics of this chapter;

- Chapter 3 is an essay about wood deterioration and preservation. Themes like causes of deterioration, moisture on wood and Risk Classes according to the humidity are addressed. The importance of wood preservation, preservation products, types of treatments and recommendations are suggested on this chapter. The importance of the application of these products is the main reason of the performance of the tests on Chapter 5, where new approaches are tested;

- Chapter 4 describes the compression tests realized on the samples, including the preparation of those, and the equipment used on the tests and the detailed description of the tests. Analysis of the results, such as volumes and dimensions´ variation are registered. Conclusions on the results of compression tests on cubes are drawn;

- Chapter 5 describes the experimental research on the durability of wood elements. All the procedures are described, including Water Cycles, Freeze-Thaw Cycles and Water Drop Analysis. This last one test was realised at the *Ormylia Art Diagnosis Centre* in Thessaloniki, Greece. It also compares the results obtained on each sample, according to the application of two types of coating solutions that incorporate or not incorporate nano-materials respectively (solutions B and A), on each Cycle. The conception of each Solution is also described. It is possible to understand the performance of the coatings applied in order to protect the wood samples against the consequences from the exposure to the different humidity conditions the samples were submitted during the tests which is a representation of real use comparable situations of rain and snow/ice conditions;

- Finally, Chapter 6 presents the main conclusions of this work, such as what were the best combination of technics to measure the waterproofing, and what was the coat with the best performance or what was the most adverse environmental condition tested.

2

WOOD MECHANICS AND PHYSICS GENERAL CONCEPTS

The mechanical properties presented in this chapter were obtained from tests of small samples of wood considered as “clear” and “straight grained” because they did not contain characteristics such as knots, cross grain, checks, and splits. Clear wood specimens are usually considered “homogeneous” in wood mechanics.

Variability, or variation in properties, is common to all materials. Because wood is a natural material and the tree is subject to many constantly changing influences (such as moisture, soil conditions, and growing space), wood properties vary considerably, even in clear material [2].

2.1. ORTHOTROPIC NATURE OF WOOD

Wood may be described as an orthotropic material. That is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. The longitudinal axis *L* is parallel to the fibre (grain); the radial axis *R* is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis T is perpendicular to the grain but tangent to the growth rings. These axes are shown in Figure 2.1 [2].

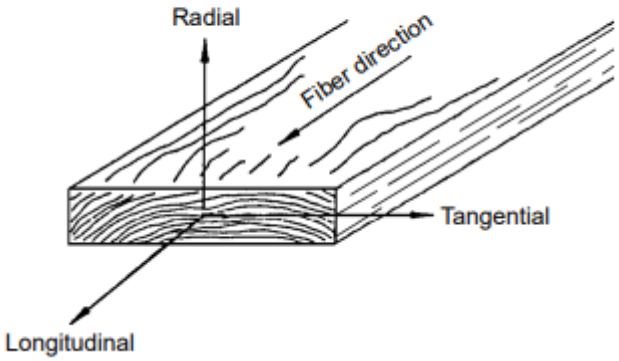


Figure 2.1 – Three principal axes of wood with respect to grain direction and growth rings [2]

2.2. ELASTIC PROPERTIES

Twelve constants are needed to describe the elastic behaviour of wood: three moduli of elasticity *E*, three moduli of rigidity *G*, and six Poisson´s ratios μ. The moduli of elasticity and Poisson’s ratios are related by expressions of the form,

$$\frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j}, \quad i \neq j \;\; i,j = L,R,T$$

(Formula 2.1)

General relations between stress and strain for a homogeneous orthotropic material can be found in texts on anisotropic elasticity [2].

2.2.1. MODULUS OF ELASTICITY

Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed. When loaded to higher stress levels, plastic deformation or failure occurs. The three moduli of elasticity, which are denoted by *EL*, *ER*, and *ET*, respectively, are the elastic moduli along the longitudinal, radial, and tangential axes of wood. These moduli are usually obtained from compression tests; however, data for *ER* and *ET* are not extensive.

Average values of *ER* and *ET* for samples from a few species are presented in Table 2.1 as ratios with *EL*; the Poisson's ratios are shown in Table 2.2. The elastic ratios, as well as the elastic constants themselves, vary within and between species and with moisture content and specific gravity. The modulus of elasticity determined from bending, *EL*, rather than from an axial test, may be the only modulus of elasticity available for a species. Average *EL* values obtained from bending tests. Representative coefficients of variation of *EL* determined with bending tests for clear wood are reported in Table 2.3. As tabulated, *EL* includes an effect of shear deflection; *EL* from bending can be increased by 10% to remove this effect approximately.

2.2.2. POISSON´S RATIO

When a member is loaded axially, the deformation perpendicular to the direction of the load is proportional to the deformation parallel to the direction of the load. The ratio of the transverse to axial strain is called Poisson's ratio. The Poisson's ratios are denoted by *μLR*, *μRL*, *μLT*, *μTL*, *μRT*, and *μTR*. The first letter of the subscript refers to direction of applied stress and the second letter to direction of lateral deformation. For example, *μLR* is the Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis. Average values of Poisson's ratios for samples of a few species are given in Table 2.2. Values for *μRL* and *μTL* are less precisely determined than are those for the other Poisson's ratios. Poisson's ratios vary within and between species and are affected by moisture content and specific gravity.

Table 2.1 – Elastic ratios for various species at approximately 12% moisture content[a] [2]

Species	E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L
Hardwoods					
Ash, white	0.080	0.125	0.109	0.077	—
Balsa	0.015	0.046	0.054	0.037	0.005
Basswood	0.027	0.066	0.056	0.046	—
Birch, yellow	0.050	0.078	0.074	0.068	0.017
Cherry, black	0.086	0.197	0.147	0.097	—
Cottonwood, eastern	0.047	0.083	0.076	0.052	—
Mahogany, African	0.050	0.111	0.088	0.059	0.021
Mahogany, Honduras	0.064	0.107	0.066	0.086	0.028
Maple, sugar	0.065	0.132	0.111	0.063	—
Maple, red	0.067	0.140	0.133	0.074	—
Oak, red	0.082	0.154	0.089	0.081	—
Oak, white	0.072	0.163	0.086	—	—
Sweet gum	0.050	0.115	0.089	0.061	0.021
Walnut, black	0.056	0.106	0.085	0.062	0.021
Yellow-poplar	0.043	0.092	0.075	0.069	0.011
Softwoods					
Baldcypress	0.039	0.084	0.063	0.054	0.007
Cedar, northern white	0.081	0.183	0.210	0.187	0.015
Cedar, western red	0.055	0.081	0.087	0.086	0.005
Douglas-fir	0.050	0.068	0.064	0.078	0.007
Fir, subalpine	0.039	0.102	0.070	0.058	0.006
Hemlock, western	0.031	0.058	0.038	0.032	0.003
Larch, western	0.065	0.079	0.063	0.069	0.007
Pine					
Loblolly	0.078	0.113	0.082	0.081	0.013
Lodgepole	0.068	0.102	0.049	0.046	0.005
Longleaf	0.055	0.102	0.071	0.060	0.012
Pond	0.041	0.071	0.050	0.045	0.009
Ponderosa	0.083	0.122	0.138	0.115	0.017
Red	0.044	0.088	0.096	0.081	0.011
Slash	0.045	0.074	0.055	0.053	0.010
Sugar	0.087	0.131	0.124	0.113	0.019
Western white	0.038	0.078	0.052	0.048	0.005
Redwood	0.089	0.087	0.066	0.077	0.011
Spruce, Sitka	0.043	0.078	0.064	0.061	0.003
Spruce, Engelmann	0.059	0.128	0.124	0.120	0.010

[a] E_L may be approximated by increasing modulus of elasticity values in Table 4–3 by 10%.

This adjusted bending *EL* can be used to determine *ER* and *ET* based on the ratios in Table 2.1.

Table 2.2 – Poisson´s ratios for various species at approximately 12% moisture content [2]

Species	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Hardwoods						
Ash, white	0.371	0.440	0.684	0.360	0.059	0.051
Aspen, quaking	0.489	0.374	—	0.496	0.054	0.022
Balsa	0.229	0.488	0.665	0.231	0.018	0.009
Basswood	0.364	0.406	0.912	0.346	0.034	0.022
Birch, yellow	0.426	0.451	0.697	0.426	0.043	0.024
Cherry, black	0.392	0.428	0.695	0.282	0.086	0.048
Cottonwood, eastern	0.344	0.420	0.875	0.292	0.043	0.018
Mahogany, African	0.297	0.641	0.604	0.264	0.033	0.032
Mahogany, Honduras	0.314	0.533	0.600	0.326	0.033	0.034
Maple, sugar	0.424	0.476	0.774	0.349	0.065	0.037
Maple, red	0.434	0.509	0.762	0.354	0.063	0.044
Oak, red	0.350	0.448	0.560	0.292	0.064	0.033
Oak, white	0.369	0.428	0.618	0.300	0.074	0.036
Sweet gum	0.325	0.403	0.682	0.309	0.044	0.023
Walnut, black	0.495	0.632	0.718	0.378	0.052	0.035
Yellow-poplar	0.318	0.392	0.703	0.329	0.030	0.019
Softwoods						
Baldcypress	0.338	0.326	0.411	0.356	—	—
Cedar, northern white	0.337	0.340	0.458	0.345	—	—
Cedar, western red	0.378	0.296	0.484	0.403	—	—
Douglas-fir	0.292	0.449	0.390	0.374	0.036	0.029
Fir, subalpine	0.341	0.332	0.437	0.336	—	—
Hemlock, western	0.485	0.423	0.442	0.382	—	—
Larch, western	0.355	0.276	0.389	0.352	—	—
Pine						
Loblolly	0.328	0.292	0.382	0.362	—	—
Lodgepole	0.316	0.347	0.469	0.381	—	—
Longleaf	0.332	0.365	0.384	0.342	—	—
Pond	0.280	0.364	0.389	0.320	—	—
Ponderosa	0.337	0.400	0.426	0.359	—	—
Red	0.347	0.315	0.408	0.308	—	—
Slash	0.392	0.444	0.447	0.387	—	—
Sugar	0.356	0.349	0.428	0.358	—	—
Western white	0.329	0.344	0.410	0.334	—	—
Redwood	0.360	0.346	0.373	0.400	—	—
Spruce, Sitka	0.372	0.467	0.435	0.245	0.040	0.025
Spruce, Engelmann	0.422	0.462	0.530	0.255	0.083	0.058

Table 2.3 – Average coefficients of variation for some mechanical properties of clear wood [2]

Property	Coefficient of variation[a] (%)
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending	25
Compression parallel to grain	18
Compression perpendicular to grain	28
Shear parallel to grain, maximum shearing strength	14
Tension parallel to grain	25
Side hardness	20
Toughness	34
Specific gravity	10

[a]Values based on results of tests of green wood from approximately 50 species. Values for wood adjusted to 12% moisture content may be assumed to be approximately of the same magnitude.

2.2.3. MODULUS OF RIGIDITY

The modulus of rigidity, also called shear modulus, indicates the resistance to deflection of a member caused by shear stresses. The three moduli of rigidity denoted by *GLR, GLT*, and *GRT* are the elastic constants in the *LR, LT,* and *RT* planes, respectively. For example, *GLR* is the modulus of rigidity based on shear strain in the *LR* plane and shear stresses in the *LT* and *RT* planes. Average values of shear moduli for samples of a few species expressed as ratios with *EL* are given in Table 2.1. As with moduli of elasticity, the moduli of rigidity vary within and between species and with moisture content and specific gravity [2].

2.3. STRENGHT PROPERTIES

2.3.1. COMMON PROPERTIES

Mechanical properties most commonly measured and represented as “strength properties” for design include modulus of rupture in bending, maximum stress in compression parallel to grain, compressive stress perpendicular to grain, and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain, and hardness:

- Modulus of rupture — Reflects the maximum load carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen; the Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit;

- Work to maximum load in bending — Ability to absorb shock with some permanent deformation and more or less injury to a specimen; Work to maximum load is a measure of the combined strength and toughness of wood under bending stresses;

- Compressive strength parallel to grain — Maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least dimension of less than 11;

- Compressive stress perpendicular to grain — Reported as stress at proportional limit; There is no clearly defined ultimate stress for this property;

- Shear strength parallel to grain — Ability to resist internal slipping of one part upon another along the grain; Values presented are average strength in radial and tangential shear planes;

- Impact bending — In the impact bending test, a hammer of given weight is dropped upon a beam from successively increased heights until rupture occurs or the beam deflects 152 mm (6 in.) or more; The height of the maximum drop, or the drop that causes failure, is a comparative value that represents the ability of wood to absorb shocks that cause stresses beyond the proportional limit;

- Tensile strength perpendicular to grain — Resistance of wood to forces acting across the grain that tend to split a member; Values presented are the average of radial and tangential observations;

- Hardness — Generally defined as resistance to indentation using a modified Janka hardness test, measured by the load required to embed a 11.28-mm (0.444-in.) ball to one-half its diameter; Values presented are the average of radial and tangential penetrations;

- Tensile strength parallel to grain — Maximum tensile stress sustained in direction parallel to grain; Relatively few data are available on the tensile strength of various species of clear wood

parallel to grain; Table 2.4 lists average tensile strength values for a limited number of specimens of a few species; In the absence of sufficient tension test data, modulus of rupture values are sometimes substituted for tensile strength of small, clear, straight grained pieces of wood; The modulus of rupture is considered to be a low or conservative estimate of tensile strength for clear specimens (this is not true for lumber).

Table 2.4 – Average parallel-to-grain tensile strength of some wood species[a] [2]

Species	Tensile strength (kPa (lb/in^2))	
Hardwoods		
Beech, American	86,200	(12,500)
Elm, cedar	120,700	(17,500)
Maple, sugar	108,200	(15,700)
Oak		
Overcup	77,900	(11,300)
Pin	112,400	(16,300)
Poplar, balsam	51,000	(7,400)
Sweetgum	93,800	(13,600)
Willow, black	73,100	(10,600)
Yellow-poplar	109,600	(15,900)
Softwoods		
Baldcypress	58,600	(8,500)
Cedar		
Port-Orford	78,600	(11,400)
Western redcedar	45,500	(6,600)
Douglas-fir, interior north	107,600	(15,600)
Fir		
California red	77,900	(11,300)
Pacific silver	95,100	(13,800)
Hemlock, western	89,600	(13,000)
Larch, western	111,700	(16,200)
Pine		
Eastern white	73,100	(10,600)
Loblolly	80,000	(11,600)
Ponderosa	57,900	(8,400)
Virginia	94,500	(13,700)
Redwood		
Virgin	64,800	(9,400)
Young growth	62,700	(9,100)
Spruce		
Engelmann	84,800	(12,300)
Sitka	59,300	(8,600)

[a]Results of tests on small, clear, straight-grained specimens tested green. For hardwood species, strength of specimens tested at 12% moisture content averages about 32% higher; for softwoods, about 13% higher.

2.3.2. LESS COMMON PROPERTIES

Strength properties less commonly measured in clear wood include torsion, toughness, rolling shear, and fracture toughness. Other properties involving time under load include creep, creep rupture or duration of load, and fatigue strength.

- Torsion strength — Resistance to twisting about a longitudinal axis; For solid wood members, torsional shear strength may be taken as shear strength parallel to grain; Two-thirds of the value for torsional shear strength may be used as an estimate of the torsional shear stress at the proportional limit;

- Toughness — Energy required to cause rapid complete failure in a centrally loaded bending specimen. Table 2.5 give average toughness values for samples of a few hardwood species.

Average coefficients of variation for toughness as determined from approximately 50 species are shown in Table 2.3.

- Creep and duration of load — Time-dependent deformation of wood under load; If the load is sufficiently high and the duration of load is long, failure (creep–rupture) will eventually occur; The time required to reach rupture is commonly called duration of load; Duration of load is an important factor in setting design values for wood;

- Fatigue — Resistance to failure under specific combinations of cyclic loading conditions: frequency and number of cycles, maximum stress, ratio of maximum to minimum stress, and other less-important factors; The main factors affecting fatigue in wood are discussed later in this chapter; The discussion also includes interpretation of fatigue data and information on fatigue as a function of the service environment;

- Rolling shear strength — Shear strength of wood where shearing force is in a longitudinal plane and is acting perpendicular to the grain; Few test values of rolling shear in solid wood have been reported; In limited tests, rolling shear strength averaged 18% to 28% of parallel-to-grain shear values. Rolling shear strength is about the same in the longitudinal–radial and longitudinal–tangential planes;

- Fracture toughness — Ability of wood to withstand flaws that initiate failure; Measurement of fracture toughness helps identify the length of critical flaws that initiate failure in materials.

Table 2.5 – Average toughness values for a few hardwood species[a] [2]

			Toughness	
Species	Moisture content	Specific gravity	Radial (J (in-lbf))	Tangential (J (in-lbf))
Birch, yellow	12%	0.65	8,100 (500)	10,100 (620)
Hickory (mocker-	Green	0.64	11,400 (700)	11,700 (720)
nut, pignut, sand)	12%	0.71	10,100 (620)	10,700 (660)
Maple, sugar	14%	0.64	6,000 (370)	5,900 (360)
Oak, red				
Pin	12%	0.64	7,000 (430)	7,000 (430)
Scarlet	11%	0.66	8,300 (510)	7,200 (440)
Oak, white				
Overcup	Green	0.56	11,900 (730)	11,100 (680)
	13%	0.62	5,500 (340)	5,000 (310)
Sweetgum	Green	0.48	5,500 (340)	5,400 (330)
	13%	0.51	4,200 (260)	4,200 (260)
Willow, black	Green	0.38	5,000 (310)	5,900 (360)
	11%	0.4	3,400 (210)	3,700 (230)
Yellow-poplar	Green	0.43	5,200 (320)	4,900 (300)
	12%	0.45	3,600 (220)	3,400 (210)

To date there is no standard test method for determining fracture toughness in wood. Three types of stress fields, and associated stress intensity factors, can be defined at a crack tip: opening mode (I), forward shear mode (II), and transverse shear mode (III) (Figure 2.2a). A crack may lie in one of these three planes and may propagate in one of two directions in each plane. This gives rise to six crack-propagation systems (*RL, TL, LR, TR, LT*, and *RT*) (Figure 2.2b). Of these crack propagation systems, four systems are of practical importance: *RL, TL, TR*, and *RT*.

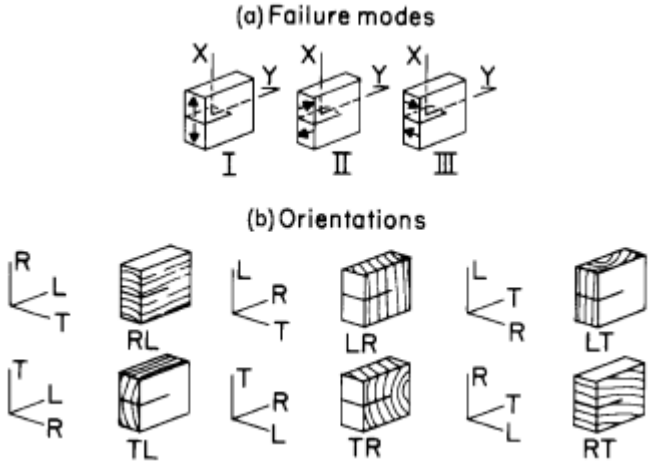


Figure 2.2 – Possible crack propagation systems for wood [2]

Each of these four systems allow for propagation of a crack along the lower strength path parallel to the grain. The *RL* and *TL* orientations in wood (where *R* or *T* is perpendicular to the crack plane and *L* is the direction in which the crack propagates) will predominate as a result of the low strength and stiffness of wood perpendicular to the grain. It is therefore one of these two orientations that is most often tested. Values for Mode I fracture toughness range from 220 to 550 kPa$\sqrt{m}$ (200 to 500 lbf / in² $\sqrt{in.}$) and for Mode II range from 1,650 to 2,400 kPa m (1,500 to 2,200 lbf / in² $\sqrt{in.}$). Table 2.6 summarizes selected mode I and mode II test results at 10% to 12% moisture content available in the literature. The limited information available on moisture content effects on fracture toughness suggests that fracture toughness is either insensitive to moisture content or increases as the material dries, reaching a maximum between 6% and 15% moisture content; fracture toughness then decreases with further drying. [2]

2.4. VIBRATION PROPERTIES

The vibration properties of primary interest in structural materials are the speed of sound and internal friction (damping capacity).

2.4.1. SPEED OF SOUND

The speed of sound in a structural material is a function of the modulus of elasticity and density. In wood, the speed of sound also varies with grain direction because the transverse modulus of elasticity is much less than the longitudinal value (as little as 1/20). The speed of sound across the grain is about one-fifth to one-third of the longitudinal value. For example, a piece of wood with a longitudinal modulus of elasticity of 12.4 GPa (1.8 × 106 lbf/in²) and density of 480 kg/m³ (30 lb/ft³) would have a speed of sound in the longitudinal direction of about 3,800 m/s (12,500 ft/s). In the transverse direction, modulus of elasticity would be about 690 MPa (100 × 10³ lbf/in²) and the speed of sound approximately 890 m/s (2,900 ft/s).

The speed of sound decreases with increasing temperature or moisture content in proportion to the influence of these variables on modulus of elasticity and density. The speed of sound decreases slightly with increasing frequency and amplitude of vibration, although for most common applications this effect is too small to be significant. There is no recognized independent effect of species on the speed of sound. Variability in the speed of sound in wood is directly related to the variability of modulus of elasticity and density.

Table 2.6 – Summary of selected fracture toughness results [2]

	Fracture toughness ($kPa\sqrt{m}$ ($lbf/in^2\sqrt{in.}$))			
	Mode I		Mode II	
Species	*TL*	*RL*	*TL*	*RL*
Douglas-fir	320 (290)	360 (330)		2,230 (2,030)
Western hemlock	375 (340)		2,240 (2,040)	
Pine				
Western white	250 (225)	260 (240)		
Scots	440 (400)	500 (455)	2,050 (1,860)	
Southern	375 (340)		2,070 (1,880)	
Ponderosa	290 (265)			
Red spruce	420 (380)		2,190 (1,990)	1,665 (1,510)
Northern red oak	410 (370)			
Sugar maple	480 (430)			
Yellow-poplar	517 (470)			

2.4.2. Internal Friction

When solid material is strained, some mechanical energy is dissipated as heat. Internal friction is the term used to denote the mechanism that causes this energy dissipation. The internal friction mechanism in wood is a complex function of temperature and moisture content. In general, there is a value of moisture content at which internal friction is minimum. On either side of this minimum, internal friction increases as moisture content varies down to zero or up to the fibre saturation point. The moisture content at which minimum internal friction occurs varies with temperature. At room temperature (23ºC (73ºF)), the minimum occurs at about 6% moisture content; at −20ºC (−4ºF), it occurs at about 14% moisture content, and at 70ºC (158ºF), at about 4%. At 90ºC (194ºF), the minimum is not well defined and occurs near zero moisture content.

Similarly, there are temperatures at which internal friction is minimum, and the temperatures of minimum internal friction vary with moisture content. The temperatures of minimum internal friction are higher as the moisture content is decreased. For temperatures above 0ºC (32ºF) and moisture content greater than about 10%, internal friction increases strongly as temperature increases, with a strong positive interaction with moisture content. For very dry wood, there is a general tendency for internal friction to decrease as the temperature increases.

The value of internal friction, expressed by logarithmic decrement, ranges from about 0.1 for hot, moist wood to less than 0.02 for hot, dry wood. Cool wood, regardless of moisture content, would have an intermediate value [2].

2.5. Natural Characteristics Affecting Properties

Clear straight-grained wood is used for determining fundamental mechanical properties; however, because of natural growth characteristics of trees, wood products vary in specific gravity, may contain cross grain, or may have knots and localized slope of grain. Natural defects such as pitch pockets may occur as a result of biological or climatic elements influencing the living tree. These wood characteristics must be taken into account in assessing actual properties or estimating the actual performance of wood products.

2.5.1. SPECIFIC GRAVITY

The substance of which wood is composed is actually heavier than water; its specific gravity is about 1.5 regardless of wood species. In spite of this, the dry wood of most species floats in water, and it is thus evident that part of the volume of a piece of wood is occupied by cell cavities and pores. Variations in the size of these openings and in the thickness of the cell walls cause some species to have more wood substance per unit volume than other species and therefore higher specific gravity. Thus, specific gravity is an excellent index of the amount of wood substance contained in a piece of wood; it is a good index of mechanical properties as long as the wood is clear, straight grained, and free from defects. However, specific gravity values also reflect the presence of gums, resins, and extractives, which contribute little to mechanical properties.

In fact, mechanical properties within a species tend to be linearly, rather than curvilinear, related to specific gravity; where data are available for individual species, linear analysis is suggested.

2.5.2. KNOTS

A knot is that portion of a branch that has become incorporated in the bole of a tree. The influence of a knot on the mechanical properties of a wood member is due to the interruption of continuity and change in the direction of wood fibres associated with the knot. The influence of knots depends on their size, location, shape, and soundness; attendant local slope of grain; and type of stress to which the wood member is subjected.

The shape (form) of a knot on a sawn surface depends upon the direction of the exposing cut. A nearly round knot is produced when lumber is sawn from a log and a branch is sawn through at right angles to its length (as in a flatsawn board). An oval knot is produced if the saw cut is diagonal to the branch length (as in a bastard-sawn board) and a “spiked” knot when the cut is lengthwise to the branch (as in a quartersawn board).

Knots are further classified as intergrown or encased (Figure 2.3). As long as a limb remains alive, there is continuous growth at the junction of the limb and the bole of the tree, and the resulting knot is called intergrown. After the branch has died, additional growth on the trunk encloses the dead limb, resulting in an encased knot; bole fibres are not continuous with the fibres of the encased knot. Encased knots and knotholes tend to be accompanied by less cross-grain than are intergrown knots and are therefore generally less problematic with regard to most mechanical properties.

Most mechanical properties are lower in sections containing knots than in clear straight-grained wood because (a) the clear wood is displaced by the knot, (b) the fibres around the knot are distorted, resulting in cross grain, (c) the discontinuity of wood fibre leads to stress concentrations, and (d) checking often occurs around the knots during drying. Hardness and strength in compression perpendicular to the grain are exceptions, where knots may be objectionable only in that they cause nonuniform wear or nonuniform stress distributions at contact surfaces.

Knots have a much greater effect on strength in axial tension than in axial short-column compression, and the effects on bending are somewhat less than those in axial tension.

For this reason, in a simply supported beam, a knot on the lower side (subjected to tensile stresses) has a greater effect on the load the beam will support than does a knot on the upper side (subjected to compressive stresses). In long columns, knots are important because they affect stiffness. In short or intermediate columns, the reduction in strength caused by knots is approximately proportional to their size; however, large knots have a somewhat greater relative effect than do small knots. Knots in round timbers, such as poles and piles, have less effect on strength than do knots in sawn timbers. Although the grain is irregular around knots in both forms of timber, the angle of the grain to the surface is smaller in naturally round timber than in sawn timber. Furthermore, in round timbers there is no discontinuity in wood fibres, which results from sawing through both local and general slope of grain.

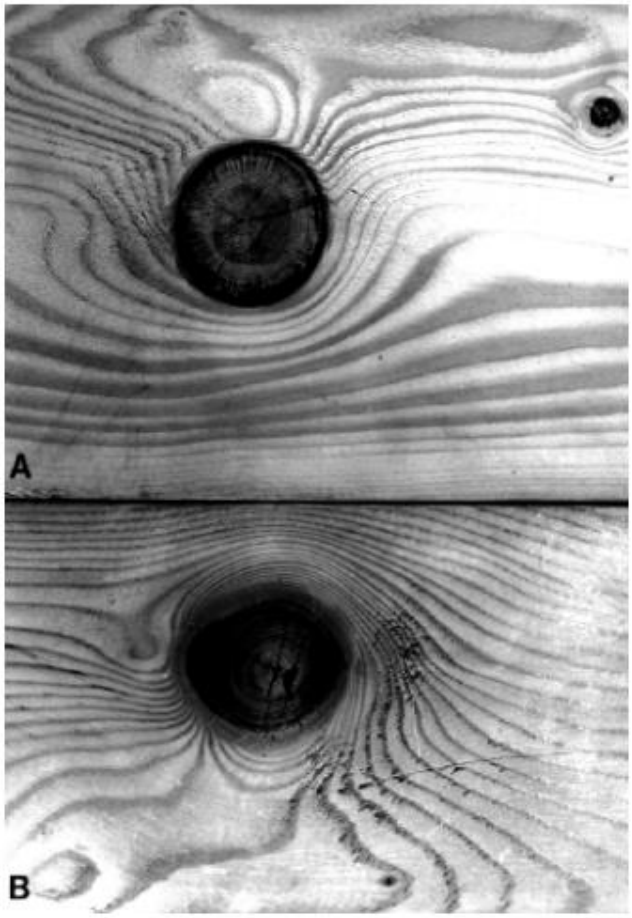


Figure 2.3 – Types of knots. A: encased knot; B: intergrown [2]

2.5.3. SLOPE OF GRAIN

In some wood product applications, the directions of important stresses may not coincide with the natural axes of fibre orientation in the wood. This may occur by choice in design, from the way the wood was removed from the log, or because of grain irregularities that occurred while the tree was growing.

Elastic properties in directions other than along the natural axes can be obtained from elastic theory. Strength properties in directions ranging from parallel to perpendicular to the fibres can be approximated using a Hankinson-type formula (Bodig and Jayne 1982):

$$N = \frac{PQ}{P\sin^n\theta + Q\cos^n\theta}$$

(Formula 2.2)

where N is strength at angle θ from fibre direction, Q strength perpendicular to grain, P strength parallel to grain, and n an empirically determined constant.

This formula has been used for modulus of elasticity as well as strength properties. Values of n and associated ratios of Q/P tabulated from available literature are as present in table 2.7.

Table 2.7 – Values of *n* and associated ratios of *Q/P* [2]

Property	*n*	*Q/P*
Tensile strength	1.5–2	0.04–0.07
Compression strength	2–2.5	0.03–0.40
Bending strength	1.5–2	0.04–0.10
Modulus of elasticity	2	0.04–0.12
Toughness	1.5–2	0.06–0.10

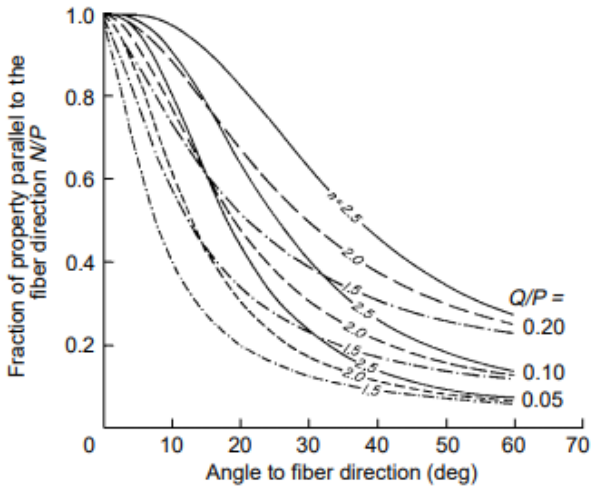


Figure 2.4 – Effect of grain angle on mechanical property of clear wood according to Hankinson-type formula. *Q/P* is ratio of mechanical property across the grain (*Q*) to that parallel to the grain (*P*); *n* is an empirically determined constant [2]

The Hankinson-type formula can be graphically depicted as a function of *Q/P* and *n*. Figure 2.4 shows the strength in any direction expressed as a fraction of the strength parallel to fibre direction, plotted against angle to the fibre direction *θ*. The plot is for a range of values of *Q/P* and *n*.

The term slope of grain relates the fibre direction to the edges of a piece. Slope of grain is usually expressed by the ratio between 25 mm (1 in.) of the grain from the edge or long axis of the piece and the distance in millimetres (inches) within which this deviation occurs (*tan θ*). The effect of grain slope on some properties of wood, as determined from tests, is shown in Table 2.8. The values for modulus of rupture fall very close to the curve in Figure 2.4 for *Q/P* = 0.1 and *n* = 1.5. Similarly, the impact bending values fall close to the curve for *Q/P* = 0.05 and *n* =1.5, and the compression values for the curve for *Q/P* = 0.1, n = 2.5.

The term cross grain indicates the condition measured by slope of grain. Two important forms of cross grain are spiral and diagonal (Figure 2.5). Other types are wavy, dipped, interlocked, and curly.

Spiral grain is caused by winding or spiral growth of wood fibres about the bole of the tree instead of vertical growth. In sawn products, spiral grain can be defined as fibres lying in the tangential plane of the growth rings, rather than parallel to the longitudinal axis of the product (see Fig. 2.5 for a simple case). Spiral grain in sawn products often goes undetected by ordinary visual inspection. The best test for spiral grain is to split a sample section from the piece in the radial direction. A visual method of determining the presence of spiral grain is to note the alignment of pores, rays, and resin ducts on a flatsawn face. Drying checks on a flatsawn surface follow the fibres and indicate the slope of the fibre. Relative change in electrical capacitance is an effective technique for measuring slope of grain.

Diagonal grain is cross grain caused by growth rings that are not parallel to one or both surfaces of the sawn piece. Diagonal grain is produced by sawing a log with pronounced taper parallel to the axis (pith) of the tree. Diagonal grain also occurs in lumber sawn from crooked logs or logs with butt swell.

Cross grain can be quite localized as a result of the disturbance of a growth pattern by a branch. This condition, termed local slope of grain, may be present even though the branch (knot) may have been removed by sawing. The degree of local cross grain may often be difficult to determine. Any form of cross grain can have a deleterious effect on mechanical properties or machining characteristics.

Table 2.8 – Strength of wood members with various grain slopes compared with strength of a straight-grained member[a] [2]

Maximum slope of grain in member	Modulus of rupture (%)	Impact bending (%)	Compression parallel to grain (%)
Straight-grained	100	100	100
1 in 25	96	95	100
1 in 20	93	90	100
1 in 15	89	81	100
1 in 10	81	62	99
1 in 5	55	36	93

[a]Impact bending is height of drop causing complete failure (0.71-kg (50-lb) hammer); compression parallel to grain is maximum crushing strength.

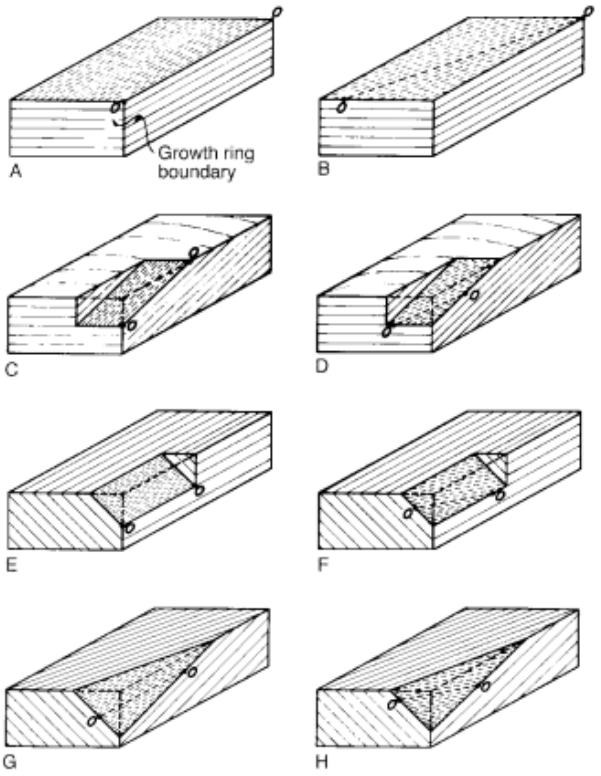


Figure 2.5 – Relationship of fibre orientation (*O*-*O*) to axes, as shown by schematic of wood specimens containing straight grain and cross grain. Specimens *A* through *H* do not. Specimens *A* and *E* contain no cross grain; *B*, *D*, *F* and *H* have spiral grain; *C*, *D*, *G* and *H* have diagonal grain [2]

2.5.4. ANNUAL RING ORIENTATION

Stresses perpendicular to the fibre (grain) direction may be at any angle from 0° (*T*) to 90º (*R*) to the growth rings (Figure 2.6). Perpendicular-to-grain properties depend somewhat upon orientation of annual rings with respect to the direction of stress. The compression perpendicular-to-grain values were derived from tests in which the load was applied parallel to the growth rings (*T* direction); shear parallel-to-grain and tension perpendicular-to-grain values are averages of equal numbers of specimens with 0º and 90º growth ring orientations. In some species, there is no difference in 0º and 90º orientation properties. Other species exhibit slightly higher shear parallel or tension perpendicular-to-grain properties for the 0º orientation than for the 90º orientation; the converse is true for about an equal number of species.

The effects of intermediate annual ring orientations have been studied in a limited way. Modulus of elasticity, compressive perpendicular-to-grain stress at the proportional limit, and tensile strength perpendicular to the grain tend to be about the same at 45º and 0º, but for some species these values are 40% to 60% lower at the 45º orientation. For those species with lower properties at 45º ring orientation, properties tend to be about equal at 0º and 90º orientations. For species with about equal properties at 0º and 45º orientations, properties tend to be higher at the 90º orientation.

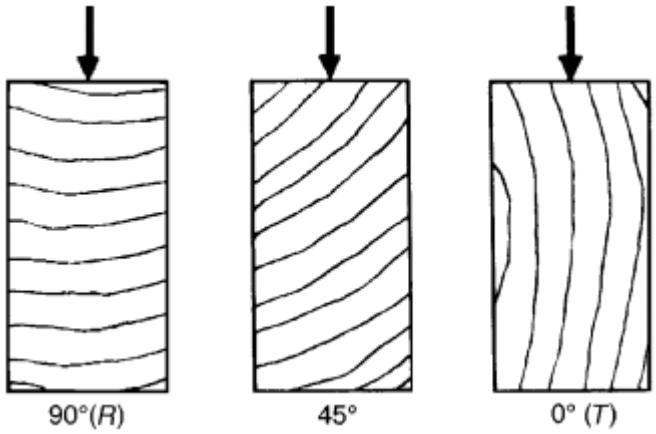


Figure 2.6 – Direction of load in relation to direction of annual growth rings: 90º or perpendicular (*R*), 45º, 0º or parallel (*T*) [2]

2.5.5. REACTION WOOD

Abnormal woody tissue is frequently associated with leaning boles and crooked limbs of both conifers and hardwoods. It is generally believed that such wood is formed as a natural response of the tree to return its limbs or bole to a more normal position, hence the term reaction wood. In softwoods, the abnormal tissue is called compression wood; it is common to all softwood species and is found on the lower side of the limb or inclined bole. In hardwoods, the abnormal tissue is known as tension wood; it is located on the upper side of the inclined member, although in some instances it is distributed irregularly around the cross section. Reaction wood is more prevalent in some species than in others.

Many of the anatomical, chemical, physical, and mechanical properties of reaction wood differ distinctly from those of normal wood. Perhaps most evident is the increase in density compared with that of normal wood. The specific gravity of compression wood is commonly 30% to 40% greater than that of normal wood; the specific gravity of tension wood commonly ranges between 5% and 10% greater than that of normal wood, but it may be as much as 30% greater.

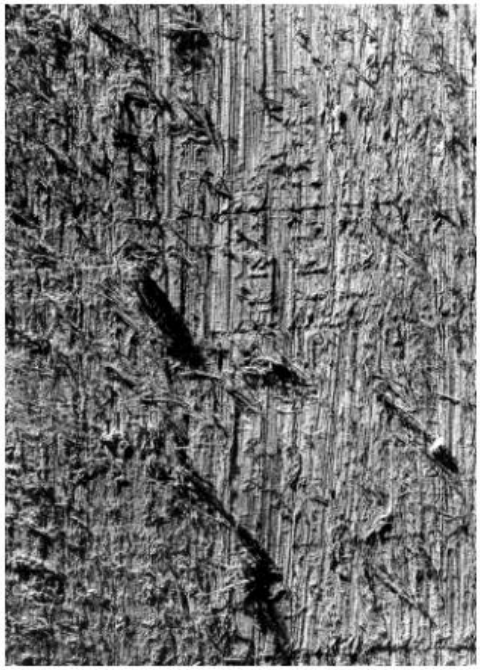


Figure 2.7 – Projecting tension wood fibres on sawn surface of mahogany board [2]

Compression wood is usually somewhat darker than normal wood because of the greater proportion of latewood, and it frequently has a relatively lifeless appearance, especially in woods in which the transition from early wood to latewood is abrupt. Because compression wood is more opaque than normal wood, intermediate stages of compression wood can be detected by transmitting light through thin cross sections; however, borderline forms of compression wood that merge with normal wood can commonly be detected only by microscopic examination.

Tension wood is more difficult to detect than is compression wood. However, eccentric growth as seen on the transverse section suggests its presence. Also, because it is difficult to cleanly cut the tough tension wood fibres, the surfaces of sawn boards are “woolly,” especially when the boards are sawn in the green condition (Figure 2.7). In some species, tension wood may be evident on a smooth surface as areas of contrasting colours. Examples of this are the silvery appearance of tension wood in sugar maple and the darker colour of tension wood in mahogany.

Reaction wood, particularly compression wood in the green condition, may be stronger than normal wood. However, compared with normal wood with similar specific gravity, reaction wood is definitely weaker. Possible exceptions to this are compression parallel-to-grain properties of compression wood and impact bending properties of tension wood.

Because of the abnormal properties of reaction wood, it may be desirable to eliminate this wood from raw material. In logs, compression wood is characterized by eccentric growth about the pith and the large proportion of latewood at the point of greatest eccentricity (Figure 2.8A). Fortunately, pronounced compression wood in lumber can generally be detected by ordinary visual examination.

Compression and tension wood undergo extensive longitudinal shrinkage when subjected to moisture loss below the fibre saturation point. Longitudinal shrinkage in compression wood may be up to 10 times that in normal wood and in tension wood, perhaps up to 5 times that in normal wood. When reaction wood and normal wood are present in the same board, unequal longitudinal shrinkage causes internal stresses that result in warping. In extreme cases, unequal longitudinal shrinkage results in axial tension failure over a portion of the cross section of the lumber (Figure 2.8B). Warp sometimes occurs in rough lumber but more often in planed, ripped, or resawn lumber (Figure 2.8C).

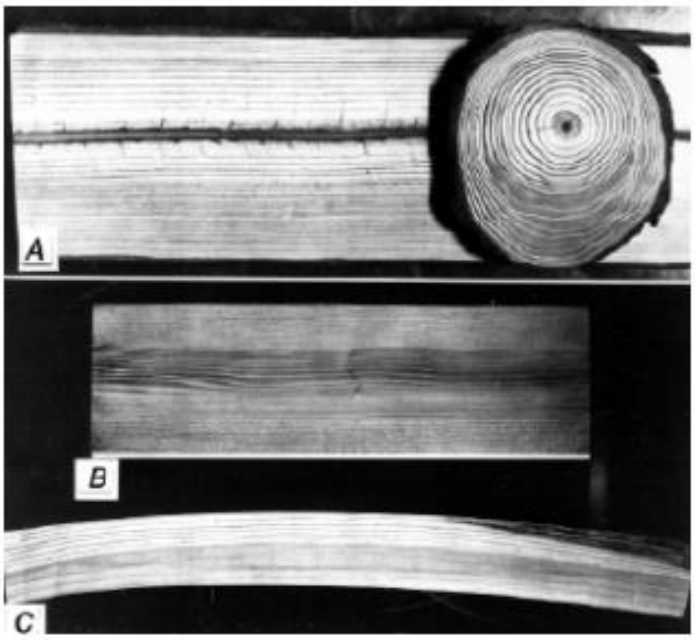


Figure 2.8 – Effects of compression wood. A: eccentric growth about pith in cross section containing compression wood-dark area in lower third of cross section is compression wood; B: axial tension break caused by excessive longitudinal shrinkage of compression wood; C: warp caused by excessive longitudinal shrinkage [2]

2.5.6. JUVENILE WOOD

Juvenile wood is the wood produced near the pith of the tree; for softwoods, it is usually defined as the material 5 to 20 rings from the pith depending on species. Juvenile wood has considerably different physical and anatomical properties than that of mature wood (Figure 2.9). In clear wood, the properties that have been found to influence mechanical behaviour include fibril angle, cell length, and specific gravity, the latter a composite of percentage of latewood, cell wall thickness, and lumen diameter. Juvenile wood has a high fibril angle (angle between longitudinal axis of wood cell and cellulose fibrils), which causes longitudinal shrinkage that may be more than 10 times that of mature wood. Compression wood and spiral grain are also more prevalent in juvenile wood than in mature wood and contribute to longitudinal shrinkage. In structural lumber, the ratio of modulus of rupture, ultimate tensile stress, and modulus of elasticity for juvenile to mature wood ranges from 0.5 to 0.9, 0.5 to 0.95, and 0.45 to 0.75, respectively. Changes in shear strength resulting from increases in juvenile wood content can be adequately predicted by monitoring changes in density alone for all annual ring orientations. The same is true for perpendicular-to-grain compressive strength when the load is applied in the tangential direction. Compressive strength perpendicular-to-grain for loads applied in the radial direction, however, is more sensitive to changes in juvenile wood content and may be up to eight times less than that suggested by changes in density alone. The juvenile wood to mature wood ratio is lower for higher grades of lumber than for lower grades, which indicates that juvenile wood has greater influence in reducing the mechanical properties of high-grade structural lumber. Only a limited amount of research has been done on juvenile wood in hardwood species.

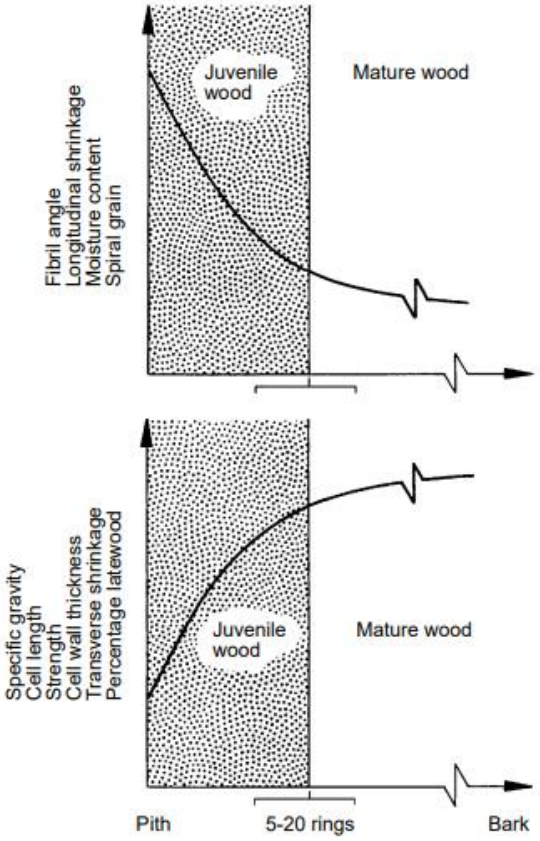


Figure 2.9 – Properties of juvenile wood [2]

2.5.7. COMPRESSION FAILURES

Excessive compressive stresses along the grain that produce minute compression failures can be caused by excessive bending of standing trees from wind or snow; felling of trees across boulders, logs, or irregularities in the ground; or rough handling of logs or lumber. Compression failures should not be confused with compression wood. In some instances, compression failures are visible on the surface of a board as minute lines or zones formed by crumpling or buckling of cells (Figure 2.10A), although the failures usually appear as white lines or may even be invisible to the naked eye. The presence of compression failures may be indicated by fibre breakage on end grain (Figure 2.10B). Since compression failures are often difficult to detect with the unaided eye, special efforts, including optimum lighting, may be required for detection. The most difficult cases are detected only by microscopic examination.

Products containing visible compression failures have low strength properties, especially in tensile strength and shock resistance. The tensile strength of wood containing compression failures may be as low as one-third the strength of matched clear wood. Even slight compression failures, visible only under a microscope, may seriously reduce strength and cause brittle fracture. Because of the low strength associated with compression failures, many safety codes require certain structural members, such as ladder rails and scaffold planks, to be entirely free of such failures.

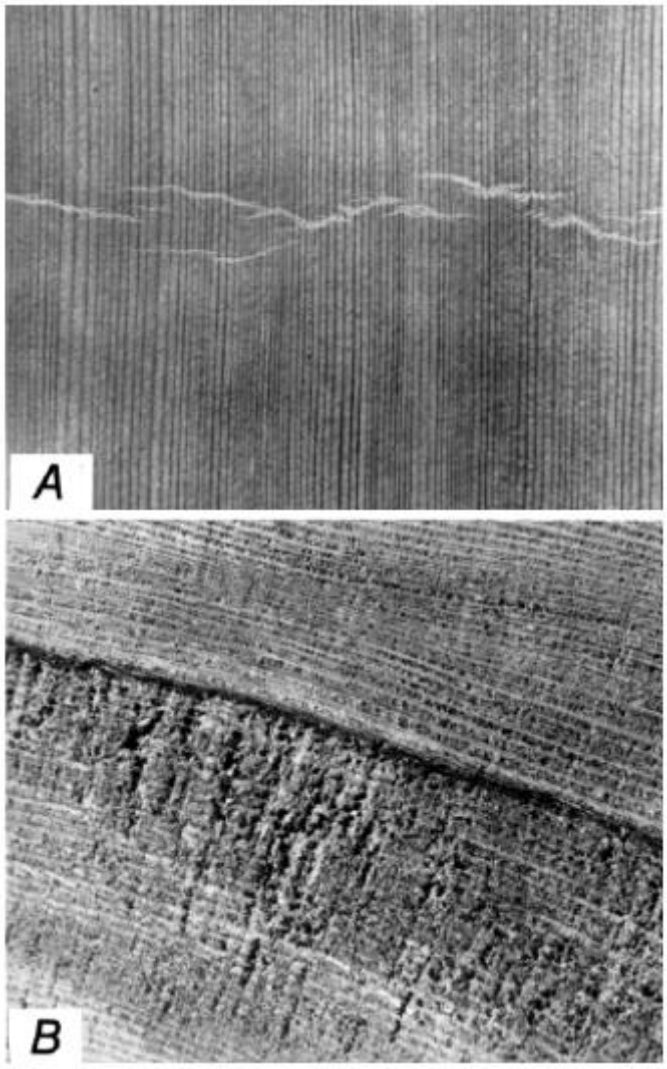


Figure 2.10 – Compression failures. A: compression failure shown by irregular lines across grain; B: fibre breakage in end-grain surfaces of spruce lumber caused by compression failures below dark line [2]

2.5.8. PITCH POCKETS

A pitch pocket is a well-defined opening that contains free resin. The pocket extends parallel to the annual rings; it is almost flat on the pith side and curved on the bark side. Pitch pockets are confined to such species as the pines, spruces, Douglas-fir, tamarack, and western larch. The effect of pitch pockets on strength depends upon their number, size, and location in the piece. A large number of pitch pockets indicates a lack of bond between annual growth layers, and a piece with pitch pockets should be inspected for shake or separation along the grain.

2.5.9. BIRD PECK

Maple, hickory, white ash, and a number of other species are often damaged by small holes made by woodpeckers. These bird pecks often occur in horizontal rows, sometimes encircling the tree, and a brown or black discoloration known as a mineral streak originates from each hole. Holes for tapping maple trees are also a source of mineral streaks. The streaks are caused by oxidation and other chemical changes in the wood. Bird pecks and mineral streaks are not generally important in regard to strength of structural lumber, although they do impair the appearance of the wood.

2.5.10. EXTRACTIVES

Many wood species contain removable extraneous materials or extractives that do not degrade the cellulose–lignin structure of the wood. These extractives are especially abundant in species such as larch, redwood, western red cedar, and black locust.

A small decrease in modulus of rupture and strength in compression parallel to grain has been measured for some species after the extractives have been removed. The extent to which extractives influence strength is apparently a function of the amount of extractives, the moisture content of the piece, and the mechanical property under consideration.

2.5.11. PROPERTIES OF TIMBER FROM DEAD TREES

Timber from trees killed by insects, blight, wind, or fire may be as good for any structural purpose as that from live trees, provided further insect attack, staining, decay, or drying degrade has not occurred. In a living tree, the heartwood is entirely dead and only a comparatively few sapwood cells are alive. Therefore, most wood is dead when cut, regardless of Figure 2.10. Compression failures. A, compression failure shown by irregular lines across grain; B, fibre breakage in end-grain surfaces of spruce lumber caused by compression failures below dark line, whether the tree itself is living or not. However, if a tree stands on the stump too long after its death, the sapwood is likely to decay or to be attacked severely by wood-boring insects, and eventually the heartwood will be similarly affected. Such deterioration also occurs in logs that have been cut from live trees and improperly cared for afterwards. Because of variations in climatic and other factors that affect deterioration, the time that dead timber may stand or lie in the forest without serious deterioration varies.

Tests on wood from trees that had stood as long as 15 years after being killed by fire demonstrated that this wood was as sound and strong as wood from live trees. Also, the heartwood of logs of some more durable species has been found to be thoroughly sound after lying in the forest for many years.

On the other hand, in non-resistant species, decay may cause great loss of strength within a very brief time, both in trees standing dead on the stump and in logs cut from live trees and allowed to lie on the ground. The important consideration is not whether the trees from which wood products are cut are alive or dead, but whether the products themselves are free from decay or other degrading factors that would render them unsuitable for use [2].

2.6. EFFECTS OF MANUFACTURING AND SERVICE ENVIRONMENTS

2.6.1. MOISTURE CONTENT

Many mechanical properties are affected by changes in moisture content below the fibre saturation point. Most properties related to the characteristics mentioned before increase with decrease in moisture content. The relationship that describes these changes in clear wood property at about 21ºC (70ºF) is

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{\left(\frac{12-M}{M_p-12}\right)}$$

(Formula 2.3)

where P is the property at moisture content *M* (%), P12 the same property at 12% *MC*, *Pg* the same property for green wood, and *Mp* moisture content at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of the strength–moisture content relationship for dry wood. This assumed linear relationship results in an *Mp* value that is slightly less than the fibre saturation point. Table 4.9 gives values of *Mp* for a few species; for other species, *Mp* = 25 may be assumed.

Table 2.9 – Intersection moisture content values for selected species[a] [2]

Species	M_p (%)
Ash, white	24
Birch, yellow	27
Chestnut, American	24
Douglas-fir	24
Hemlock, western	28
Larch, western	28
Pine, loblolly	21
Pine, longleaf	21
Pine, red	24
Redwood	21
Spruce, red	27
Spruce, Sitka	27
Tamarack	24

[a]Intersection moisture content is point at which mechanical properties begin to change when wood is dried from the green condition.

Care should be exercised when adjusting properties below 12% moisture. Although most properties will continue to increase while wood is dried to very low moisture content levels, for most species some properties may reach a maximum value and then decrease with further drying (Figure 2.11). For clear Southern Pine, the moisture content at which a maximum property has been observed is given in Table 2.10.

This increase in mechanical properties with drying assumes small, clear specimens in a drying process in which no deterioration of the product (degrade) occurs. For 51-mm- (2-in.-) thick lumber containing knots, the increase in property with decreasing moisture content is dependent upon lumber quality. Clear, straight-grained lumber may show increases in properties with decreasing moisture content that approximate those of small, clear specimens. However, as the frequency and size of knots increase, the reduction in strength resulting from the knots begins to negate the increase in property in the clear wood portion of the lumber. Very low quality lumber, which has many large knots, may be insensitive to changes in moisture content. Figures 4.12 and 4.13 illustrate the effect of moisture content on the properties of lumber as a function of initial lumber strength.

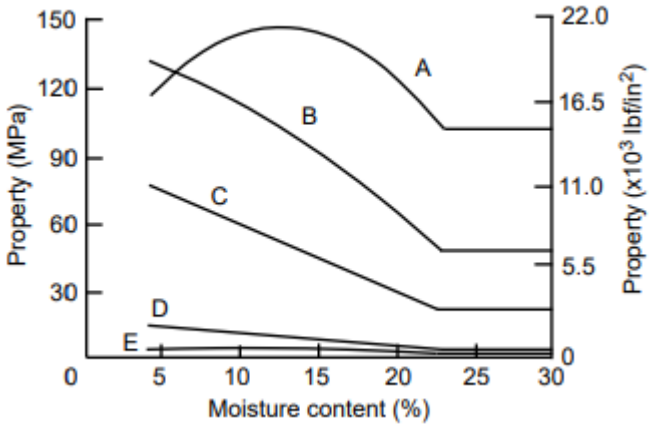


Figure 2.11 – Effect of moisture content on wood strength properties. A: tension parallel to grain; B: bending; C: compression parallel to grain; D: compression perpendicular to grain; E: tension perpendicular to grain [2]

Table 2.10 – Moisture content for maximum property value in drying clear Southern Pine from green to 4% moisture content [2]

Property	Moisture content at which peak property occurs (%)
Ultimate tensile stress parallel to grain	12.6
Ultimate tensile stress perpendicular to grain	10.2
MOE tension perpendicular to grain	4.3
MOE compression parallel to grain	4.3
Modulus of rigidity, G_{RT}	10.0

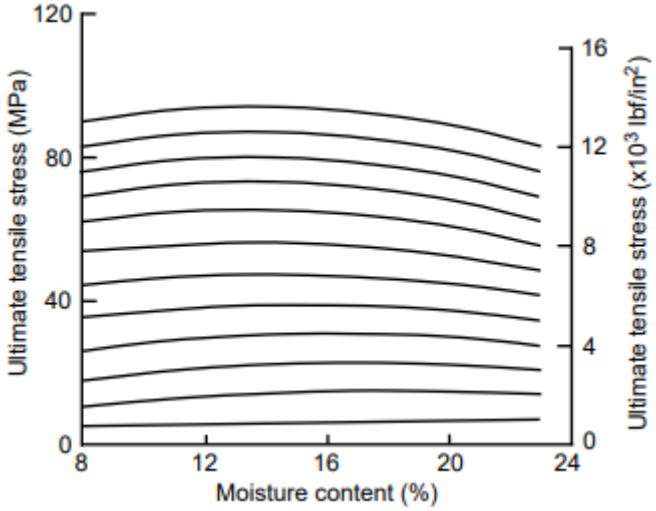


Figure 4.12 – Effect of moisture content on tensile strength of lumber parallel to grain [2]

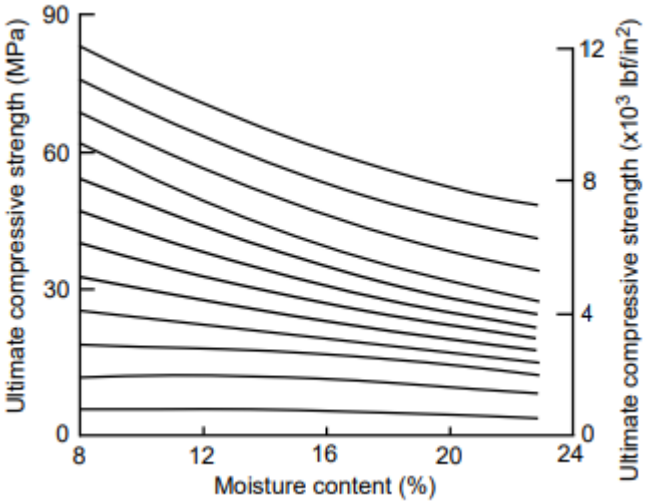


Figure 4.13 – Effect of moisture on compressive strength of lumber parallel to grain [2]

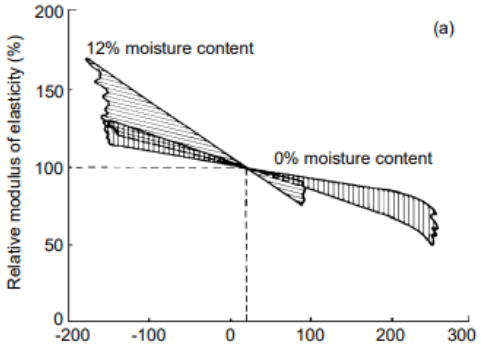
2.6.2. TEMPERATURE – REVERSIBLE EFFECTS

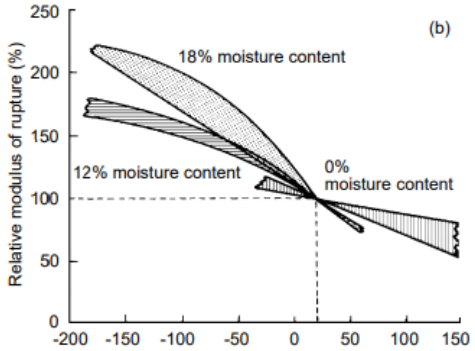
In general, the mechanical properties of wood decrease when heated and increase when cooled. At a constant moisture content and below approximately 150ºC (302ºF), mechanical properties are approximately linearly related to temperature. The change in properties that occurs when wood is quickly heated or cooled and then tested at that condition is termed an immediate effect. At temperatures below 100ºC (212ºF), the immediate effect is essentially reversible; that is, the property will return to the value at the original temperature if the temperature change is rapid.

Figure 2.14 illustrates the immediate effect of temperature on modulus of elasticity parallel to grain, modulus of rupture, and compression parallel to grain, 20ºC (68ºF), based on a composite of results for clear, defect-free wood. This figure represents an interpretation of data from several investigators.

The width of the bands illustrates variability between and within reported trends. Table 2.11 lists changes in clear wood properties at −50ºC (−58ºF) and 50ºC (122ºF) relative to those at 20ºC (68ºF) for a number of moisture conditions. The large changes at −50ºC (−58ºF) for green wood (at fibre saturation point or wetter) reflect the presence of ice in the wood cell cavities.

The strength of dry lumber, at about 12% moisture content, may change little as temperature increases from −29ºC (−20ºF) to 38ºC (100ºF). For green lumber, strength generally decreases with increasing temperature. However, for temperatures between about 7ºC (45ºF) and 38ºC (100ºF), the changes may not differ significantly from those at room temperature. Table 2.12 provides equations that have been used to adjust some lumber properties for the reversible effects of temperature.





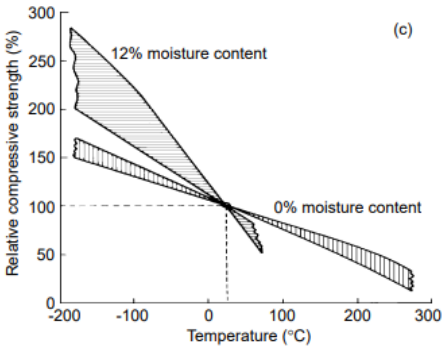


Figure 2.14 – Immediate effect of temperature at two moisture content levels relative to value at 20ºC (68ºF) for clear, defect-free wood: (a) modulus of elasticity parallel to grain, (b) modulus of rupture in bending, (c) compressive strength parallel to grain. The plot is a composite of results from several studies. Variability in reported trends is illustrated by with of bands [2]

2.6.3. TEMPERATURE – IRREVERSIBLE EFFECTS

In addition to the reversible effect of temperature on wood, there is an irreversible effect at elevated temperature. This permanent effect is one of degradation of wood substance, which results in loss of weight and strength. The loss depends on factors that include moisture content, heating medium, temperature, exposure period, and to some extent, species and size of piece involved.

The permanent decrease of modulus of rupture caused by heating in steam and water is shown as a function of temperature and heating time in Figure 2.15, based on tests of clear pieces of Douglas-fir and Sitka spruce. In the same studies, heating in water affected work to maximum load more than modulus of rupture (Figure 2.16). The effect of heating dry wood (0% moisture content) on modulus of rupture and modulus of elasticity is shown in Figures 2.17 and 2.18, respectively, as derived from tests on four softwoods and two hardwoods.

Figure 4.19 illustrates the permanent loss in bending strength of Spruce–Pine–Fir standard 38- by 89-mm (nominal 2- by 4-in.) lumber heated at 66o C (150o F) and about 12% moisture content. During this same period, modulus of elasticity barely changed. Most in-service exposures at 66°C (150°F) would be expected to result in much lower moisture content levels. Additional results for other lumber products and exposure conditions will be reported as Forest Products Laboratory studies progress.

The permanent property losses discussed here are based on tests conducted after the specimens were cooled to room temperature and conditioned to a range of 7% to 12% moisture content. If specimens are tested hot, the percentage of strength reduction resulting from permanent effects is based on values already reduced by the immediate effects. Repeated exposure to elevated temperature has a cumulative effect on wood properties. For example, at a given temperature the property loss will be about the same after six 1-month exposure as it would be after a single 6-month exposure.

The shape and size of wood pieces are important in analysing the influence of temperature. If exposure is for only a short time, so that the inner parts of a large piece do not reach the temperature of the surrounding medium, the immediate effect on strength of the inner parts will be less than that for the outer parts. However, the type of loading must be considered. If the member is to be stressed in bending, the outer fibres of a piece will be subjected to the greatest stress and will ordinarily govern the ultimate strength of the piece; hence, under this loading condition, the fact that the inner part is at a lower temperature may be of little significance.

Table 2.11 – Approximate middle-trend effects of temperature on mechanical properties of clear wood and various moisture conditions [2]

Property	Moisture condition[a] (%)	Relative change in mechanical property from 20°C (68°F) at –50°C (–58°F) (%)	Relative change in mechanical property from 20°C (68°F) at +50°C (+122°F) (%)
MOE parallel to grain	0	+11	–6
	12	+17	–7
	>FSP	+50	—
MOE perpendicular to grain	6	—	–20
	12	—	–35
	≥20	—	–38
Shear modulus	>FSP	—	–25
Bending strength	≤4	+18	–10
	11–15	+35	–20
	18–20	+60	–25
	>FSP	+110	–25
Tensile strength parallel to grain	0–12	—	–4
Compressive strength parallel to grain	0	+20	–10
	12–45	+50	–25
Shear strength parallel to grain	>FSP	—	–25
Tensile strength perpendicular to grain	4–6	—	–10
	11–16	—	–20
	≥18	—	–30
Compressive strength perpendicular to grain at proportional limit	0–6	—	–20
	≥10	—	–35

[a]FSP indicates moisture content greater than fiber saturation point.

For extended noncyclic exposures, it can be assumed that the entire piece reaches the temperature of the heating medium and will therefore be subject to permanent strength losses throughout the volume of the piece, regardless of size and mode of stress application. However, in ordinary construction wood often will not reach the daily temperature extremes of the air around it; thus, long-term effects should be based on the accumulated temperature experience of critical structural parts.

Table 2.12 – Percentage change in bending properties of lumber with change in temperature[a] [2]

Property	Lumber grade[b]	Moisture content	$((P–P_{70}) / P_{70})100 = A + BT + CT^2$ A	B	C	Temperature range T_{min}	T_{max}
MOE	All	Green	22.0350	–0.4578	0	0	32
		Green	13.1215	–0.1793	0	32	150
		12%	7.8553	–0.1108	0	–15	150
MOR	SS	Green	34.13	–0.937	0.0043	–20	46
		Green	0	0	0	46	100
		12%	0	0	0	–20	100
	No. 2 or less	Green	56.89	–1.562	0.0072	–20	46
		Green	0	0	0	46	100
		Dry	0	0	0	–20	100

[a]For equation, P is property at temperature T in °F; P_{70}, property at 21°C (70°F).
[b]SS is Select Structural.

2.6.4. Time under Load – Rate of Loading

Mechanical property values are usually referred to as static strength values. Static strength tests are typically conducted at a rate of loading or rate of deformation to attain maximum load in about 5 min. Higher values of strength are obtained for wood loaded at a more rapid rate and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in 1 s is approximately 10% higher than that obtained in a standard static strength test. Over several orders of magnitude of rate of loading, strength is approximately an exponential function of rate. See Chapter 6 for application to treated woods.

Figure 2.20 illustrates how strength decreases with time to maximum load. The variability in the trend shown is based on results from several studies pertaining to bending, compression, and shear.

2.6.5. Creep and Relaxation

When initially loaded, a wood member deforms elastically. If the load is maintained, additional time-dependent deformation occurs. This is called creep. Creep occurs at even very low stresses, and it will continue over a period of years. For sufficiently high stresses, failure eventually occurs. This failure phenomenon, called duration of load (or creep rupture), is discussed in the next section.

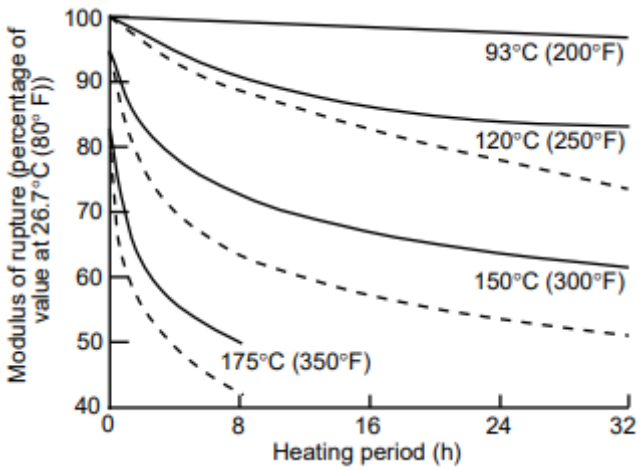


Figure 2.15 – Permanent effect of heating in water (solid line) and steam (dashed line) on modulus of rupture of clear, defect-free wood. All data based on tests of Douglas-fir and Sitka spruce at room temperature [2]

At typical design levels and use environments, after several years the additional deformation caused by creep may approximately equal the initial, instantaneous elastic deformation. For illustration, a creep curve based on creep as a function of initial deflection (relative creep) at several stress levels is shown in Figure 2.21; creep is greater under higher stresses than under lower ones.

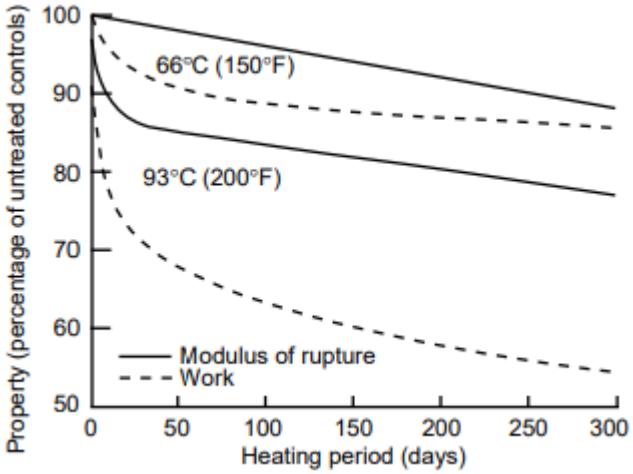


Figure 2.16 – Permanent effect of water on work to maximum load and modulus of rupture of clear, defect-free wood. All data based on tests of Douglas-fir and Sitka spruce at room temperature [2]

Ordinary climatic variations in temperature and humidity will cause creep to increase. An increase of about 28ºC (50ºF) in temperature can cause a two- to threefold increase in creep. Green wood may creep four to six times the initial deformation as it dries under load.

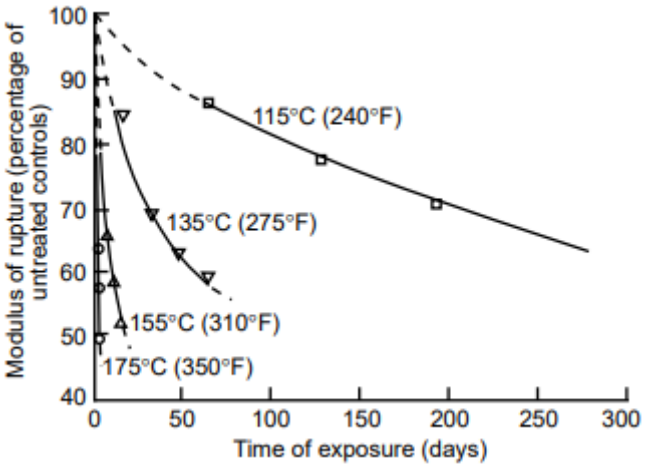


Figure 2.17 – Permanent effect of oven heating at four temperatures on modulus of rupture, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature [2]

Unloading a member results in immediate and complete recovery of the original elastic deformation and after time, a recovery of approximately one-half the creep at deformation as well. Fluctuations in temperature and humidity increase the magnitude of the recovered deformation.

Relative creep at low stress levels is similar in bending, tension, or compression parallel to grain, although it may be somewhat less in tension than in bending or compression under varying moisture conditions. Relative creep across the grain is qualitatively similar to, but likely to be greater than, creep parallel to the grain. The creep behavior of all species studied is approximately the same.

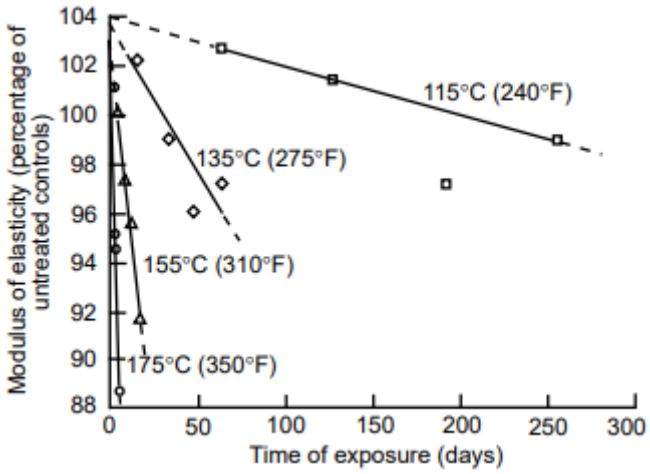


Figure 2.18 – Permanent effect of oven heating at four temperatures on modulus of elasticity, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature.

If instead of controlling load or stress, a constant deformation is imposed and maintained on a wood member, the initial stress relaxes at a decreasing rate to about 60% to 70% of its original value within a few months. This reduction of stress with time is commonly called relaxation [2].

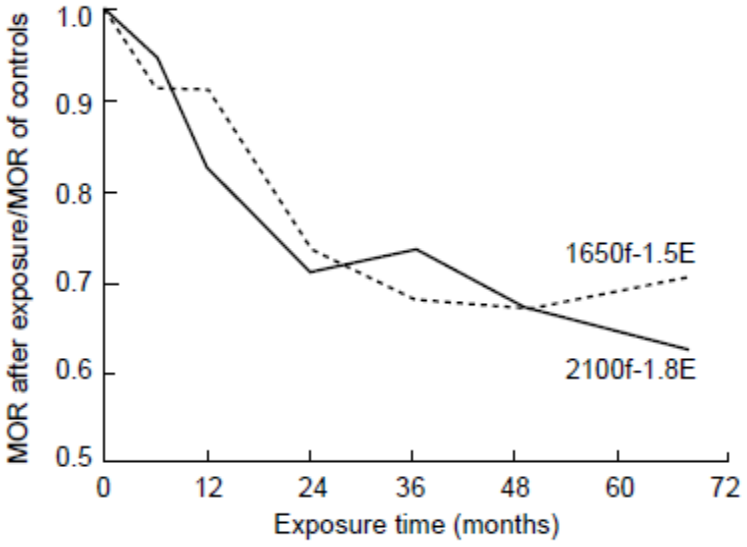


Figure 2.19 – Permanent effect of heating at 66º C (150º F) on modulus of rupture for two grades of machine-stress rated Spruce-Pine-Fir lumber at 12% moisture content. All tests conducted at room temperature [2]

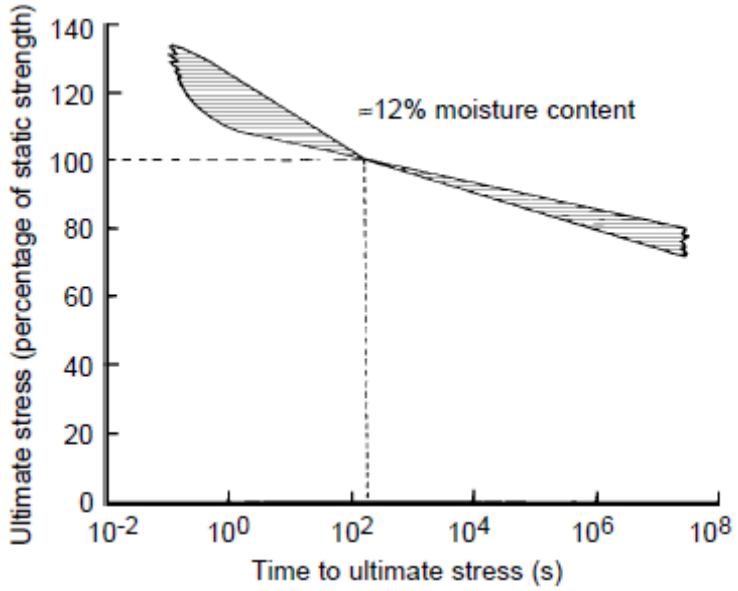


Figure 2.20 – Relationship of ultimate stress at short-time loading to that at 5-min loading, based on composite of results from rate-of-load studies on bending, compression, and shear parallel to grain. Variability in reported trends is indicated by width of band [2]

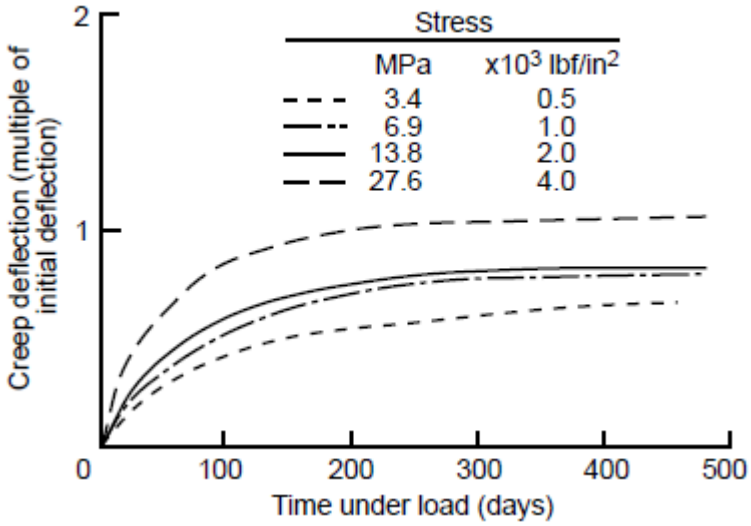


Figure 2.21 – Influence of four levels of stress on creep [2]

3

WOOD DETERIORATION AND PRESERVATION – ABIOTIC AGENTS

First of all, it is important to mention the importance of referring moisture and not humidity, although these two concepts have similar meanings, and are usually used as synonyms.
Humidity refers to the amount of water content (concentration in specific) that is present in the air or the amount of water vapour that is present in the atmosphere.
Moisture refers to the presence of liquid (water content), usually water in any object or material.
In order to better understand the relation of wood with moisture, it is important to study the causes of deterioration and how maintenance should be done to preserve wood materials.

3.1. CAUSES OF DETERIORATION

When referring to the Causes of Deterioration of wood, it is possible to find biotic and abiotic agents.

In the biotic group, it is possible to include fungi, insects, other xylophages and marine xylophages. The abiotic group is composed by sun, rain and wind. Some other agents like fire and other chemical compounds have to be considered.

In this dissertation, and as the main subject is related to the relation of moisture and wood, it is important to focus on the abiotic group, which is the group where it is possible to find the atmospheric agents.

3.1.1. ABIOTIC AGENTS

Pathologies with abiotic characteristics are the main agents of deterioration of wood. From the atmospheric agents that cause deterioration on wood stand out solar radiation, rain and interchange of cycles of drying and wetting.

When exposed to rain water, the process of deterioration can be faster, since the running of water particles cleans the wood surface, originating a clean wood surface exposed to several adverse conditions.

Moisture content is not by itself, a deterioration cause, since it is possible to verify that the higher its value, the lower will be the wood´s mechanical resistance, the higher its volumetric expansion and the higher its susceptibility to being submitted to biological agents.

What really originates the deterioration of wood, by rain water action, solar radiation and temperature, is the interchange of cycles of drying and wetting, resulting on the consequent volumetric variation of the material. This variation causes internal stresses in the piece of wood, resulting in the appearance of slits (usually longitudinal), curvatures and warping.

It is important to mention that this pathology, beyond resulting in the aging of the cellular structure and the decrease of material resistance, reinforces the attack of biological agents, since the opening of slits originate new ways to attack and allows a higher retention of humidity on the wood elements [3].

From the Abiotic group of agents, it is important to mention the ones that have more influence when the deterioration is related with moisture.

3.1.1.1. Rain

The action of rain originates the increase of the water content in the wood surface, leading to the formation of slits and cracks. The rain water is the cause that makes wood components to dilute causing superficial deterioration, colour alteration, decrease of mechanical resistance and increase of superficial absorption capacity. The humidity is normally a reversible phenomenon, as the resistance is restored after drying.

Figure 3.1 – Rain water effect on wood [4]

When there is protection on the wood surface, wood is not affected by the action of rain until this protection disappears. The existence of cracks on ink film or varnish, dramatically reduces the protecting effect related with this action [5].

3.1.1.2. Moisture on Wood

The main physical property of wood, when relating its durability to the action of deteriorating agents, is its hygroscopicity. It affects its water content and eventually originates volume variations, and therefore originates the stretching and swelling of the wooden pieces.

It is very important to understand the hygroscopicity of the material for a correct use. It also has a high influence on the protection and durability of the wood [5].

3.2. RISK CLASSES

The Risk Classes are a concept defined by the European standard EN 335:2013 with the purpose of evaluating the risk of deterioration in function of the place where the wood material is going to be placed [6].

The main factor which influences the Risk Classes is humidity. However, there are other factors that are considered such as exposure to the environmental elements, contact with the soil, fresh water or salty water.

It is possible to divide the circumstances of risk in 5 Classes:

- Class 1 – Elements protected from environmental elements, not exposed to humidity (H≤20%);

  In this environment the water content is very low, so the attacks from superficial mould fungi, bluish or ligneous fungi is insignificant. However, the attack is possible from xylophage insects, including termites, but the frequency and importance of this risk depends on the geographical region. In this class, the most worrisome xylophagous are the dry wood weevils (insects).

- Class 2 – Elements under roofs, protected from environmental elements, with high humidity ambient (H>20%);

  In this case the water content of wood (H), occasionally exceeds 20%, that allows attacks from ligneous fungi. Wood that is used with decorative purpose, can be affected by the chromatic variation that results from the development of superficial moulds and from blue fungi. The risk of attack from insects is the same of Class 1.
- Class 3 – Uncovered and non-grounded elements, with frequent moisture (H>20%);

  The risks associated with Class 3 are the same mentioned in Class 2, with the provision that, water contents higher than 20% are reached more often than in class 2.

- Class 4 – Elements in contact with soil or fresh water;

  In this environment the water content permanently exceeds the 20% value. This allows the attack from ligneous fungi, being the termites an additional and very important risk in certain regions. Certain elements placed out of contact with the soil (or water), can be attacked by weevils;

- Class 5 – Elements in permanent contact with salty water.

  This Risk Class is very similar to Risk Class 4. However, the attack from invertebrate marine organisms, is the main problem. In salty water, particularly in hot waters, organisms like Limnoria spp. and Teredo spp., see figure 3.2, can be the cause of important destructions. Areas out of water contact, for example in port structures´ pillars, are exposed to attacks by xylophagous insects, including termites [7].

Figure 3.2 – Limnoria spp. and Teredo spp. [8] [9]

3.3. WOOD PRESERVATION

In order to preserve the wood material, it is important to apply a coating that in contact with the surface will increase its durability and protect the timber elements from other harmful agents.

Painting is a very common procedure and it brings a lot of other properties to the material.

3.3.1. COATING BY PAINTING

The application of a coating on the wood material by painting on any surface is made with the purpose of decoration or to preserve the material, or even by other possible reason. Generally, it is pretended that coating is multifunctional, for example, it is pretended to preserve the material and to improve the visual aspect. It can also be used to improve the conditions of indoor lighting and at the same time promoting the sanitary conditions of the architectural spaces.

Therefore, in the various functional aspects, a coating by painting is used for:

- Decoration – One of the most important aspects, changing the visual aspect of any surface or structure;

- Protection – The application of a coating by painting on a surface can increase its durability and contribute to a reduction of reparation and maintenance costs;

- Cleaning and Sanitary – Generally the painted surfaces are silky and have less porousity, so that makes is easier to clean and keep them clean;

- Lighting and Efficiency – It results from the application to light colours that allows the lighting of enclosed spaces or to decrease the tiring effect of intense light;

- Special Functions – Functions associated to special characteristics of mechanical or chemical resistance, provided by painting that prevent the development of micro-organisms or other degradation agents.

The wooden elements need adequate treatment and finishing.

It is also important to be aware that the preservation and the prevention are actions as important as the ones mentioned before. The next procedures are extremely important to consider:

- Eventual Preservation treatment;

- Eventual Fireproof treatment;

- Use always Protection and Finishing treatment.

The natural durability of wood and its Risk Classes, are related with the eventual necessity of application of an appropriate preservation and preventive treatment [5].

3.3.2. PRESERVATION PRODUCTS

Preservation products are chemical substances with the purpose to secure a higher resistance to deterioration to wood originated by living organisms. These products are applied on wood to avoid biological attacks from xylophages fungi, lenhivorous insects or by marine xylophages.

The existence of multiple wood species submitted to biological agents' attacks makes it extremely necessary to perform preservative and/or curative treatments.

There is also a big number of preservative products on the market to apply on wood. This enhances the difficulties to make a complete description about their composition. Therefore, it is presented in the following paragraphs a short description of its composition.

These products are composed by active materials, fastening products and solvents. The active materials with insecticides or fungicides properties fix themselves on the wood by fastening products, and both penetrate on wood through the solvent.

The preservative wood products distinguish themselves by their chemical nature, physical properties and toxicity level related to xylophagous agents. In general, the preservative product must obey to a certain number of fundamental conditions:

- Perform a toxic, inhibitory or repulsive action against the biological agents that destroy wood;
- Have a good long-term efficiency in what concerns to protecting wood, according to the exposure conditions of the treated wood;
- Have an easy impregnation on wood, using an adequate procedure;
- Do not change wood properties, according to the future purpose of it.

More than this properties, it is also important to have in mind that other important properties according to the purpose of wood´s use, have to be considered:

- Odour and residual colour of the treated wood;
- Corrosive action for metals;
- Eventual degradation of plastics;
- Compatibility with adhesives and finishing products;
- Toxicity to man, animal or plant;
- Do not increase the flammability of the wood.

Due to the high number of preservative products of wood in the market, all the products must have their adequate technical and safety data sheet, where it is specified the composition of the product, application doses, security measures to have in mind, eventual protection systems, first aids against possible intoxications, etc.

After selecting the type of wood to use in the construction, it is necessary to know the two more important properties related to its preservation effects – natural durability and impregnability. The preventive protection of wood elements goes through chemical treatments or to the selection of better constructive dispositions, when related to wood elements´ durability. Some wood species with very high natural durability, often dispense any preventive treatment.

The chemical protection determines the quantity of product necessary to apply related to attacks that can happen. This is normally associated with Risk Classes (section 3.2). The constructive actions pretend to decrease the possible attack from multiple pathological agents, protecting the wood, maintaining it dry and ventilated.

Summing up, there are multiple aspects that can preventively influence the protection on wood, such as:

- Risk Classes (section 3.2);

- Type of Treatment;
- Selection of the Treatment´s Method;
- Quality Control of the Protective Treatment;
- Constructive Measures [5].

3.3.2.1 Type of Treatment

The elimination systems of xylophagous agents can have a treatment function or also a preventive function, avoiding possible future attacks. The preventive function is the most appropriate.

There are multiple elimination methods that can be divided into two big groups, according to the systems applied:

- Physical Methods – Consist in modifying the bugs´ environmental conditions with the purpose to cause their death, and perform only a treatment action. Some of the existing methods, are the freezing, gamma and alteration of the environment where they live (Thermo Lignum process). These methods require very specific technics and can only be performed in laboratories or by specialized companies.

- Chemical Methods – These methods consist on the application of toxic substances with the purpose to eliminate the xylophagous agents. It can be applied in gas or in liquid state. The gas products only have a preventive action, since its efficiency ends when their application is over. On the other hand, the liquid insecticides, once diluted with the solvent, have a better penetration on wood. The success of this application, depends on the capacity of reaching every area of the wood species that has suffered the attack, the type of wood (impregnability), the quantity of the product applied and the treatment method applied.

Almost all protectors are not efficient if the practitioner does not select the most appropriate product or method related to the concerned biological agent and if the product is not applied using the correct method [5].

3.3.2.2. Selection of Treatment

After defining the more important conditions related to the use of the wooden elements on construction, and knowing the different methods of application of preservative wood products on wood, it is possible to select the most appropriate product to pretended treatment.

When selecting the treatment´s method and the preservative product, it is important to have an experienced opinion of a professional with high knowledge on this subject and about the treatment´s characteristics and preservative products. Other specifications and rules can be found in regulations.

Two types of procedures of treatment of wood can be distinguished:

- Passive Treatment – It is based on the capacity of wood in absorbing the preservative, being this capacity irregular and not controllable. In this first procedure are included treatments like brushing, spraying and soaking;

- Active Treatment – It is based on artificial methods (mainly vacuum-pressure techniques), allowing a higher control on the quantity of product absorbed by wood. This type of system includes all methods that use autoclave.

Other authors, with less expression, divide the treatment´s systems in procedures without precision and procedures with precision, that would correspond to the above mentioned passive and active treatments

respectively. Specific cases and with short industrial application, are for instance the method of replacement of the sapwood and the diffusion method.

In some woods not so impregnable, it is recommended to apply incisions in the wood material, making it go through rollers, facilitating the introduction of the protector [5].

Some examples of treatments are:

- Brushing;
- Spraying;
- Injection;
- Rapid or Prolonged Immersion and Localized Immersion;
- Hot-Cold Immersion in Open Tank;
- Pressure Impregnation;
- Vacuum Impregnation;
- Diffusion.

Table 3.1 – Treatment method according to type of protection

Risk Class	Type of Protection (penetration)	Treatment Method
1	Superficial (average of 3 mm and minimum of 1 mm)	Brushing Spraying Short Immersion (> 3 m)
2	Superficial (average of 3 mm and minimum of 1 mm)/Medium (average over 3 mm)	Brushing Spraying Short Immersion (> 3 m) Prolonged Immersion Autoclave (double vacuum)
3	Medium (average over 3 mm)/Deep (average highly over 75% of the impregantion volume)	Prolonged Immersion Autoclave (double vacuum) Autoclave (pressure-vacuum)
4	Deep (average highly over 75%	Autoclave (pressure-vacuum)
5	Deep (average highly over 75%	Autoclave (pressure-vacuum)

Table 3.1 shows the advised treatment to apply according to the type of protection.

Table 3.2 – Treatment method according to the nature of protection product

Treatment Method	Type of Protection
Brushing	Organic Solvent Hydrodispersible Mixed Products
Spraying	Organic Solvent Hydrodispersible Mixed Products
Rapid Immersion	Organic Solvent Hydrodispersible Mixed Products
Prolonged Immersion	Hydrodispersible Mixed Products Organic Solvent Water-soluble salts
Diffusion	Water-soluble salts
Autoclave (pressure-vacuum)	Water-soluble salts Organic Solvent Mixed Products
Autoclave (vacuum-vacuum)	Organic Solvent

In Table 3.2, it is possible to get information about the advised treatment according to the type of protection, superficial, medium or deep.

3.3.2.3. Properties that Influence the Application of the Products

The wood elements need a good and effective treatment in order to be protected against environmental conditions and use. Through an effective finishing, durability and aesthetics are guaranteed in a long term period.

It is important to understand what are the properties of wood that have the bigger influence, when selecting the product to apply:

- Aspect – The natural colour of wood can be a characteristic pretended to maintain, or in other hand that is pretended to be modified. This will interferes when selecting the product. In the market, there are different products capable of preserving or changing the natural colour of wood. Velatures are great products that can be used to preserve the natural aspect of wood and to enhance its veins;

- Moisture Content – When using wood in outdoor conditions, the water content of the timber elements at the painting moment must be between 15% and 20%. If this value is higher, there would be finishing problems, since the moment of painting because later, when expelling the water, the water or vapour will accumulate underneath the coating film (waterproof), producing a lack of adherence of this and its consequent prominence;

- Coefficient of Contraction – Wood is a material subjected to water content variations, always adapting to the environmental conditions where is placed. These variations often cause high stresses which cause the break of the skin of the element. To minimize this problem, it is recommended to use woods with low coefficient of contraction or woods that had been improved by the introduction of resins, and that are painted with coatings with great elasticity, capable of accompanying dimensional variations.

- Porosity – Porosity influences the quantity of product absorbed by wood, by varying the doses, yields and working times of coatings. A very porous wood will need larger amounts of product than a less porous, in order to achieve the same result.

- Contents of Exhausts - Wood exudates and extracts are metabolic complex substances, more or less viscous. Resins, oils, gums, waxes, antioxidants and dyes are some examples. The presence of this substances on the wood´s surface hinders, slows or prevents the polymerization or drying of the coatings. A thorough cleaning helps to prevent the extracts from appearing at the surface [7].

3.3.2.4. Quality Control of Protection Treatment

The efficiency of a product while facing a degrading agent is evidenced by "effectiveness tests". In these tests, it is determined the minimum dose to use so that the product eliminates and prevents the development of the degrading agent. The efficiency of the wood´s protecting products is defined in standard EN 599-1 “Natural durability of wood and wood products, Performance of the wood preservatives determined by biological tests. Part 1: Specifications for the different risk classes” [6]. This test allows obtaining the “reference biological value” which can be defined as the quantity expressed in g/m^2 or kg/m^3, of the preservative product, determined through tests, that assures an effective protection against the concerned biotic organism. This value cannot be used in reality, since it is necessary to have in mind the presence of other agents. Therefore, the regulation fixes the “critical value”, that is the minimum quantity of preservative product necessary to ensure the efficiency according to the Risk Class [5].

3.4. RECOMMENDATIONS

A good principle for the success of a finishing is the understanding of the importance of the activities that precede the application of the finishing paint.

The ideal surface corresponds to a rough surface. However, paints may have better results when applied on slightly polished or slightly sanded surfaces. Before applying the product, we must ensure that the surface of wood is clean, defatted, free of cracks, knots and fungus spots.

The best results in the application of surface products are achieved with new or newly mechanized tools and using dry wood. However, there are jobs that consist on repairing surfaces already painted, so additional care is required. Initially, the condition of the old paint must be analyzed, and the surface must be properly prepared. It is not always necessary to completely eliminate the previous paint. Sometimes, it is enough to perform a simple wash with a solution of detergent and sanding with sandpaper the areas of paint that are properly adhered, to obtain the necessary adhesion for the new coat of paint [7].

4

EXPERIMENTAL RESEARCH COMPRESSION

4.1. INTRODUCTION

In order to understand the physical resistance of oak, compression tests were applied on 6 clean cube samples made of red oak wood, raised in Greece. The loads applied on cubes, were applied in the direction of the fibres of the wood and also to the perpendicular direction of the fibres, in order to understand the difference of strength resistance in this different cases.

The main purpose of this tests was to understand the behaviour of wood specimens when submitted to loads applied on different directions of its fibres, in order to understand the correct position in what concerns the placement of wood materials.

4.2. GENERAL DESCRIPTION OF THE TESTS AND SAMPLES

Dimensions were measured before and after the compression tests.

The room environment where these compression tests were performed, had the same conditions recommended by the European Standard EN408:2010 and that suggests that the laboratory test shall normally be maintained at the standard environment of (20 +/- 2) ªC and (65 +/- 5) %relative humidity, but when other conditions apply, they shall be reported EN408:2010 [10].

Figure 4.1 – Oven used on the heating of samples

Before submitting the cubes to the compression tests, it was decided to adapt the cubes to different environmental conditions. 2 cubes (samples 1 and 2) were placed inside a recipient with water at room environment, around 20ºC, and a relative humidity of around 65% for a period of 24h. The other 4 cubes left (3 to 6), were placed into an oven at 40ºC, for a period of 24h. The Figure 4.1 shows the oven use on the heating of samples.

The normative applied to realize the compression tests, was EN408:2010 [10].

4.3. EQUIPMENT USED ON THE TESTS

The machine used to perform the compression tests was a *Matest, compression testing machine*, with the specifications defined on Table 4.1, see also fig. 4.2.

Table 4.1 - Machine description [11]

COMPRESSION TESTING MACHINES 1300 kN CAPACITY to test cylinders up to dia. 160x320 mm and cubes up to 150 mm side**.** TECHNICAL SPECIFICATIONS: - Max. vertical daylight: 336 mm - Compression platens dia. 216 mm - Gauges dia. 250 mm with specific resistance scales for cubes 150 mm and cylinders dia. 150 - 160 mm - Gauges divisions: 1300 kN div. 4 kN - 600 kN div. 2 kN - Hydraulic device to stop the piston's stroke at its max excursion to avoid pumping the piston out of the cylinder. - Calibration accuracy: Grade 1.0 - Max. ram travel 55 mm approx. - Power supply (motorized models): 230 V 1 ph 50 Hz 750 W - Dimensions: 630x350x1260 mm - Weight: 540÷580 kg

Figure 4.2 - "Matest" compression testing machine

4.4. DETAILED DESCRIPTION OF THE TESTS

4.4.1. PREVIOUS ACTION

Before any change of condition or performance of compression test, the cube dimensions were measured. The measurements were obtained with a KONAN-JAPAN Pro-Cal scale, see Table 4.2 and Figure 4.3.

Table 4.2 – Cubes´ dimensions and Volumes

(mm)	a	b	c	Volume (mm³)
1	54,84	55,60	54,88	167334,83
2	55,82	55,20	54,79	168822,45
3	54,95	54,91	54,87	165559,50
4	54,94	55,10	54,40	164679,35
5	55,49	54,99	54,87	167430,05
6	54,96	55,22	54,82	166372,74

After the 24h mentioned before, the period to the cubes to acquire the pretended conditions, the compression tests were performed on the cubes 1 to 4.

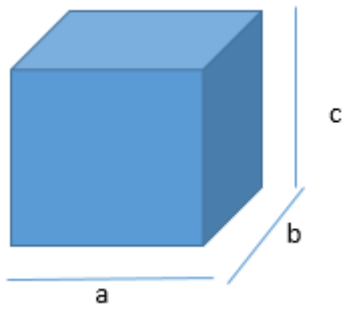


Figure 4.3 - Cube dimensions

In the meanwhile, the cubes 5 and 6 were placed into room environment conditions, as mentioned before in this chapter, to understand the variance of weight aggravated by the change of temperature on the wood surface. After being taken out of the oven, the weight immediately after leaving the oven was respectively 119,54g and 118,84g. A further measurement would be done after 24h.

4.4.2. COMPRESSION TESTS

The compression tests on the samples involved the application of an increasing load at a certain rhythm of growth, until failure.

Each of the samples was submitted to the appliance of an increasing load at a speed of 0,5 MPa/s.

When the load was applied in the perpendicular direction of the fibres, it was stopped when a 10% decreasing of the dimension was observed.

Then, the compression tests continued.

The load applied to the cube number 1 was applied v, and the maximum load value was 113,6 KN.

The next figure shows the deformations on the sample after being submitted to the compression load.

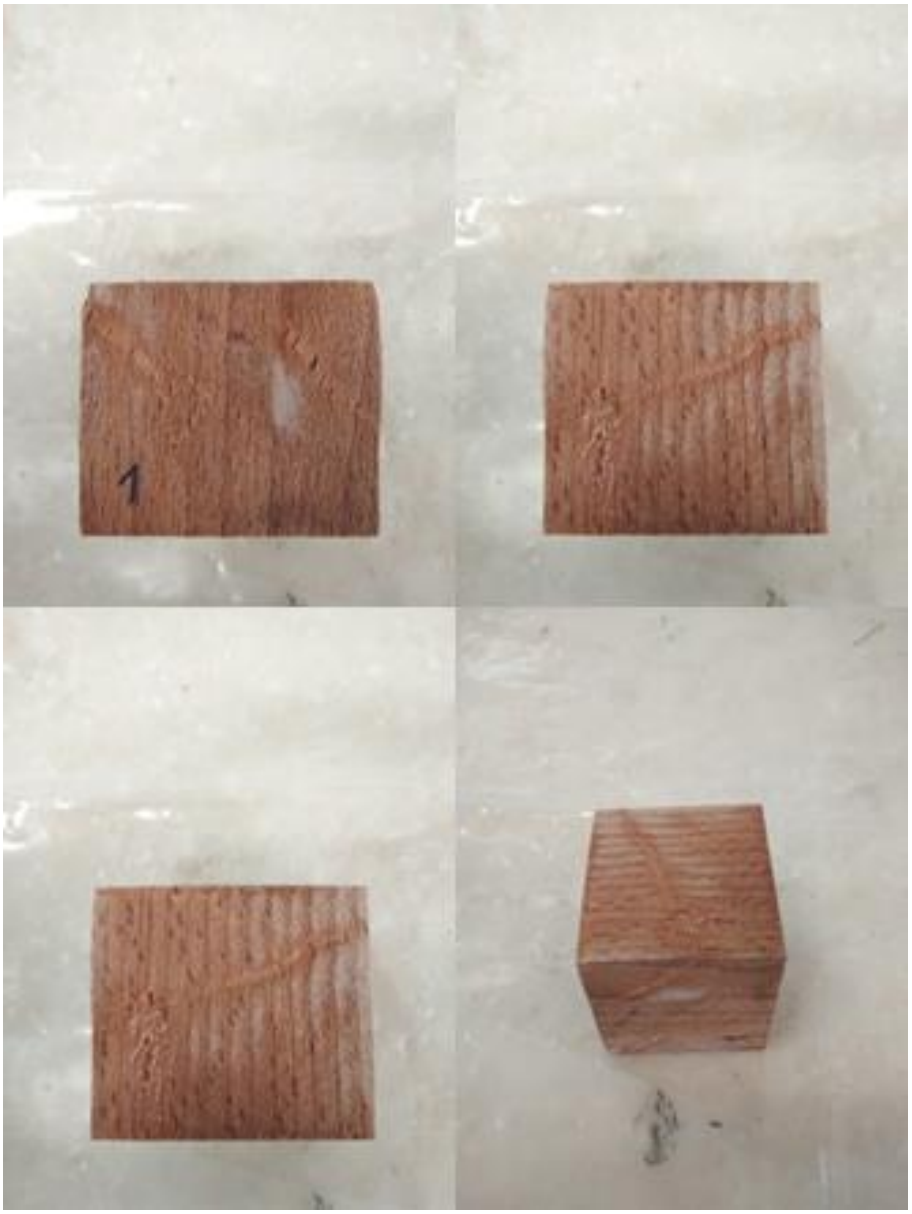


Figure 4.4 - Cube 1 deformation after compression tests when load applied in the direction of the fibres

The load applied to the cube number 2 was applied in the perpendicular direction of the fibres, and the maximum load value was 11,4 KN.

The next figure shows the deformations on the sample after being submitted to the compression load.

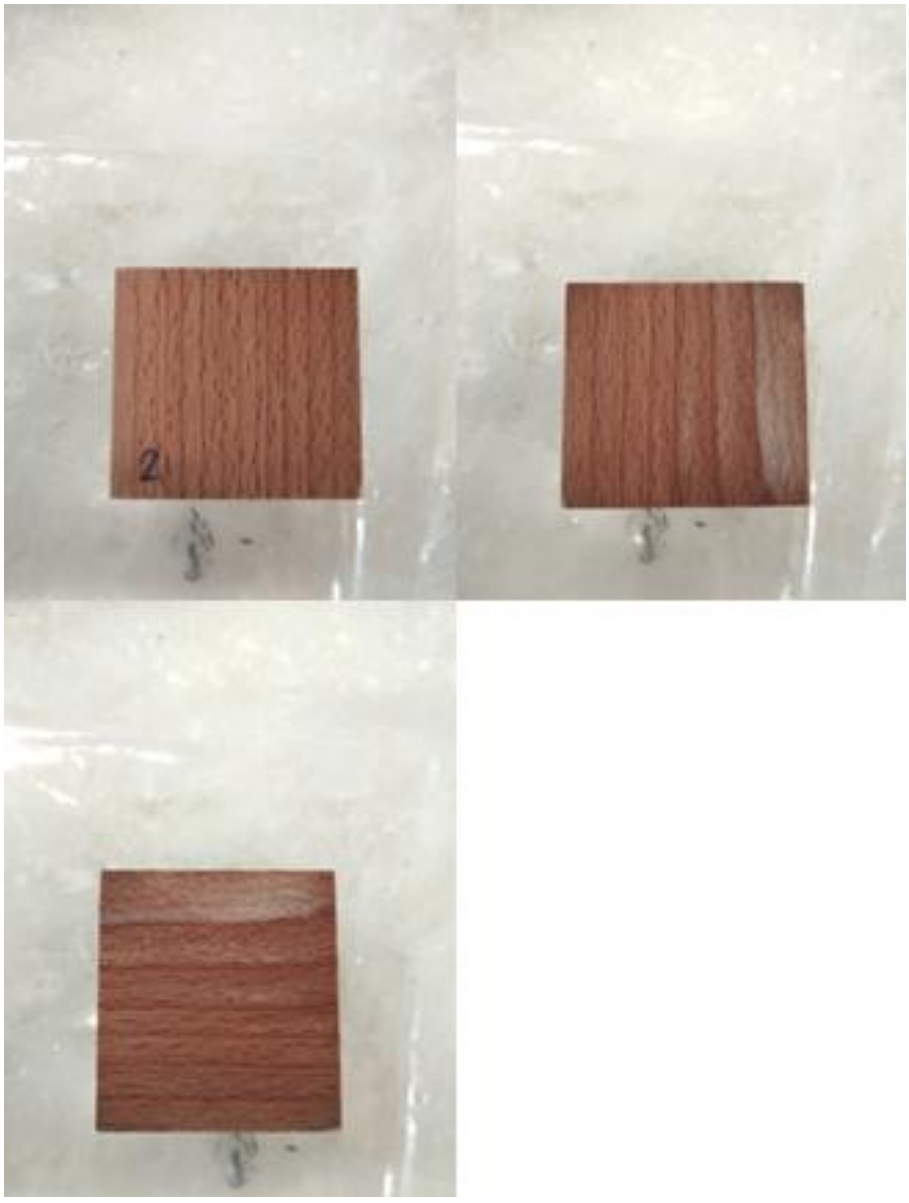


Figure 4.5 - Cube 2 deformation after compression tests when load applied in the perpendicular direction of the fibres

The load applied to the cube number 3 was applied in the direction of the fibres, and the maximum load value was 179,3 KN.

The next figure shows the deformations on the sample after subjected to compression load.

Figure 4.6 - Cube 3 deformation after compression tests when load applied in the direction of the fibres

The load applied to the cube number 4 was applied in the perpendicular direction of the fibres, and the maximum load value was 103,7 KN.

The next figure shows the deformations on the sample after being submitted to the compression loads.

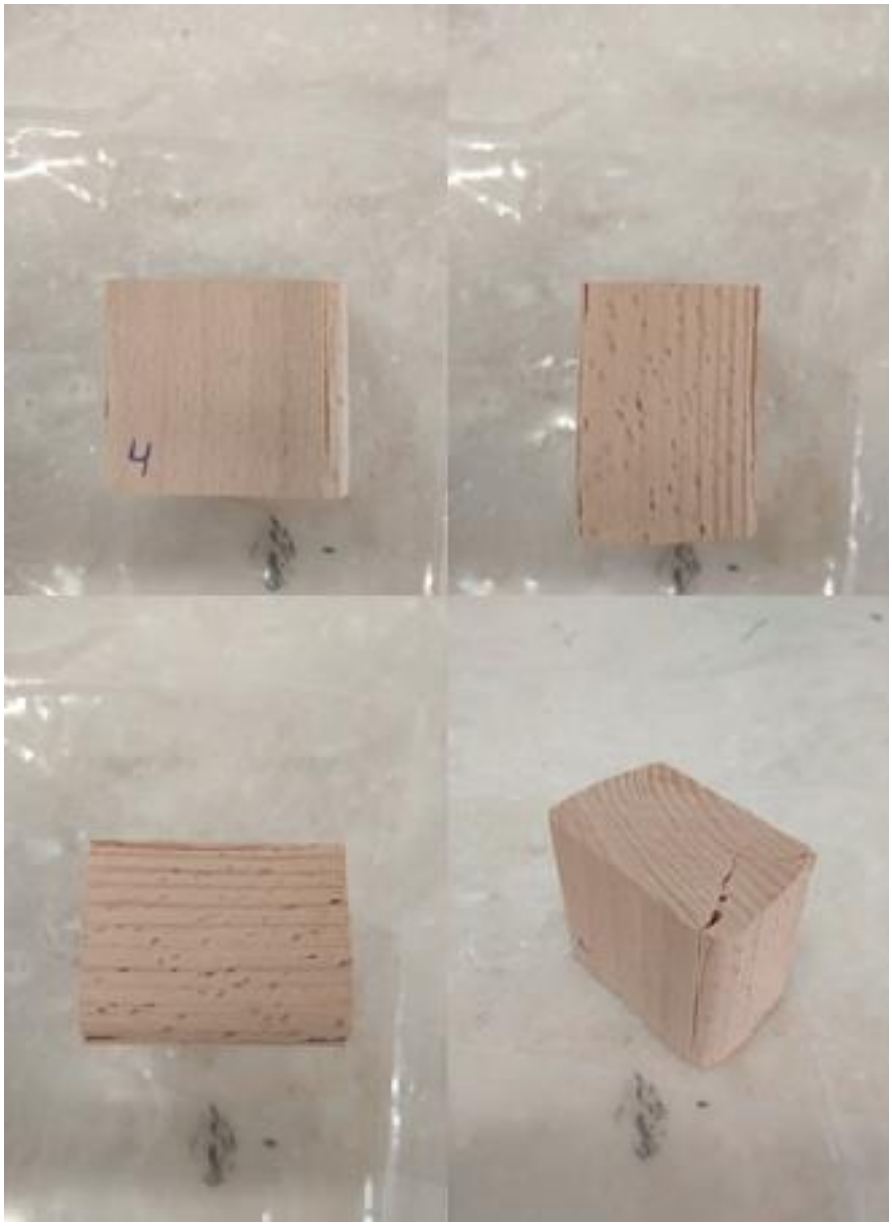


Figure 4.7 - Cube 4 deformation after compression tests when load applied in the perpendicular direction of the fibres

After the tests were performed, the cubes´ dimensions and Volumes were measured again (samples 1 to 4), see Tables 4.3 and Table 4.4.

Table 4.3 – Cubes´ dimensions and Volumes after compression tests

(mm)	a	b	c	Volume (mm³)
1	62,50	58,30	52,00	189475,00
2	59,02	59,80	54,87	193657,96
3	54,50	54,34	54,01	159952,24
4	64,65	41,51	55,10	147867,54

Twenty four hours after being in room environment conditions, the samples 5 and 6 were measured. 120,99g and 120,27g was the respective weight, after the period mentioned before.

Table 4.4 – Cubes´ dimensions and Volumes after 24h in room environment

(mm)	a	b	c	Volume (mm³)
5	55,27	54,57	54,87	165492,52
6	54,71	54,81	54,82	164386,27

This is the result of the process of assessing the properties in room environment conditions. It is also possible to conclude with certainty that heating the samples to a temperature of 40ºC led to a significant decrease on the weight of the samples.

Table 4.4 shows the new dimensions of the cubes after the period mentioned before.

Then the compression tests continued.

The load applied to the cube number 5 was applied in the perpendicular direction of the fibres, and the maximum load value was 56,8 KN.

The next figure shows the deformations on the sample after being submitted to the compression loads.

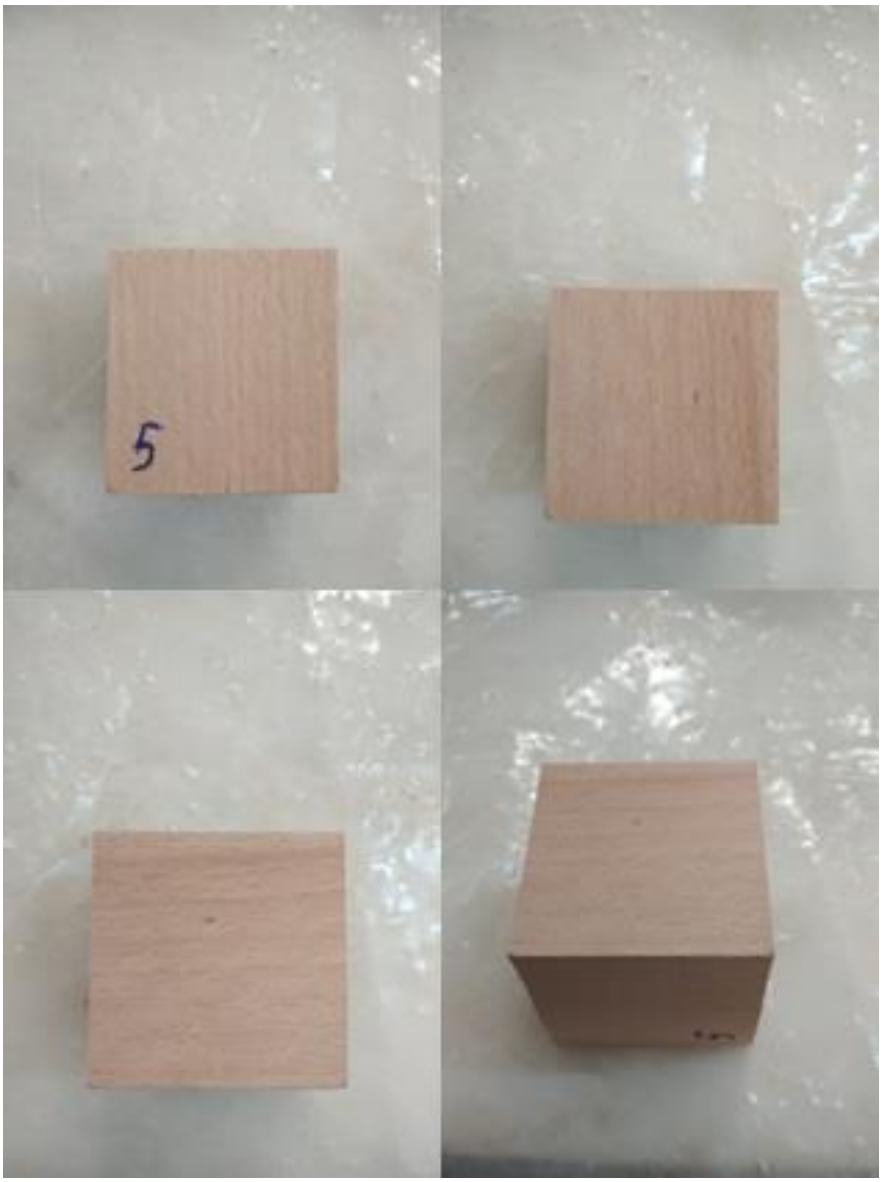


Figure 4.8 - Cube 5 deformation after compression tests when load applied in the perpendicular direction of the fibres

The load applied to the cube number 6 was applied in the direction of the fibres, and the maximum load value was 198,6 KN.

The next figure shows the deformations on the sample after being submitted to the compression loads.

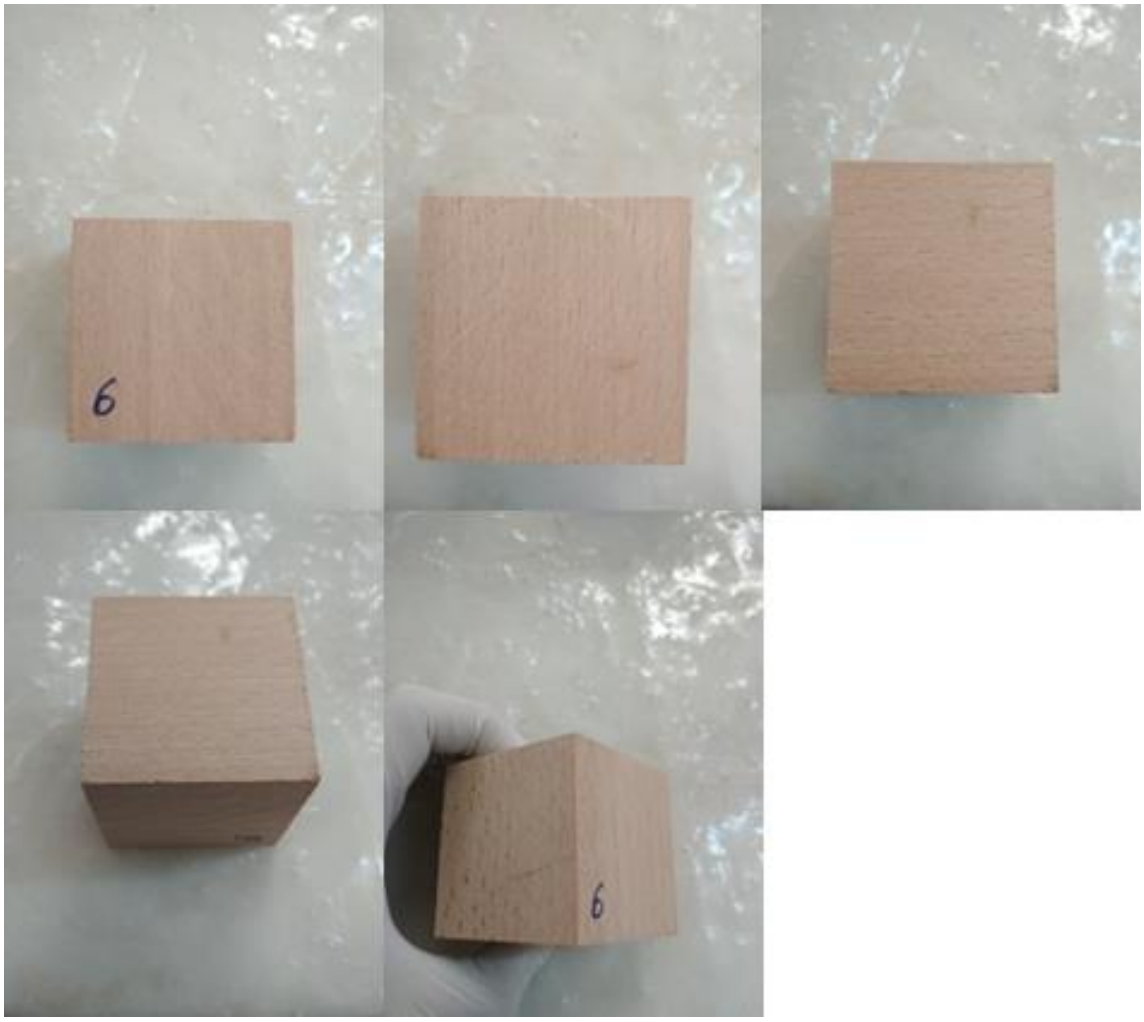


Figure 4.9 - Cube 6 deformation after compression tests when load applied in the direction of the fibres

After the tests were performed, the cubes´ dimensions and Volumes were measured again.

Table 4.5 – Cubes' dimensions and Volumes after compression tests

(mm)	a	b	c	Volume (mm^3)
5	51,80	55,11	54,92	156780,01
6	54,87	54,94	54,19	163358,89

4.5. ANALYSIS OF RESULTS

Analysing the variation on the dimensions, it is possible to understand how the wood reacted to the compression loads, depending on the different environmental conditions the samples were submitted to and also on the direction in relation to the fibres.

The Table 4.6 shows the change of volume in percentage (samples 1 to 4).

Table 4.6 – Volume variation in percentage

%	Volume
1	↗ 13,23
2	↗ 14,71
3	↘ 3,39
4	↘ 10,21

Due to the fact that the samples 1 and 2 were submitted to water conditions, it is normal to have an increase of volume. The wood samples absorbed a certain quantity of water through the pores, increasing the dimensions, which resulted on an increase of volume.

It is also important to point that in this case, the fact that the loads were applied on the direction or perpendicularly to the fibres didn´t have a significant effect when analysing the volume variation.

On the other hand, the samples 3 and 4 were submitted to an environment where the samples were heated to a temperature of 40ºC, which led to a significant decrease on the weight of the samples. This resulted in a decrease of volume.

In this case, it is also important to point that when the load is applied perpendicularly to the fibres (sample 4), the volume variation is higher to when is applied on the direction of the fibres.

When it concerns the question of the variation of volume, and when the sample suffered a previous heating, the direction of the appliance of the fibres matters.

Table 4.7 shows the change of volume in percentage (samples 5 and 6).

Table 4.7 – Volume variation in percentage

%	Volume
5	↘ 6,36
6	↘ 1,81

In the case of the samples 5 and 6, it is important to mention that they suffered a previous heating during 24h and, after that heating process, they were placed into room environment conditions, in order to understand and compare the results when the wood recovers its original conditions.

It is possible to mention that, when the load is applied perpendicularly to the fibres (sample 5), the volume variation is higher than when it is applied on the direction of the fibres.

Comparing the samples 3 and 4, with the samples 5 and 6, it is possible to conclude that the wood recovers its original properties, when it acquires the previous environmental conditions, in this case room conditions.

4.6. CONCLUSIONS

Visually, it is possible to observe that the cube samples number 5 and 6, were the ones that presented less deformation.

Considering this, it is also possible to conclude, that the process of heating the cubes had a positive impact on the resistance properties of the material.

Also the cubes suffered a smaller variation of volume, when submitted to a previous heating and after acquiring the room environmental conditions.

According to the maximum load results, it is possible to conclude that when the load is applied on the direction of the wood fibres, it can support a higher load comparing to the results when the load is applied perpendicularly to the fibres.

It is also important to point that, in the case the wood samples were submitted to a previous heating and the load was applied perpendicularly to the fibres, the volume variation was higher than when it was applied on the direction of the fibres.

5

EXPERIMENTAL RESEARCH DURABILITY

5.1. GENERAL DESCRIPTION

In this stage of the experimental part, it was important to focus on the main subject developed on this dissertation, the durability tests.

Durability tests were applied on 12 samples made of red oak wood, produced in Greece (the same type used on chapter 4. Experimental Research – Compression).

Two different coatings were applied on the samples. The coating (A) was a mixture of water and SILRES® WH, while the coating (B) was a mixture of water, SILRES® WH and Silica, fumed (nanomaterial). Some of the samples were texted with the different coatings, while some other samples were used in a clean (without any treatment) condition.

The application of the different coatings, respected the conditions recommended by the EUROPEAN STANDARD – EN 927-5 Paints and varnishes - Coating materials and coating systems for exterior wood - Part 5: Assessment of the liquid water permeability [12].

After the application of the coatings, the samples were submitted to different environmental conditions. The final results were studied, so conclusions could be drawn.

5.1.1. GENERAL DESCRIPTION OF THE SAMPLES

Dimensions were measured before and after the compression tests.

Figure 5.1 shows the original condition of the samples used. They were submitted to cleaning, using spatula and brush, due to the fact that the samples showed some traces of glue. The cleaning steps followed the same conditions described in the previous chapter (5.1) [12].

Figure 5.1 – Original samples´ condition

Figure 5.2 – Cleaned and numbered samples; “KANON-JAPAN Pro-Cal” scale

After the cleaning, and before any change of condition or appliance of coating, the samples were numbered and measured using “KANON-JAPAN Pro-Cal” scale. See Tabel 5.1, Figure 5.2 and Figure 5.3.

Table 5.1 – Samples Dimensions and Volumes

(mm)	a	b	c	Volume (mm^3)
1	23,08	160,81	8,16	30285,80
2	22,96	160,83	8,06	29762,81
3	22,82	160,86	8,17	29990,64
4	22,77	160,30	7,96	29054,25
5	22,98	160,15	8,13	29920,41
6	23,11	160,33	7,98	29567,71
7	23,10	160,26	8,09	29949,23
8	23,06	160,32	7,98	29501,89
9	23,06	160,18	7,95	29365,32
10	22,95	160,24	7,85	28868,44
11	22,97	160,30	7,99	29419,91
12	23,07	160,31	8,04	29734,75

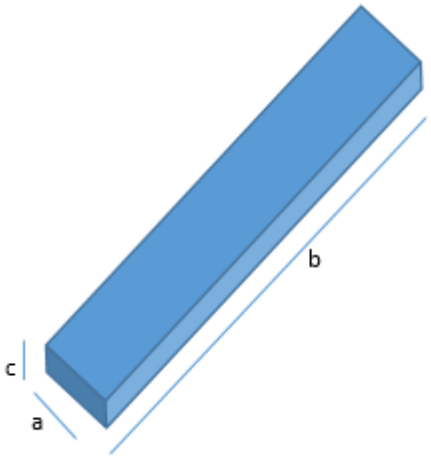


Figure 5.3 – Samples Dimensions

5.2. SOLUTIONS AND COATINGS

In order to prepare the samples´ coatings, the steps to prepare the solutions followed the conditions recommended in the EN 927-5 [12].

5.2.1. SOLUTION A

The solution A consists in a mixture of water and SILRES® WH [13].

SILRES® WH is a Silicone Resin Emulsion that consists in a water thinnable, solventless emulsion of a functional silicone resin. Dilute solutions of SILRES® WH serve as high-quality water repellents for impregnating wood surfaces in order to improve its resistance to the penetration of water both in the liquid and vapour forms.

Undiluted SILRES® WH may also serve as high-quality hydrophobizing additive for aqueous wood coatings/wood stains.

It is water based. Allows the development of a long lasting beading effect on wood.

Concedes a significant reduction of capillary water absorption of wood, particularly after weathering. Increases the durability and longevity of wood stains/coatings for wood because of excellent hydrophobizing properties and helps to minimize all harmful effects caused by water uptake.

SILRES® WH is used in undiluted form as hydrophobizing additive for aqueous wood stains/wood coatings during or after their production. Wood stains/wood coatings modified with SILRES® WH are characterized by excellent water repellence and outstanding water resistance, especially after weathering.

For the use as hydrophobic impregnate for wood, SILRES® WH must be diluted with water. It is recommended by the manufacturer a % of solid contents of around 5 to 10% of the mixture. The application on wood is done by brushing, spraying or flooding.

In order to prepare the solution A, a proportion of 1:10 for SILRES® WH/Water ratio was used.

400g of Water were added to 40g of SILRES® WH. The first attempt to homogenize the solution was done by using a spoon. However, this rudimentary procedure, was not successful in order to obtain a satisfactory final homogeneous solution.

Therefore, another procedure was performed. The ultrasonic cleaner, Branson 2510 Ultrasonic Cleaner, was used. The recipient with the solution inside was submitted to 30min inside the ultrasonic cleaner.

The Branson 2510MT Ultrasonic Cleaner is designed for performance, control, durability, and reliability for a variety of applications. The Branson 2510MT is powerful enough to remove heavy oils, buffing compounds, and proteins, consistent enough to manage difficult laboratory cleaning, while also safe enough for delicate components or fine jewelry.

Figure 5.4 - Branson 2510MT Ultrasonic Cleaner

Ultrasonic sound waves move through a cleaning solution, creating an effect called cavitation, which is the rapid formation and collapse of microscopic bubbles. The 40kHz transducers provide increased cleaning power with built-in sweep frequency for uniform cleaning throughout the bath. The temperature readout accuracy is ± 4º C.

In the next table, it is possible to observe the equipment specifications, see Table 5.2.

As a result of the appliance of this procedure, it resulted a homogeneous solution, ready to be applied as a coating to the samples.

With the solution A ready to be applied, the samples 1, 2, 3 and 10 were selected to be coated. The appliance procedure followed the rules recommended in the previous section [12].

A first coat was applied using a brush, covering all the surfaces of the samples. After 10 minutes of absorption a second coat was applied, in order to guarantee that the maximum of solution possible would be absorbed by the samples.

The samples stayed in room environment conditions as recommended in EN 927-5. 7 full days was the time considered [12].

Table 5.2 - Branson 2510MT Ultrasonic Cleaner specifications [14]

Tank Capacity	Tank Size	Overall Size	Weight	Max Input Power	Heater Power	Max. Draw Power Req. (Watts)*
½ gal. (1.91 L)	L: 6” W: 5.5” D: 4”	L: 10” W: 12” D: 11.5”	7 lbs. (3.2KG)	80W	0 63 63	80 143 143
¾ gal. (2.81 L)	L: 9.5” W: 5.5” D: 4”	L: 13.5” W: 12” D: 11.5”	9 lbs. (4 KG)	130W	0 109 109	13 239 239
1-1/2 gal. (5.71 L)	L= 11.5” W= 6” D: 6”	L= 16” W= 12” D: 14.5”	12 lbs. (5.4 KG)	130W	0 205 205	130 335 335
2-1/2 gal. (9.51 L)	L= 11.5” W: 9.5” D: 6”	L= 16” W: 15.5” D: 14.5”	14 lbs. (6.4 KG)	185W	0 284 284	185 469 469
5-1/2 gal. (20.81 L)	L: 19.5” W: 11.5” D: 6”	L: 24” W: 18” D: 14.5”	26 lbs. (11.8 KG)	320W	0 561 561	320 881 881

5.2.2. SOLUTION B

To prepare the solution B, the same components of Solution A were considered as in the previous solution with an addiction of a nanomaterial, Silica fumed, S5130-100G, produced by SIGMA-ALDRICH company. [15]

Silica fumed is a powder state material with a surface area of 395 $m^2/g \pm 25\ m^2/g$ and density 2.3 lb/cu.ft at 25 °C (bulk density)(lit.). This nanomaterial has interesting thickening and thixotropic properties, and an enormous external surface area.

Silica, fumed may be synthesized by high temperature hydrolysis of $SiCl_4$ in $O_2(N_2)/H_2$ flame. It is amorphous in nature and possesses very high specific area.

The micro droplets of amorphous silica fuse into a branch and form a chain, like an agglomerate and constituting therefore not a homogeneous mixture.

In order to prepare the solution B, a proportion of 1:10 for SILRES® WH/Water ratio was used, plus the addition of the nanomaterial, at the rate of 1,5%, of the weight of the basic solution (which corresponds to solution A).

200g of Water were added to 20g of SILRES® WH. Considering 1,5% of the weight of Water + + SILRES® WH, 3,3g of nanomaterial were added to the first components. The first attempt to homogenize the solution was done by using a spoon. However, this rudimentary procedure, was not successful in order to obtain a satisfactory final homogeneous solution.

Figure 5.5 – Silica fumed, S5130-100G

Therefore, another procedure was performed. The ultrasonic cleaner, Branson 2510 Ultrasonic Cleaner, was used. The recipient with the solution inside was placed inside the ultrasonic cleaner for a period of 30min.

Nevertheless, at the end of this homogenization process, it was possible to observe that some particles were still agglomerated in some particular areas of the solution, in the water, and not scattered over the whole solution as pretended.

Another technique was performed. A magnet was placed inside the solution, and the recipient was placed over a stirrer plate, see figure 5.6.

The Nuova® II magnetic stirrer, Figure 5.6, is ideal to use in cold rooms and incubators with noncondensing atmospheres. Low-profile design, with speed control for 100 to 1000rpm range. Direct-drive motor system delivers quiet, smooth stirring action at low speeds and thorough churning action at higher speeds.

Stir Plate model attributes are defined in Table 5.3.

Figure 5.6 – Solution placed over THERMOLYNE NUOVA II Plate Stirrer

After 10 minutes of working, the stirrer originated an almost perfect homogenous mixture. It was considered ready to use as coating.

With the solution B ready to be applied, the samples 4, 5, 6 and 11 were selected to be coated. The appliance procedure followed the rules recommended in the previous chapter (5.2.) [12].

Table 5.3 - THERMOLYNE NUOVA II attributes [16]

Magnetic Stirrer Type	Non-heated Stirrer
Maximum Load	20 lbs
Maximum Stirring Speed	1000 rpm
Stirring Position	Single Position
Stirring Speed Range	100 to 1000 rpm
Stirring Position	Single Position
Plate Depth	7 in
Plate Width	7 in
Maximum Stirring Speed	1000 rpm
Shipping Weight	9.9 lbs
Stirring Speed Range	100 to 1000 rpm
Construction	Porcelain-coated, stainless steel top plate
Depth	7 in
Height	4 in
Width	11 in
Power Requirements	120 Volts, 60 Hz, 0.3A, 25W
Weight	8 lbs

A first coat was applied using a brush, covering all the surfaces of the samples. After 10 minutes of absorption, a second coat was applied, so the maximum of solution would be absorbed by the samples.

The samples stayed in room environment condition as recommended in EN 927-5 [12].

7 full days was the time considered.

It is important to refer that the samples 7,8,9 and 12 were submitted to the same tests of the other samples but: without the appliance of any coating.

This procedure was used, so that these last samples could be used as references in order to compare the performance of the wood with and without coating.

5.3. WATER CYCLES

For the Water Cycles, samples 1, 4 and 7 were considered, each one with a different coating:

- Sample 1 – Coating A;
- Sample 4 – Coating B;
- Sample 7 – Clean Sample.

After the appliance of the coatings, following the recommended rules present in EN 927-5, and after waiting for 7 days, so that the coating could be absorbed following the procedures recommended in EN 927-5, the samples were measured again, see Table 5.4 [12].

Table 5.4 – Sample´s Weight before Water Cycles

Sample	Weight (g)
1	22,46
4	23,30
7	23,66

The Water Cycles consists in submitting the samples to two different periods, which alternates between 4 hours inside water and 20 hours outside water into room environment as recommended in EN 927-5 [12].

A cycle period is equivalent to 1day period. In total 9 cycles were performed.

Between all the periods and cycles, the weight of the samples was measured and noted. In order to understand the behaviour of the samples. with different coatings, when submitted to environmental changes, and also to understand how they behave under constant environmental changes, further analysis was done.

During the Water Cycles, it was possible to observe the progression of the state of the samples, respective deterioration and how the different applied coatings protected or not the surfaces.

Figure 5.7 – Samples in water condition

After the 9 days of cycles, it was possible to take conclusions about the variation on the weight of the samples, and to conclude if the different coatings became or not relevant in that aspect.

Observing the Table 5.5, it is possible to conclude that all the samples had an increase of their respective weights:

- Sample 1 ↗ 11%;
- Sample 4 ↗ 12,3%;
- Sample 7 ↗ 12,3%.

Although the fact that all the samples suffered an increase of weight, it is not possible to conclude if the coatings had an important impact on this aspect, because the increase was similar in all the samples.

Also the sample 7, that had not been previously submitted to any appliance of coating, and that we can consider as reference, had a similar increase of weight.

Figure 5.8 – Samples in room condition, after a 4 hours in water condition

In Table 5.5, the difference between the “entire number” and the “decimal number” is 4 hours, which indicates that the weight in a decimal number position, is the weight after a 4 hours´ period into water environment.

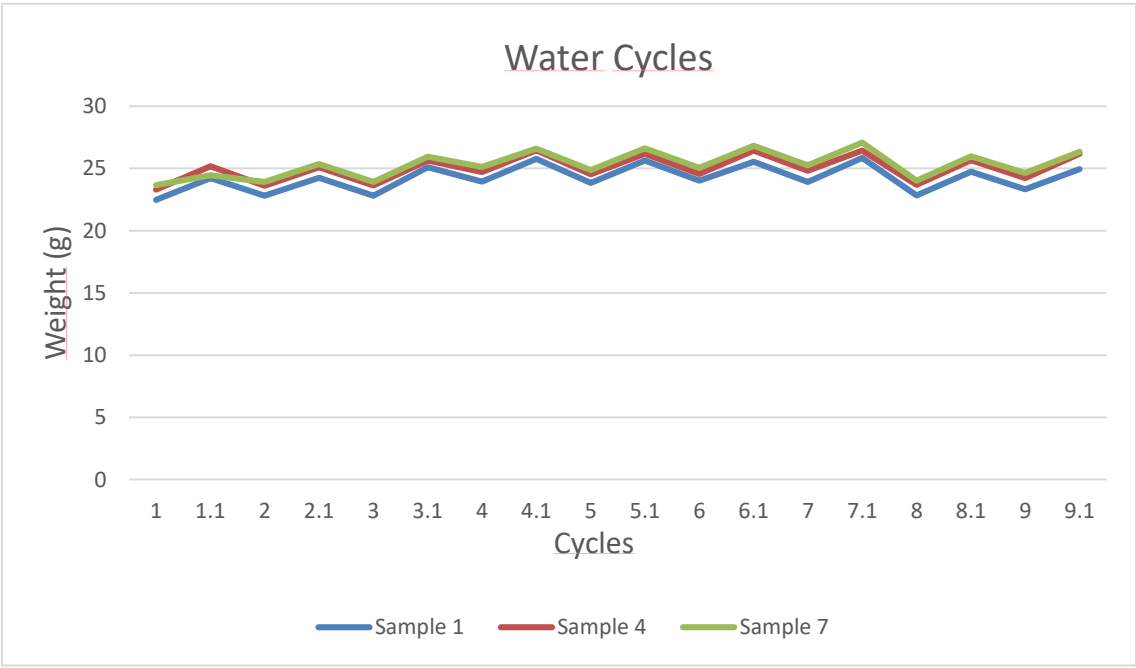


Figure 5.9 – Weight Variation Water Cycles

Table 5.5 – Weight Variation

	Weight Variation (g)		
Cycles	Sample 1	Sample 4	Sample 7
1	22,46	23,30	23,66
1.1	24,23	25,17	24,45
2	22,80	23,59	23,91
2.1	24,25	25,10	25,36
3	22,81	23,64	23,90
3.1	25,10	25,64	25,94
4	23,93	24,70	25,12
4.1	25,75	26,45	26,58
5	23,83	24,54	24,85
5.1	25,63	26,16	26,61
6	24,02	24,56	25,05
6.1	25,54	26,44	26,82
7	23,91	24,80	25,26
7.1	25,83	26,43	27,06
8	22,83	23,68	24,02
8.1	24,73	25,66	25,96
9	23,32	24,21	24,64
9.1	24,93	26,16	26,33

Figure 5.9 shows the variation of weight during the Water Cycles.

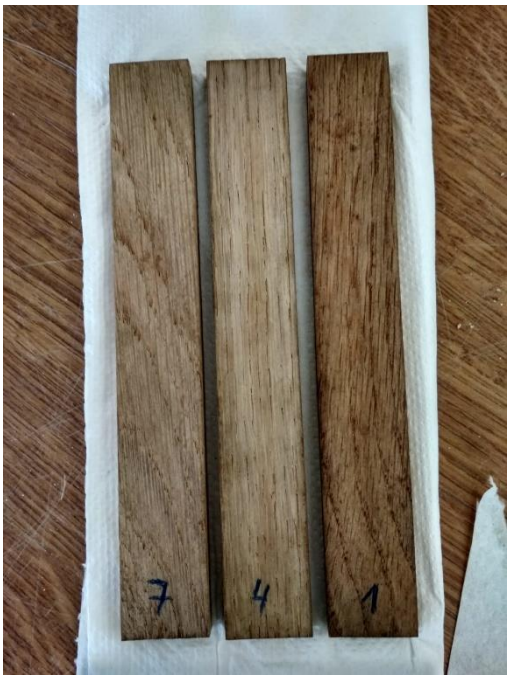


Figure 5.10 – Samples after Water Cycles

The main difference noticed after the water cycles, is the visual aspect. Comparing the original colour, Figure 5.2, and the final result presented in Figure 5.10, it is possible to observe that the colour of the wood changed drastically.

Therefore, a microscopic analysis was performed, in order to have a more precise observation on the effect of water cycles on the samples.

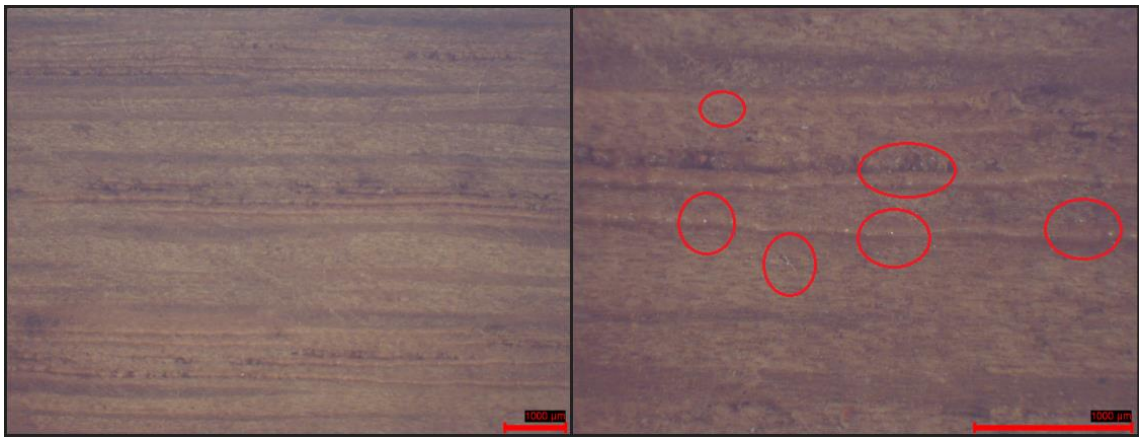


Figure 5.11 – Sample 1 microscopic analysis

Although the surface doesn´t show apparently any significant damage, it is possible to observe on the right side with red marks, that there are some small fractures. It´s still acceptable to consider that the sample maintains hydrophobic properties. It´s acceptable to consider that the coating applied, coating A, had a positive performance.

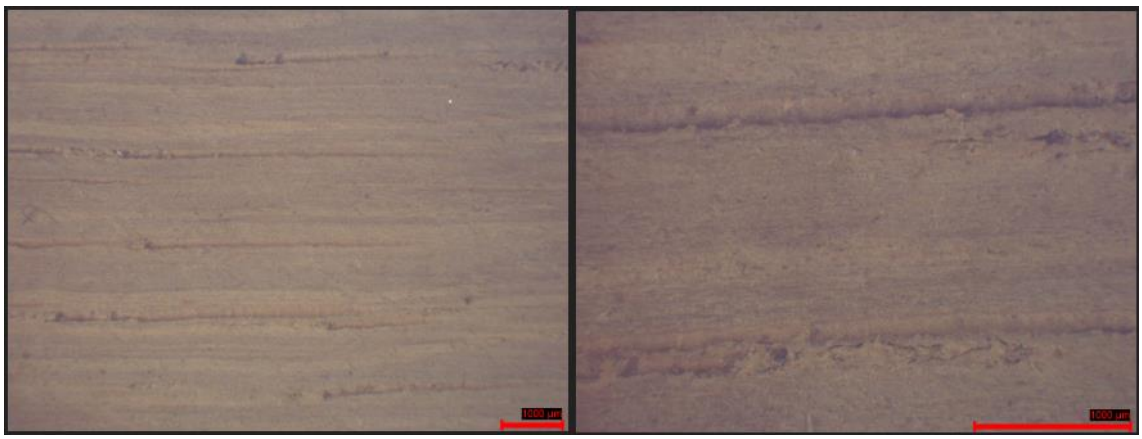


Figure 5.12 – Sample 4 microscopic analysis

After analysing the sample 4, it was possible to observe a smoother surface and the absence of fractures or any type of cracks. It´s possible to conclude that the coating applied on this sample, coating B, had an excellent performance. The sample kept a hydrophobic behaviour.

Figure 5.13 – Sample 7 microscopic analysis

It´s possible to observe that the absence of any type of protection, originated a lot of fractures and cracks in the sample. It´s impossible to consider the sample 7 hydrophobic.

Table 5.6 – Dimensions after Water Cycles

Sample	a (mm)	b (mm)	c (mm)	Volume (mm³)
1	23,27	160,31	8,21	30626,70
4	22,95	160,17	8,19	30105,63
7	23,38	160,18	8,16	30559,27

Comparing the dimensions after the Water Cycles with the initial dimensions presented in Table 5.1, it is possible to observe that all the samples´ volumes increased:

- Sample 1 ↗ 1,13%;
- Sample 4 ↗ 3,62%;
- Sample 7 ↗ 2,04%.

To complete, it is acceptable to conclude that the absence of coating in wood samples originates disadvantages that can damage the material. It´s also possible to conclude that both coatings had a positive response to Water cycles, although coating B had a more effective performance.

Sample 4 relates to a sample protected with solution B, which incorporates the nanomaterial. This sample has swelled more than the sample 7 (clean sample). One can therefore conclude that solution B is not a good solution in what concerns protection against liquid water penetration. Solution A (Sample 1) has a better behaviour in this aspect.

5.4. FREEZE-THAW CYCLES

For the Freeze-Thaw Cycles, the samples 2, 5 and 8 were considered, each one with a different coating:

- Sample 2 – Coating A;
- Sample 5 – Coating B;
- Sample 8 – Clean Sample.

After the appliance of the coatings following the recommended rules present in EN 927-5, and after waiting for 7 days so that the coatings could be absorbed following the procedures recommended in EN 927-, the samples were measured again, see Table 5.7 [12].

Table 5.7 – Sample´s Weight before Freeze-Thaw Cycles

Sample	Weight (g)
2	22,38
5	22,21
8	22,54

The Freeze-Thaw Cycles consists in submitting the samples to two different periods, which alternates between 4 hours in frozen state inside a freezer and 20 hours into room environment as recommended in EN 927-5 [12].

A cycle period is equivalent to 1day period. In total, 9 cycles were performed.

Between all the periods and cycles, the weight of the samples was measured and noted. In order to understand the behaviour of the samples with different coatings when submitted to environmental changes, and also to understand how they behave under constant environmental changes, further analysis would subsequently be done.

Figure 5.14 – Freezer used in Freeze-Thaw Cycles

During the Water Cycles, it was possible to observe the progression of the state of the samples, respective deterioration and how the different applied coatings protected or not the surfaces.

Figure 5.15 – Different stages of Freeze-Thaw Cycles

After the 9 days of cycles, it was possible to take conclusions about the variation on the weight of the samples, and to conclude if the different coatings had showed any relevance in that aspect.

Observing Table 5.8, it is possible to conclude that the samples had a very significant increase of weight:

- Sample 2 ↗ 58,9%;
- Sample 5 ↗ 63,9%;
- Sample 8 ↗ 58,6%.

Table 5.8 – Weight Variation

Weight Variation (g)			
Cycles	Sample 2	Sample 5	Sample 8
1	22,38	22,21	22,54
2	26,49	26,31	26,00
3	31,90	33,48	31,74
4	32,57	34,45	32,35
5	34,36	35,30	33,97
6	34,77	35,60	34,20
7	34,87	35,50	34,09
8	34,95	35,24	34,21
9	36,75	36,73	36,07
10	35,57	36,39	35,74

It is important to mention that, in the Freeze-Thaw Cycles, it was only possible to measure the weight one time, as the samples could only be measured when the water melted after the frozen state.

All the samples suffered a significant increase of weight. There isn´t a big different between the percentages of increase in the different samples. It´s possible to conclude that the fact that some samples were coated, didn´t protect them comparing with the clean sample. When the wood samples were submitted to a frozen condition, the coatings applied didn´t have a positive performance.

It is also possible to mention that sample 8, that had not been submitted to any appliance of coating, and that therefore may be considered as “reference sample”, had a similar increase of weight when compared with the other two samples.

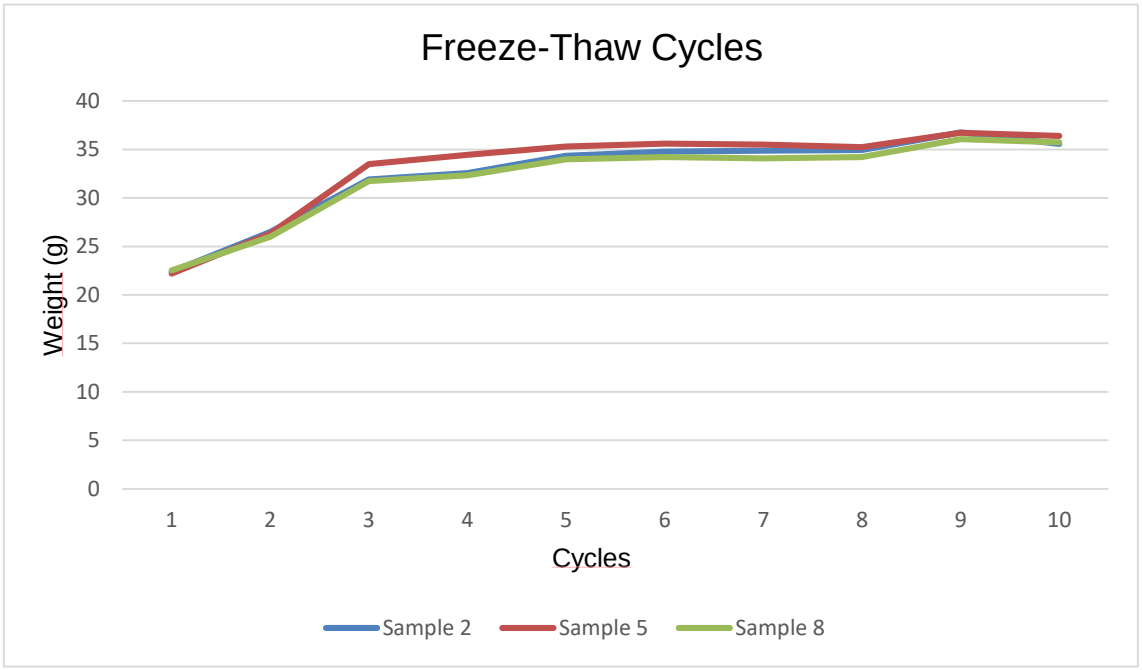


Figure 5.16 – Weight Variation Freeze-Thaw Cycles

Figure 5.17 – Samples after Freeze-Thaw Cycles

Figure 5.16, above, shows the variation of the weight during the Freeze-Thaw Cycles.

A visual analysis of the samples was performed.

Comparing with the original aspect of the samples, Figure 5.2, it is possible to observe a big difference both in the surface aspect of the samples and on the global physical condition of the samples. The final sample´s aspect is shown in Figure 5.17 and shows a darker colouring and a lot of cracks.

Therefore, a microscopic analysis was performed, in order to have a more precise observation on the effect that the Freeze-Thaw Cycles had on the samples.

Figure 5.18 – Sample 2 after Freeze-Thaw Cycles

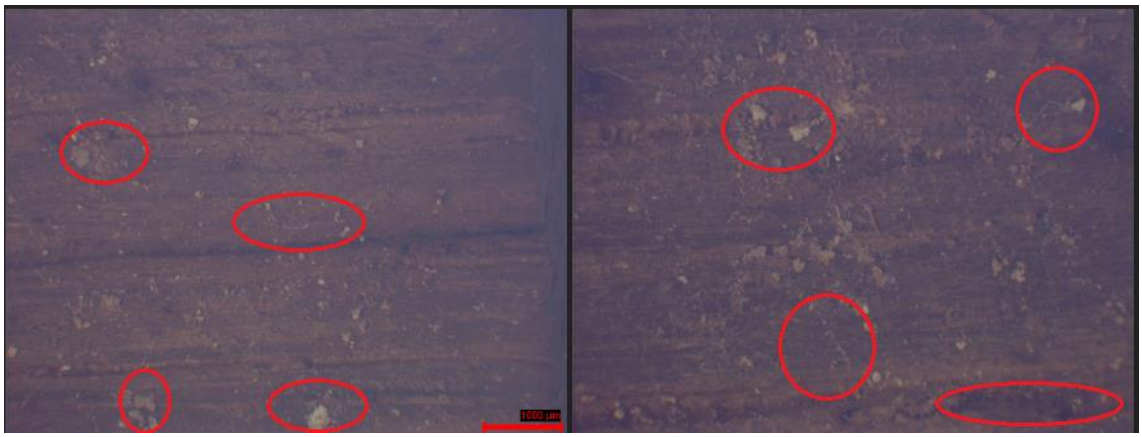


Figure 5.19 – Sample 2 microscopic analysis

The final result shows a significant colour difference of the surface of sample 2, resulting into a darker brown. It´s also clearly visible a large amount of cracks and some beginnings of larger fractures, not only at the superficial level.

Figure 5.20 – Sample 5 after Freeze-Thaw Cycles

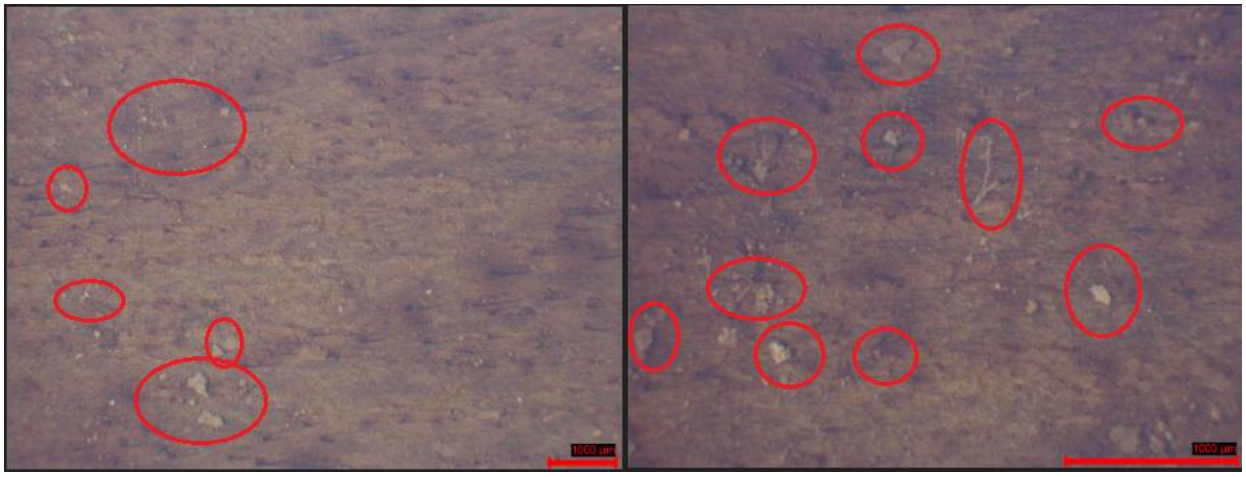


Figure 5.21 – Sample 5 microscopic analyses

Although sample 5 presented a smoother surface, it is possible to observe an organic deterioration. A significant colour difference is visible, as a darker brown is present, comparing with the original sample. A several amount of cracks and fractures are also present.

It´s curious to observe that the clean sample (sample 8) used in the Freeze-Thaw Cycles, see figures 5.22 and 5.23, although presenting the usual deterioration on wood in contact with water, was the one that presented less signs of cracks or fractures. This can mean that this type of coatings applied in the Freeze-Thaw Cycles aren´t the more efficient for this kind of environmental condition (presence of ice originated by negative temperatures).

However, further investigation should be done in order to better understand this subject.

Figure 5.22 – Sample 8 after Freeze-Thaw Cycles

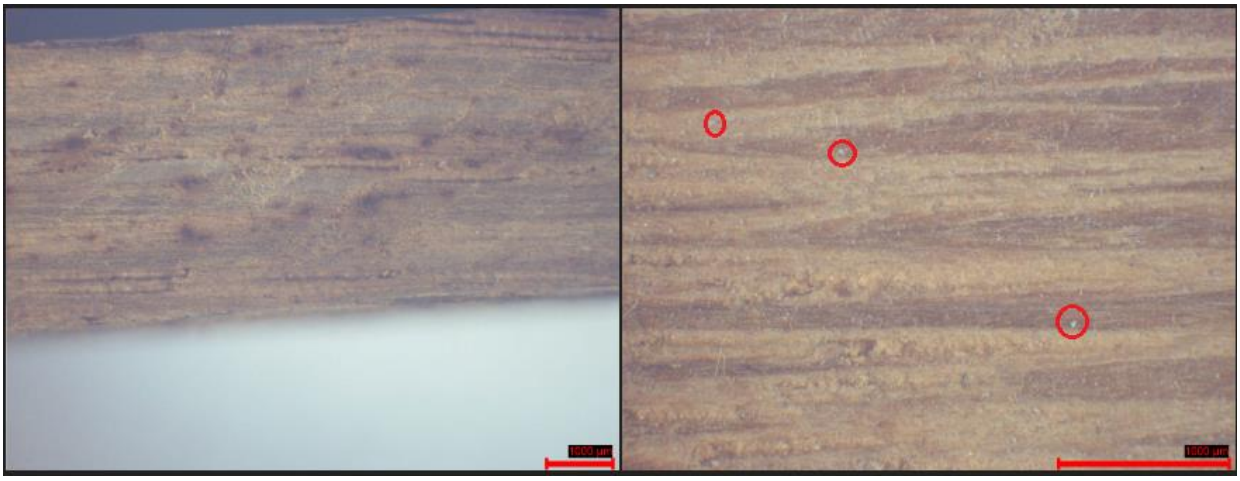


Figure 5.23 – Sample 8 microscopic analysis

Table 5.9 – Dimensions after Freeze-Thaw Cycles

(mm)	a	b	c	Volume (mm³)
2	23,98	160,10	8,43	32364,44
5	24,04	160,38	8,29	31962,39
8	24,08	160,29	8,33	32151,99

Comparing the dimensions after the Freeze-Thaw Cycles with the initial dimensions presented in Table 5.1, it is possible to notice that all the samples´ volume increased:

- Sample 2 ↗ 8,74%;
- Sample 5 ↗ 6,82%;
- Sample 8 ↗ 8,89%.

It is acceptable to conclude that all the samples suffered damages during the Freeze-Thaw Cycles. In this case, it is also possible to conclude that the coatings applied didn´t have a positive performance, since samples 2 and 5 were the most affected samples.

The clean sample had the best result, which can mean that the coatings applied helped on damaging the wood in frozen environment. However, as mentioned before, further research should be done in order to better explain the behaviour of this type of wood when in the presence of ice and very cold temperatures.

All the samples suffered a similar increase of volume. A bigger volume variation was verified comparing with the Water Cycles tests, presented in section 5.3.

5.5. WATER DROP ANALYSIS

The Water Drop Analysis test consists in water contact angle measurements using distilled water. 3 droplets of water are delivered to different points of each sample and from a height sufficiently close to the sample´s surface, so that the needle of the equipment remains in contact with the water droplet. Then, the delivery need is withdrawn with minimal perturbation to the drop. The volume of each droplet is 5µl.

At present the most widely used technique for determining contact angle *(θ)* is by the direct measurement of angle from the drop profile using a goniometer.

The Young-Dupré equation relates the work of adhesion *Wa*, or bonding energy, directly to the surface tension of the liquid, *γLV*, and the contact angle, *Ø*, that the liquid makes with the solid:

$$Wa = \gamma LV (1 + \cos Ø) \text{ dynes/cm}$$

(Formula 5.1)

The Water Drop Analysis test respected the conditions recommended by the D5725-99(2008) Standard Test Method for Surface Wettability and Absorbency of Sheeted Materials Using an Automated Contact Angle Tester, and was performed at the *Ormylia Art Diagnosis Centre*, based in Ormylia (Chalkidiki, Greece), provided by the *Ormylia Foundation* [18].

The equipment used on the performing of the tests was a Drop Shape Analyzer – DSA100B, KRÜSS Instrument, see figure 5.24.

The basic configuration of our Drop Shape Analyzer – DSA100 combines precision manual measurement of the contact angle with the technical advantages and robustness of the DSA100 system solution. The instrument enables reliable investigations of wetting to be carried out in quality assurance and research for pre-treatment and coating processes.

The sample height is adjusted exactly thanks to the fine drive on our manual lift table. The particularly delicate depositing or retrieval of the dispensed drop from the needle ensures gentle contact between sample and liquid. This prevents inaccurate measurement of the contact angle due to unintentional pre-wetting. Drops of a reproducible size for exactly reproducible conditions are generated by our manual dosing unit with the help of a micrometre screw.

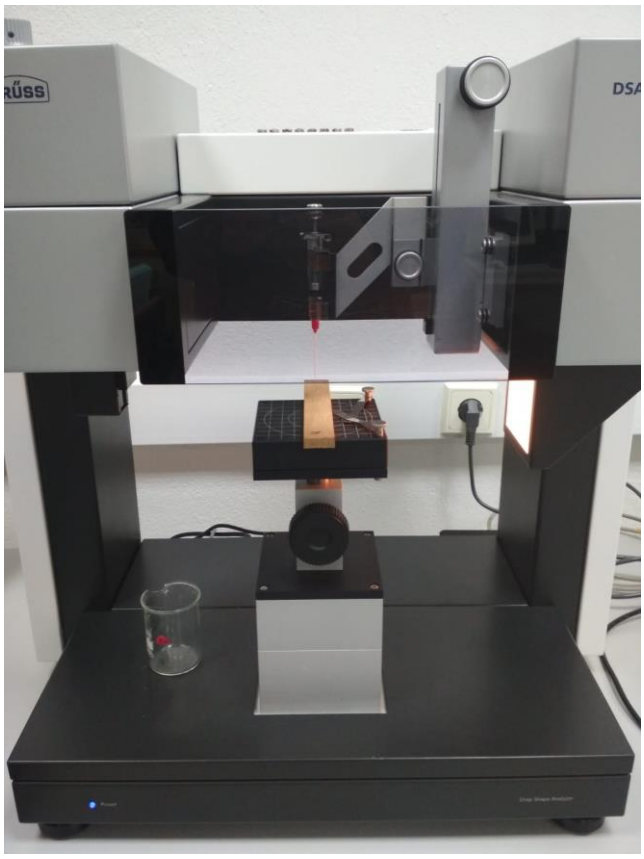


Figure 5.24 – Drop Shape Analyzer – DSA100B

The special features of the optical assembly include a particularly large sample chamber with rapid adjustment of the viewing angle as well as a high-resolution camera. Both options are also part of the basic version of the DSA100B.

Upgrades to all other system configurations are possible for the instrument and the software. One can therefore increase the degree of automation and standardization of the measuring sequence at any time. The comprehensive range of accessories for the DSA100 for adapting the measuring conditions to specific processes is also available [19].

The objective of this test is to observe the progression of the absorption of the water by the sample and register the water drop angle in order to understand that absorption.

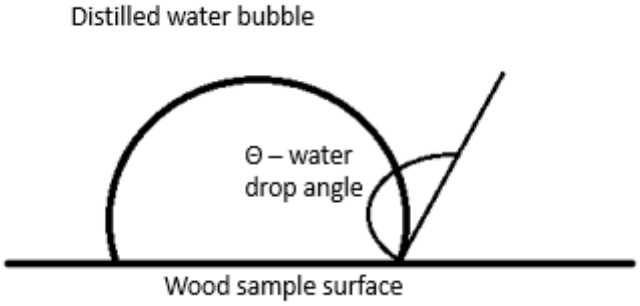


Figure 5.25 – Water Drop Angle

The water drop angle on 12 samples, samples 1 to 12, was registered from the start until the approximate time of 5 minutes, or until the water bubble stops changing which means that any significant alteration has stopped. The difference of the first and last measurements gives us a notion about the performance of the applied coating on what concerns the absorption of water by the sample.

Table 5.10 shows the results of the variation of the Water drop angles, on all the 12 samples. The bigger the angle registered, the more hydrophobic is considered the sample.

On the other hand, the more approximate the angle is from 0, the more hydrophilic (not hydrophobic) the sample is considered.

Table 5.10 – Water Drop Angle Results

Wood Sample 1			Wood Sample 2			Wood Sample 3		
No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)
1-0	00:00:00:000	137.1	2-0	00:00:00:000	107.7	3-0	00:00:00:000	114.3
1-1	00:00:14:656	123.3	2-1	00:01:17:545	95.5	3-1	00:00:38:654	105.3
1-2	00:00:27:256	117.2	2-2	00:02:07:033	83.9	3-2	00:01:05:176	100.4
1-3	00:01:16:091	109.3	2-3	00:03:04:090	71.0	3-3	00:01:57:257	90.0
1-4	00:01:52:917	106.5	2-4	00:04:21:243	65.8	3-4	00:03:22:046	79.2
1-5	00:02:19:312	105.1				3-5	00:04:34:308	70.3
1-6	00:03:31:542	100.9				3-6	00:05:25:621	58.9
1-7	00:03:46:510	100.1						
Wood Sample 4			Wood Sample 5			Wood Sample 6		
No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)
4-0	00:00:00:000	108.4	5-0	00:00:00:000	120.5	6-0	00:00:00:000	131.1
4-1	00:00:42:014	78.8	5-1	00:01:35:047	110.1	6-1	00:00:32:106	125.7
4-2	00:00:55:098	73.0	5-2	00:01:55:473	90.4	6-2	00:01:16:926	118.4
4-3	00:01:27:728	56.1	5-3	00:03:56:944	73.0	6-3	00:03:49:187	111.1
4-4	00:01:52:499	40.6	5-4	00:04:17:199	71.7	6-4	00:04:06:141	102.2
4-5	00:0:58:842	38.0				6-5	00:05:35:590	98.3
4-6	00:02:04:733	37.7				6-6	00:06:09:131	96.3
4-7	00:02:09:722	35.9						
4-8	00:02:16:082	34.0						
Wood Sample 7			Wood Sample 8			Wood Sample 9		
No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)
7-0	00:00:00:000	108.6	8-0	00:00:00:000	41.5	9-0	00:00:00:000	83.3
7-1	00:00:32:059	90.4	8-1	00:00:08:389	29.6	9-1	00:00:17:911	23.0
7-2	00:00:49:515	73.4	8-2	00:00:11:897	28.9	9-2	00:00:38:432	21.4
7-3	00:01:21:038	56.2	8-3	00:00:34:401	25.8	9-3	00:00:47:373	20.6
7-4	00:02:09:672	25.7						
7-5	00:02:12:633	24.7						
7-6	00:02:25:675	24.2						
Wood Sample 10			Wood Sample 11			Wood Sample 12		
No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)	No.	Age (h:m:s:ms)	Angle (deg)
10-0	00:00:00:000	118.6	11-0	00:00:00:000	115.7	12-0	00:00:00:000	56.7
10-1	00:00:33:873	118.6	11-1	00:00:25:920	100.6	12-1	00:00:49:600	46.9
10-2	00:00:57:873	118.6	11-2	00:00:41:199	85.5	12-2	00:01:02:690	35.2
10-3	00:01:56:463	77.2	11-3	00:00:54:447	81.3	12-3	00:01:41:255	29.4
10-4	00:01:59:671	76.1	11-4	00:01:57:694	68.5	12-4	00:01:57:395	27.4
10-5	00:02:31:333	68.9	11-5	00:03:33:000	63.2	12-5	00:02:11:589	25.5
10-6	00:03:00:009	64.3	11-6	00:04:45:195	57.0	12-6	00:02:45:204	24.0
10-7	00:03:15:315	57.2	11-7	00:05:27:033	55.4	12-7	00:03:11:336	23.1

It is possible to observe, in Figure 5.26, the difference between the initial and the final angles, that results from the analysis of all the data gathered in Table 5.9.

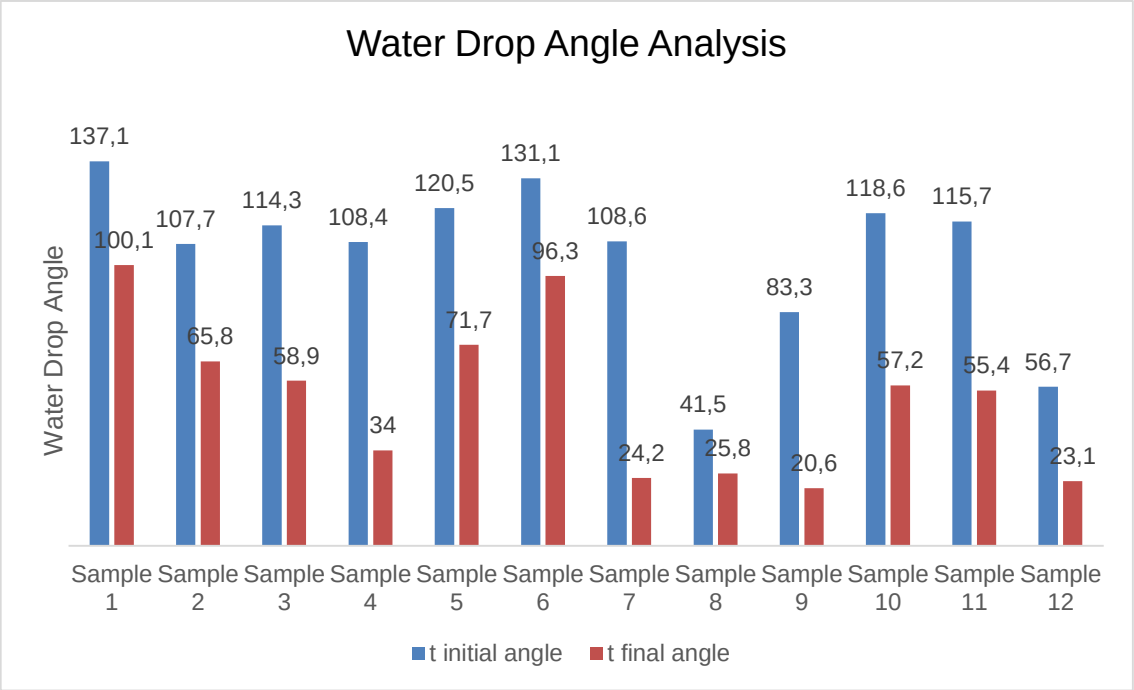


Figure 5.26 – Water Drop Angle Analysis

Figure 5.27 shows the time elapsed between the first and last measurements on each sample.

This Figure is important to help to understand the hydrophobicity of each sample, considering the time each sample took to stop the water drop absorption, or alternatively the time that the sample took until reaching an insignificant level of absorption.

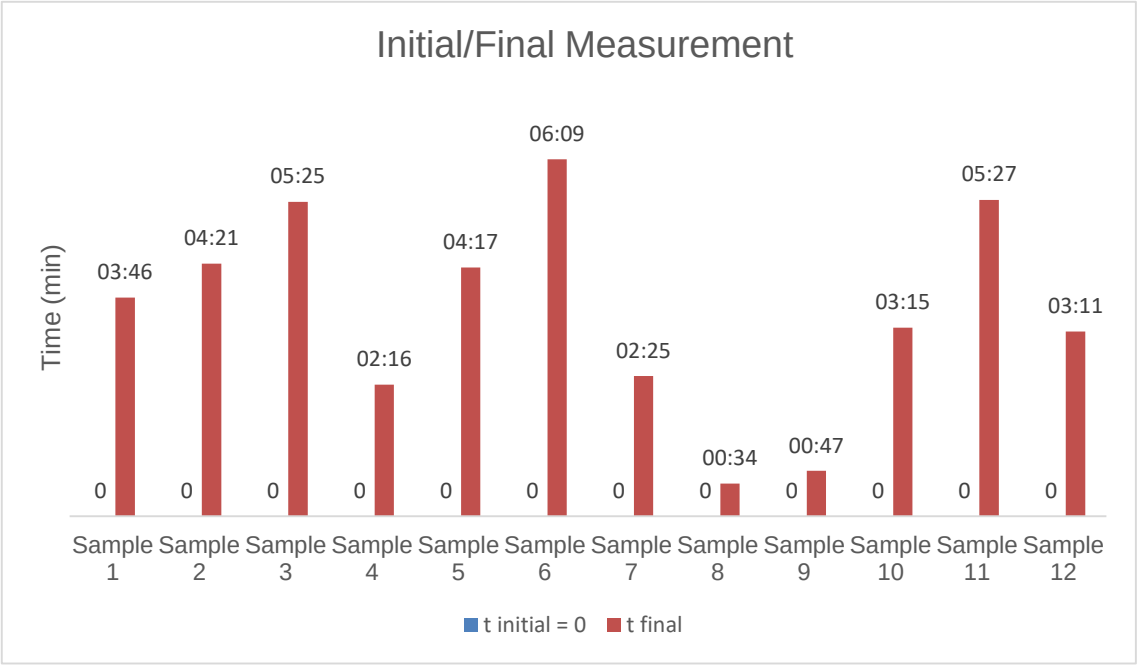


Figure 5.27 – Initial/Final Time Measurement

Table 5.11 shows the variation of the water drop angle in the beginning and in the end of the Water Drop Analysis.

Table 5.11 – Water Drop Angle Variation

Sample	θ
1	↘ 27%
2	↘ 28,9%
3	↘ 48,5%
4	↘ 68,7%
5	↘ 40,5%
6	↘ 26,5%
7	↘ 77,7%
8	↘ 37,8%
9	↘ 75,3%
10	↘ 51,8%
11	↘ 52,1%
12	↘ 59,3%

Analysing the data presented on the table above, it is possible to conclude that the average variation of the water drop angle was 49,5%, the median variation was 50,15% and the standard deviation was 17,36%.

After this statistical analysis, it is possible to conclude that samples 7 and 9 suffered the bigger variation. On the other hand, samples 1, 2 and 6 suffered the smallest variation.

Using this results, it is possible to conclude that samples with no coating, suffered the bigger variation on the Water Drop Angle, showing low hydrophobicity properties.

The samples that registered the smaller variation of the Water Drop Angle, were the samples that were previously coated (samples 1, 2, 3, 4, 5, 6, 10 and 11).

The following Figures show the microscopic observation of the samples. The image on the left represents the initial shape of the Water Drop, and the image on the right represents the final position of the Water Drop, physically showing the numerical values presented on Figures 5.29 and 5.27.

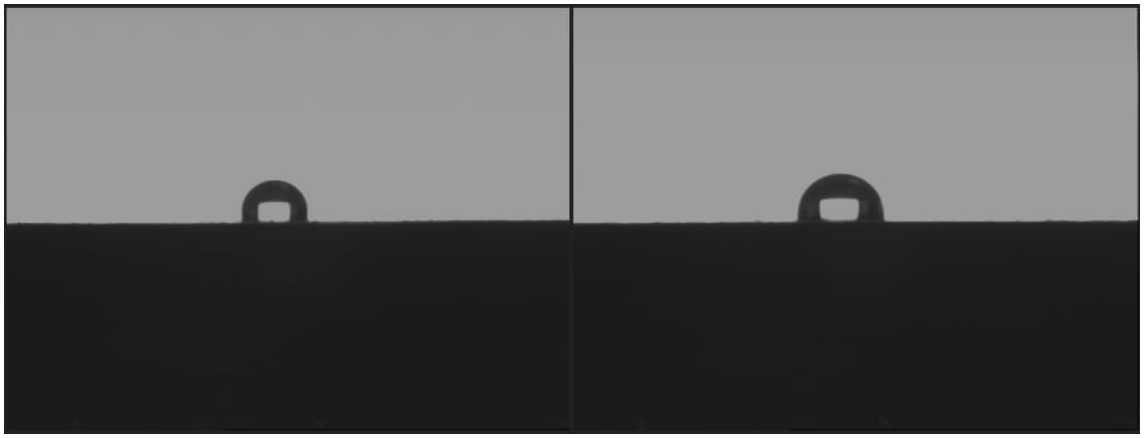


Figure 5.28 – Sample 1 Water Drop Angle variation microscopic analysis

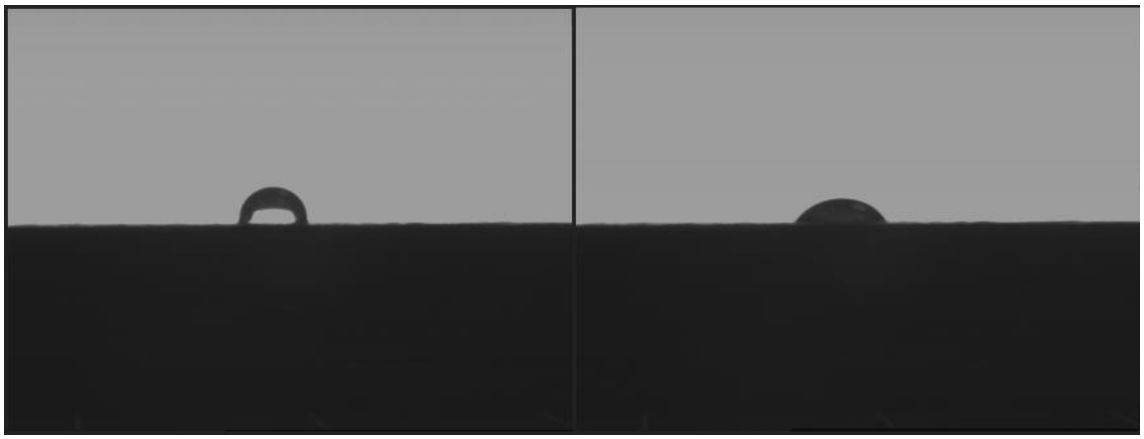


Figure 5.29 – Sample 2 Water Drop Angle variation microscopic analysis

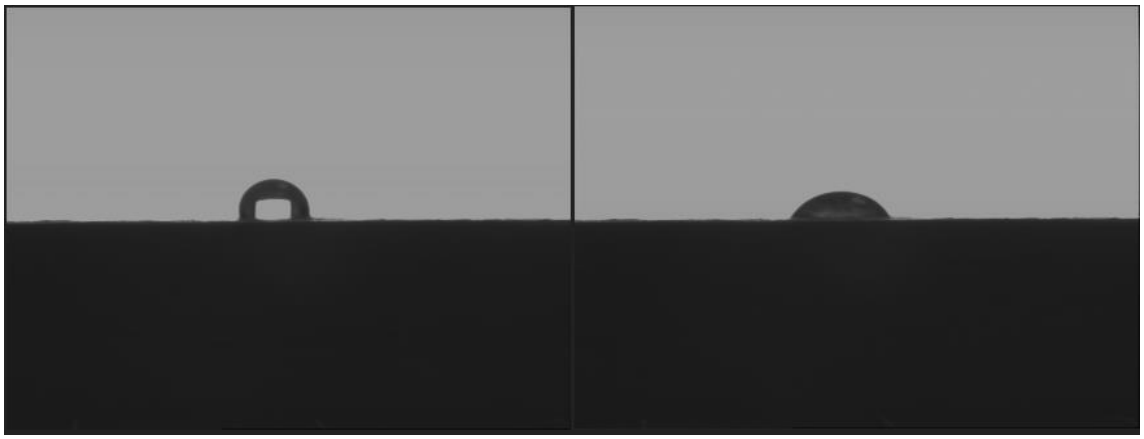


Figure 5.30 – Sample 3 Water Drop Angle variation microscopic analysis

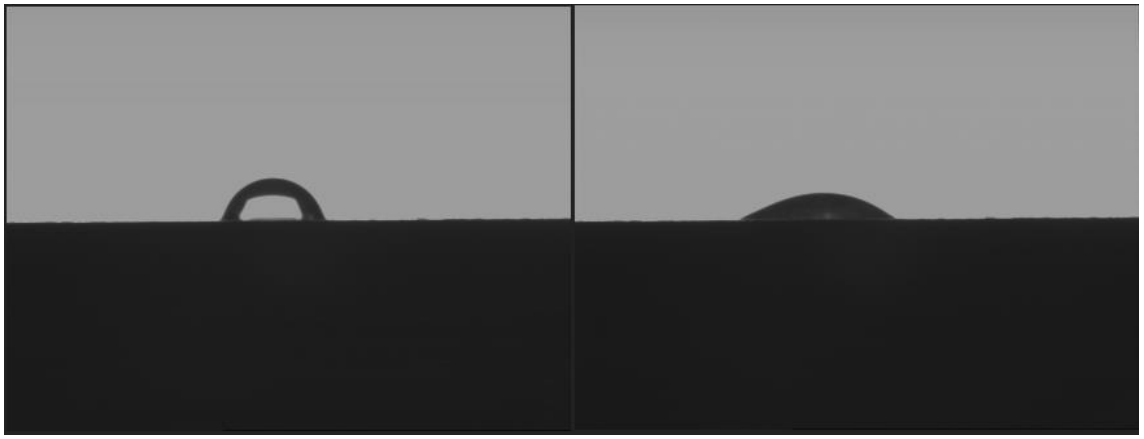


Figure 5.31 –Sample 4 Water Drop Angle variation microscopic analysis

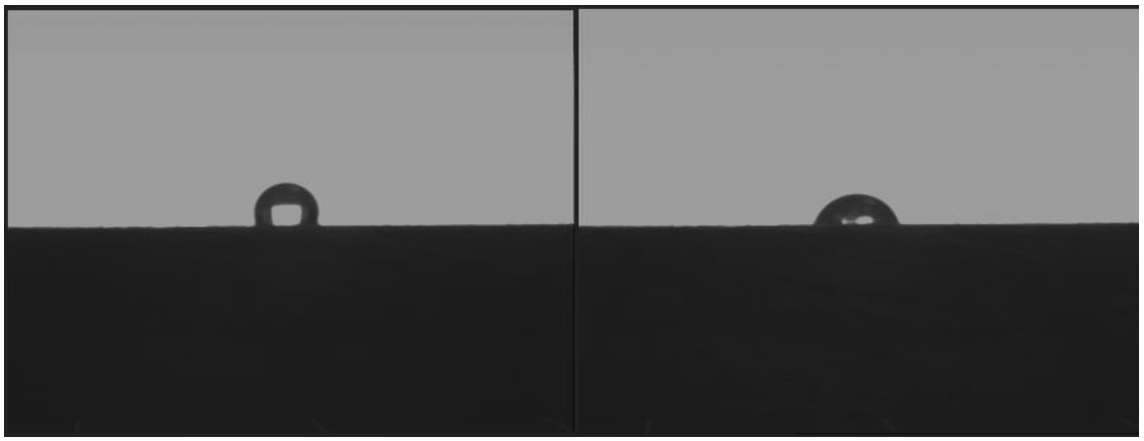


Figure 5.32 – Sample 5 Water Drop Angle variation microscopic analysis

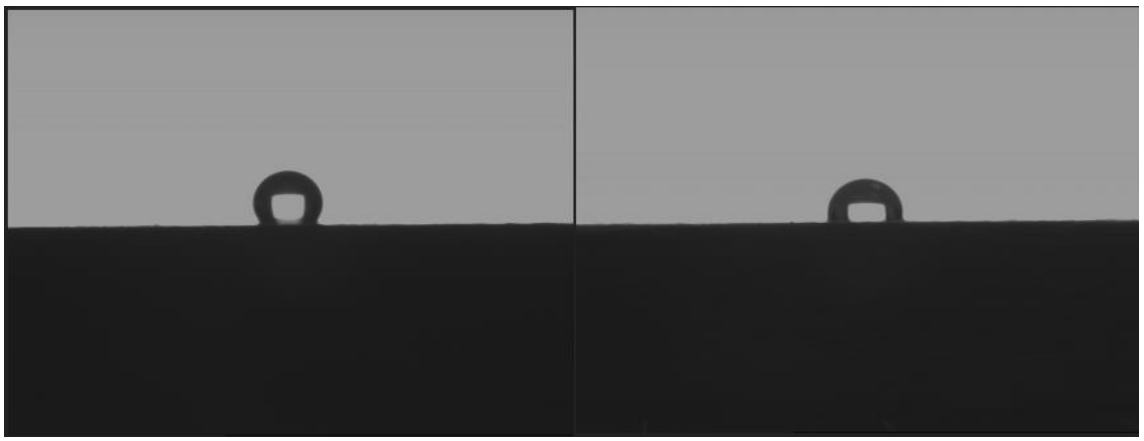


Figure 5.33 – Sample 6 Water Drop Angle variation microscopic analysis

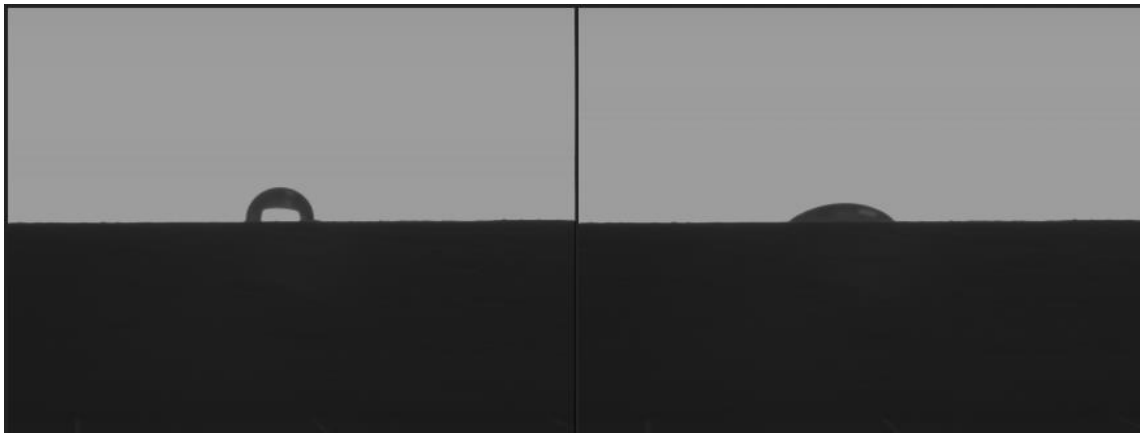


Figure 5.34 – Sample 7 Water Drop Angle variation microscopic analysis

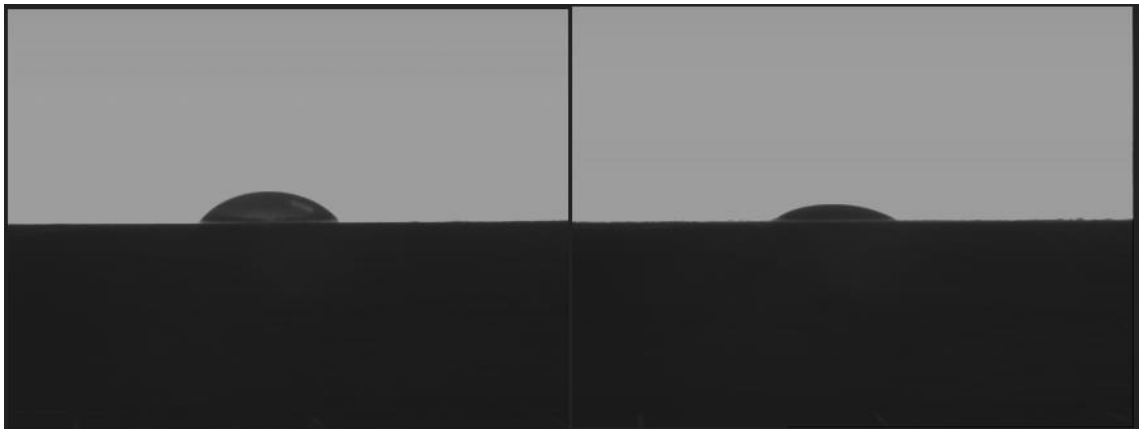


Figure 5.35 – Sample 8 Water Drop Angle variation microscopic analysis

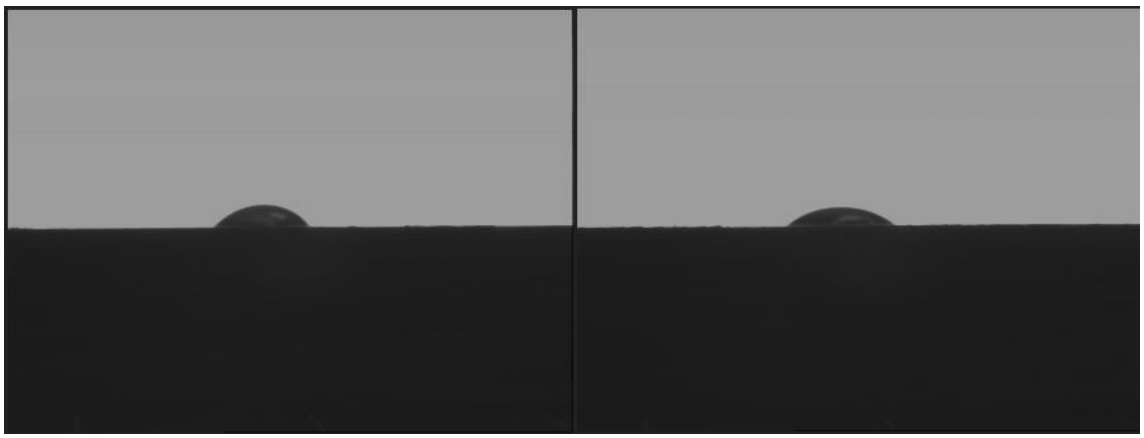


Figure 5.36 – Sample 9 Water Drop Angle variation microscopic analysis

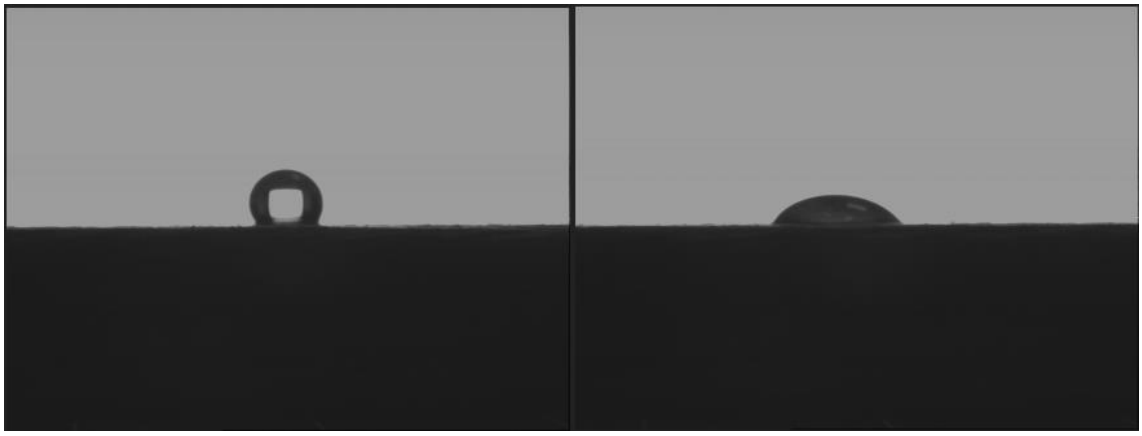


Figure 5.37 – Sample 10 Water Drop Angle variation microscopic analysis

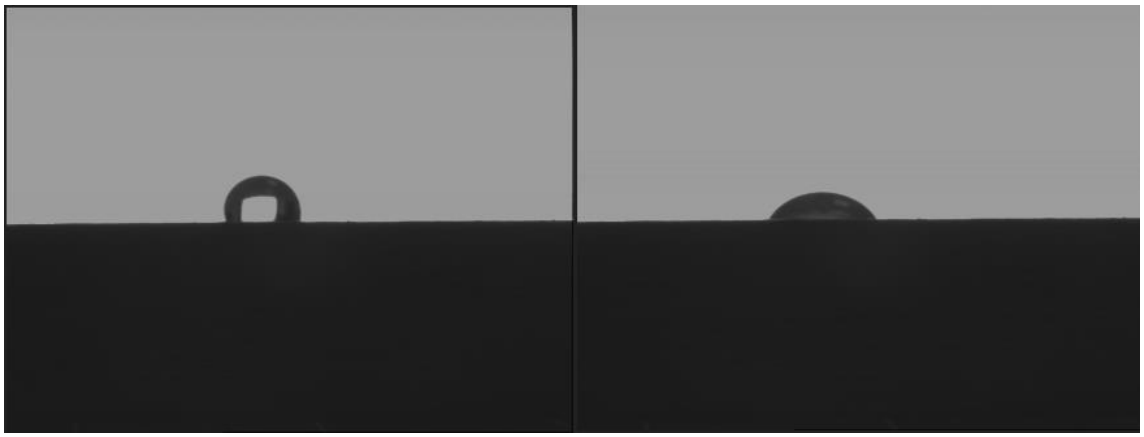


Figure 5.38 – Sample 11 Water Drop Angle variation microscopic analysis

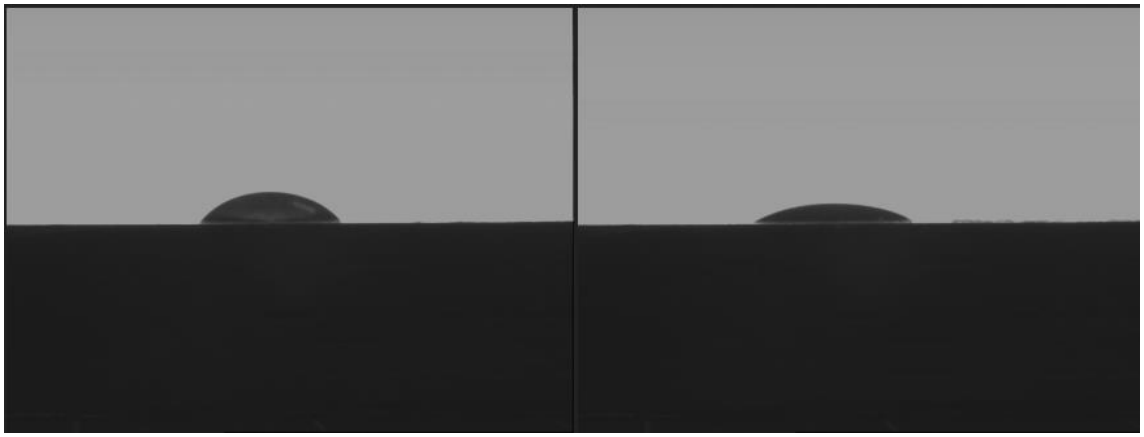


Figure 5.39 – Sample 12 Water Drop Angle variation microscopic analysis

The average water drop angle decrease for each coating group of samples was:

- Water + SILRES® WH: 38,4% (samples 1,2,3 and 10 – Solution A);
- Water + SILRES® WH + Silica, fumed: 48,63% (samples 4,5,6 and 11 – Solution B);
- No coating: 62,53% (samples 7,8,9 and 12 – clean samples - BASE).

The bigger the variation is, the less hydrophobic the sample is.

In water conditions the samples with different coatings had a similar performance, maintaining a positive hydrophobic behaviour.

On the other hand, the samples that experienced Freeze-Thaw cycles, with different coatings, didn´t have a positive hydrophobic behaviour.

Samples that didn't receive any appliance of coating showed the worst results, which shows the importance of coating the surfaces of wood materials.

Table 5.12 shows the decrease of the Water Drop Angle of each sample, the applied coating and the respective test cycles that were previously applied to each sample.

Table 5.12 – Water Drop Angle Variation and respective conditions

	Sample and respective Water Drop Angle Variation and Condition			
Coating A (Water + SILRES® WH)	1 ↘27%	2 ↘28,9%	3 ↘48,5%	10 ↘51,8%
Coating B (Water + SILRES® WH + Silica, fumed)	4 ↘68,7%	5 ↘40,5%	6 ↘26,5%	11 ↘52,1%
No coating applied	7 ↘77,7%	8 ↘37,8%	9 ↘75,3%	12 ↘52,1%
	Water Cycles	Freeze-Thaw Cycles	No previous tests	No previous tests

Analysing this table, it is possible to compare the different results of the tests performed on the different samples with the same coatings, that experienced different environmental conditions.

Samples 1 and 2, obtained a similar Water Drop Angle variation, which means that the applied coating had the similar effect on both adverse conditions. An average Water Drop Angle variation of 27,95% was registered.

Samples 3 and 10 were not submitted to any Cycle and had an average decrease of 50,15% on the Water Drop Angle, and had a very similar behaviour on this test.
This shows that coating A had a very positive performance when submitted to adverse conditions, since the Water Drop Variation is less on samples 1 and 2 than on samples 3 and 10.
Sample 4 had almost more 20% of decreasing on the Water Drop Angle than sample 5, which means that coating B is more appropriate to Freeze-Thaw conditions. However, the results are not very positive since the Water Drop Angle variation is higher comparing with the samples coated with solution A. An average Water Drop Angle variation of 54,6% was registered.

Samples 6 and 11 were not submitted to any previous test Cycles simulating environmental physical actions and had an average decrease of 39,3% on the Water Drop Angle.

It is therefore possible to conclude that the absence of coating on the samples, was beneficial for a smaller Water Drop Angle variation.

However, and considering that an experimental material was used, additional hydrophobicity tests should be performed in order to acquire a better understanding on the use of nanomaterial products to be incorporated on paints and coatings to be used on the protection of wooden elements.
When no coating was applied to the samples (samples 7, 8, 9 and 12) the results were very variable and difficult to explain.

For example, in sample 8, after the Freeze-Thaw Cycles, the test showed a significantly much better performance than the other three. Nevertheless, sample 7, that had been previously submitted to Water Cycles tests conditions, had a bad result when testing the Water Drop Angle.

Samples 9 and 12 were not submitted to any Cycle and had an average decrease of 63,7% on the Water Drop Angle, which means a high absorption of water.

Samples 7, 8, 9 and 12 showed a high initial absorption, that is possible to see in the microscopic analysis, since they were not submitted to any previous treatment.

When analysing the results of the samples with no coating, it is possible to conclude that, depending on the pretended performance and on the conditions that the material will experience when in use, a correct and correctly specified coating is indispensable to be applied, in order to maintain the hydrophobic properties.

6
CONCLUSION

6.1. FOREWORD

After performing what was proposed for this dissertation, this chapter presents the main conclusions resulting on the experimental researches performed.

Multiple aspects affect the performance of the wood materials, when submitted to adverse environmental conditions. According to the coatings and cycles that the samples were submitted to, it is possible to conclude what are the advantages and disadvantages of using each coating and what are the more adverse conditions to the wood elements.

Nowadays, the wood industry is living a good time after the decline verified on reinforced concrete use, the necessity to recovery architectural heritage and as a result of an improved appearance of new wood materials.

However, it is necessary to take advantage of this opportunity to increase the use of wood material in construction. In order to accomplish this costume, it is necessary to provide timber with resistance characteristics and durability that make possible to instil on designers, higher guarantees about the good performance of wood materials in construction.

The durability of wood can be obtained based on its natural durability or due to the application of adequate preservative products.

Nowadays, the industry of preservative products is very wide and active, and in constant evolution. Depending on the purpose of wood materials, and based on the Risk Classes defined on EN 335:2013, a very wide range of products is available [6].

New approaches were tested on this dissertation in order to understand the introduction of nanomaterials (Solution B) in the wood preservative or finishing products.

6.2. MAIN RESULTS

After the performance of the Water Cycles tests, it is possible to conclude that the absence of coating in wood samples originates circumstances that may damage the material in a very wide form. Both coatings applied (Solutions A and B) had a positive response to the Water Cycles tests, although coating B (which incorporates the nanomaterial) had a more effective performance.

Sample 4, coated with Solution B, has swelled more than sample 7 (clean sample). This means that solution B is not a good solution in what concerns to protect against liquid water penetration. Sample 1, coated with Solution A, had the better behaviour in the Water Cycles tests.

In all the Freeze-Thaw Cycles tests, it was possible to observe that all samples suffered damages. This means that the finishing solutions that were applied to the samples didn´t have a satisfactory

performance, considering that samples 2 and 5, respectively coated with Solutions A and B, were the most affected.

The clean sample, sample 8, showed the best results, which can mean that the coatings applied on the other samples helped on damaging the wood in frozen environment.

All the samples submitted to the Freeze-Thaw Cycles tests suffered a similar increase of volume. Also a bigger volume variation was verified, when comparing with the Water Cycles tests results.

According to the results on the Water Drop Analysis, the coating A had a very positive performance when submitted to adverse conditions, since the Water Drop Variation is less on samples 1 and 2, than on samples 3 and 10.

Sample 4 had a bigger decrease of the Water Drop Angle than sample 5, which means that coating B is more appropriate to Freeze-Thaw conditions. However, the results are not very positive since the Water Drop Angle variation is higher comparing with the samples coated with solution A.

It is therefore possible to conclude that the absence of coating was beneficial for a smaller Water Drop Angle variation, since samples 6 and 11, not submitted to any previous Cycles, had a smaller Water Drop Angle variation than samples 4 and 5, respectively coated with Solutions A and B.

When no coating was applied to the samples (samples 7, 8, 9 and 12 – clean samples - BASE) the results were very variable and difficult to explain.

However, it is possible to conclude that these samples showed a high initial absorption, that is possible to see in the microscopic analysis, which may be explained by the fact that they were not submitted to any previous treatment.

When analysing the results of the samples with no coating, it is possible to conclude that, depending on the pretended performance and on the conditions that the material will experience when in use, a correct and correctly specified coating is indispensable to be applied, in order to maintain the hydrophobic properties.

6.3. FURTHER RESEARCH

Considering that an experimental material was used, additional hydrophobicity tests should be performed in order to acquire a better understanding on the use of nanomaterial products to be incorporated on paints and coatings to be used on the protection of wooden elements.

The relatively small number of tests included in the research presented on this dissertation, implies that it is not possible to draw any conclusion related with the positive or negative impact of the use of nanomaterials in the production of protective coatings for timber elements. Further research is needed.

The solutions tested on this research program (A and B), better defined in chapter 5, are not reliable to protect the timber elements in a context of ice/snow situations. For this purpose, a different basic specification with a better performance on this situation must be chosen for a different “Solution A” to test if the incorporation of a specific more adequate nanomaterial (a different solution B) may eventually improve the performance of the basic solution. A complete new set of tests should be done to test this situation.

BIBLIOGRAPHIC REFERENCES

[1] Flores-Cohen I., Garcia J., Guilherme Silva L., Silva A., Neto N.; *Revestimento de Pisos.* Instituto Superior Técnico, Lisboa (retirado de apontamentos da disciplina "Tecnologia da Construção de Edifícios" de 2º ciclo do MIEC do IST, Lisboa)

[2] Green, David W., Winandy, Jerrold E., Kretschmann, David E. 1999. *Mechanical properties of wood. Wood handbook: wood as an engineering material*. Madison, WI: USDA Forest Service, Forest Products Laboratory, 1999. General technical report FPL; GTR-113: Pages 4.1-4.45

[3] Araújo Botelho Júnior J.; *Avaliação não destrutiva da capacidade resistente de estruturas de madeira de edifícios.* Departamento de Engenharia Civil da Faculdade de Engenharia da Universidade do Porto, 2006, Dissertação de Mestrado

[4] *http://assimquefaz.com.br/decoracao/como-proteger-mveis-de-madeira-do-sol-e-chuva* (Figure 3.1; consulted in 13 of April)

[5] Alves Gonçalves Silva J. P.; *Especificações de tratamentos de preservação para elementos de madeira.* Departamento de Engenharia Civil da Faculdade de Engenharia da Universidade do Porto, 2008, Dissertação de Mestrado

[6] CEN – Comité Européen de Normalisation; *BS EN 335:2013 - Durability of wood and wood-based products - Use classes: definitions, application to solid wood and wood-based products*; Brussels, 2013

[7] Moura Oliveira D.; *Especificações de Acabamentos Pintados ou Envernizados para Elementos Construtivos Exteriores em Madeira.* Departamento de Engenharia Civil da Faculdade de Engenharia da Universidade do Porto, 2008, Dissertação de Mestrado

[8] *http://invasions.si.edu/nemesis/CH-INV.jsp?Species_name=Limnoria+tripunctata* (Figure 3.2; consulted in 2 of May)

[9] *https://diply.com/photos-fascinating-uncomfortable?publisher=dipinterest&config=25* (Figure 3.2; consulted in 2 of May)

[10] European Committee for Standardization. I.S.; *EN 408:2010+A1:2012 - Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties*. Brussels, 2012

[11] *http://matest.com/en/Products/concrete/COMPRESSION-TESTING-MACHINES-1500-kN/compression-machines-1300-kn-for-cylinders-and-cubes* (Table 4.1; consulted in 2 of April)

[12] BSi British Standards. *BS EN 927-5:2006 - Paints and varnishes. Coating materials and coating systems for exterior wood. Assessment of the liquid water permeability.* 2008

[13] *https://www.wacker.com/cms/en/products/product/product.jsp?product=13814* (Solution A; consulted in 21 of May)

[14] *https://www.marshallscientific.com/v//vspfiles/specs/BransonXX10_specs.pdf* (Table 5.2; consulted in 19 of May)

[15] https://www.sigmaaldrich.com/catalog/product/aldrich/s5130?lang=en&region=GR (Solution B; consulted in 23 of May)

[16] *http://www.labwrench.com/?equipment.view/equipmentNo/1065/Thermolyne/Nuova-II/* (Table 5.3; consulted in 24 of May)

[17] *https://www.smitherspira.com/services/materials-testing/paper-surface-property-tests/water-drop-contact-an* (Formula 5.1; consulted in 29 of May)

[18] ASTM International. *ASTM D5725-99(2008), Standard Test Method for Surface Wettability and Absorbency of Sheeted Materials Using an Automated Contact Angle Tester (Withdrawn 2010)*. West Conshohocken, PA, 2008

[19] *https://www.kruss-scientific.com/products/contact-angle/dsa100/drop-shape-analyzer-dsa100b/* (consulted in 30 of May)

OTHER BIBLIOGRAPHY

https://www.woodgears.ca/hardness_test/index.html (consulted in 11 of May)

https://www.fpl.fs.fed.us/documnts/fplrp/fplrp84.pdf (consulted in 17 of April)

https://www.explainthatstuff.com/wood.html (consulted in 28 of April)

https://www.researchgate.net/publication/286033742_PEER-REVIEWED_ARTICLE_Evaluation_of_Modulus_of_Elasticity_of_Laminated_Strand_Lumber_by_Non-Destructive_Evaluation_Technique (consulted in 19 of May)

https://bioresources.cnr.ncsu.edu/resources/evaluation-of-modulus-of-elasticity-of-laminated-strand-lumber-by-non-destructive-evaluation-technique/ (consulted in 6 of June)

https://www.woodworkingnetwork.com/magazine/fdmc-magazine/temperature-change-and-its-effect-wood (consulted in 22 of May)

http://www.hubharp.com/technical_articles2/soundboard_humidity.htm (consulted in 27 of April)

http://www.cbiconsultingllc.com/wood-deterioration-2/ (consulted in 15 of June)

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4931425/ (consulted in 12 of June)

https://www.forestpests.org/hungary/longhorn1.html (consulted in 29 of June)

http://www.hampshire-antique-restoration.co.uk/P%20D%20F/THE%20THERMO.pdf (consulted in 14 of June)

http://www.icom-cc.org/ul/cms/fck-uploaded/documents/LWG/Amsterdam%201995_%20The%20Effect%20of%20the%20Thermo-Lignum%20Pest%20Eradication%20on%20Leather_%20THOMSON.pdf (consulted in 3 of June)

http://www.artdiagnosis.gr/ (consulted in 13 of May)

http://www.ormyliafoundation.gr/en/ (consulted in 13 of May)

http://www.daaam.info/Downloads/Pdfs/proceedings/proceedings_2012/0993_Hormanatal.pdf *(consulted in 3 of July)*

https://link.springer.com/article/10.1007/s10086-013-1365-z (consulted in 14 of July)