Weathering behaviour of Colorado (*Eucalyptus camaldulensis* and *Eucalyptus tereticornis*) and Balau (*Shorea* spp.)

by

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Declaration

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March 2010

ABSTRACT

Balau, a group consisting of 21 *Shorea* species, is widely used for outdoor application. In South Africa, Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of a substitute timber for decking material. One possible timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India and parts of South America because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors. The timber was initially utilized as raw material for the pulp and paper industry but is now gaining importance in structural uses like furniture, flooring and decking.

The aim of this exploratory study was to investigate relevant material properties and to examine the natural and accelerated weathering behaviour of Colorado and Balau to predict Colorado's suitability as decking material.

It was found that Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau and had a higher density than Balau. Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's. The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado's lower swelling anisotropy can result in a lower tendency to twist in service. Colorado had a higher water soluble extractive content than Balau, which can lead to the rapid initial colour changes when the timber is exposed uncoated.

The weathering performance of Colorado and Balau was investigated by exposing samples in a QUV accelerated weathering apparatus and to natural weathering at an inland and a marine location. During weathering Colorado showed a slightly higher colour change (ΔE^*) than Balau. Balau showed a higher increase in roughness (*Rz*), surface checking and check formation than Colorado. Colorado showed slightly more cup than Balau, however, Balau showed much larger amounts of twisting than Colorado. No statistically significant differences were found between the hydrophobicity of the two timbers. A coating was effective in increasing the initial hydrophobicity of samples and could maintain a relatively hydrophobic surface during weathering. No statistically significant differences were found in the effect of sample cut on timber species surface wettability. Although only long term exposure studies and using substantially more samples can confirm its weathering performance, the results of this exploratory weathering study indicated that Colorado can successfully be used as a substitute decking material for Balau.

Samevatting

Balau, ‘n houtsoort wat ongeveer 21 *Shorea*-spesies verteenwoordig, word wyd in buitenshuise aanwendings benut. In Suid-Afrika is Balau een van die mees gewilde materiale wat vir dek-doeleindes gebruik word. As gevolg van die toenemende skaarsheid van Balau, is dit van ekonomiese belang om die gebruik van ‘n moontlik plaasvervangende houtsoort vir dek-materiaal te ondersoek. Colorado, ‘n mengsel van een of meer van die volgende: *Eucalyptus camaldulensis*, *Eucalyptus tereticornis* en hibriede daarvan, kan as ‘n moontlike plaasvervanger gebruik word. Hierdie twee spesies en hulle hibriede word op groot skaal in lande soos Australië, Indië en dele van Suid-Amerika gekweek vanweë hul kort rotasieperiode en goeie aanpasbaarheid by ‘n wye verskeidenheid grond- en klimaatsfaktore. Die spesies is aanvanklik as grondstof in die pulp- en papierbedryf gebruik maar word tans al hoe belangriker in strukturele aanwendings soos byv. meubels, vloer- en dek-materiaal. Die doel van hierdie verkennende studie was om relevante materiaaleienskappe te ondersoek en om die versnelde en natuurlike verweringsgedrag van Colorado en Balau vas te stel om sodoende ‘n aanduiding van die geskiktheid van Colorado as dek-materiaal te kan kry.

Daar is gevind dat Colorado kleiner vat-lumina, minder vate/m^2 en kleiner strale as Balau besit en dat Colorado ‘n hoër digtheid het as Balau. Alhoewel beide houtsoorte relatiewe lae veselversadigingspunte (VVP) besit, is Colorado se VVP 2.3% persentasiepunte hoër as dié van Balau. Die swellingskoëffisiente (radiaal en tangensiaal) van Colorado is effens hoër as dié van Balau, maar Colorado se laer swellingsanisotropie kan op ‘n kleiner neiging tot skeeftrek dui. Colorado het ‘n hoër wateroplosbare ekstrakstofinhoud as Balau bevat, wat tot aanvanklik vinnige kleurveranderings kan lei wanneer die hout sonder oppervlaktemiddel blootgestel word.

Die verweringsgedrag van Colorado en Balau is ondersoek deur monsters aan versnelde en natuurlike verwering bloot te stel. Eersgenoemde is in ‘n QUV versnelde verweringsapparaat uitgevoer en laasgenoemde in ‘n binnelandse en ‘n mariene lokaliteit. Tydens verwering het Colorado ‘n effens hoër kleurverandering (ΔE^*) as Balau getoon. Balau het ‘n hoër toename in rofheid (Rz), oppervlaktekrake en kraakvorming as Colorado getoon. Colorado het effens meer kromgetrek terwyl Balau meer skeefgetrek het as Colorado. Geen statisties beduidende verskille kon tussen die waterwerende eienskappe van die twee houtsoorte vasgestel word nie. ‘n Oppervlakbedekking was effektief om die aanvanklike toename in waterwerende vermoë te verhoog en gedurende verwering te kon behou. Geen statisties beduidende verskille kon tussen die invloed van snit van die monster op die oppervlaktebenatbaarheid van die houtsoorte vasgestel word nie. Alhoewel slegs langtermyn blootstellingstudies en die gebruik van beduidend veel meer monsters die verweringsgedrag kan bevestig, dui die resultate van

hierdie verkennende ondersoek aan dat Colorado suksesvol as ‘n plaasvervangende dek-materiaal vir Balau gebruik kan word.

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Chapter1: Introduction and Purpose of Study

Wood has been used as a building material for many millennia and despite the invention of new building materials over the last century, the utilization of wood in the construction industry shows little sign of declining. This can be attributed to wood's versatile and attractive engineering and structural properties.

Wood that is used for indoor applications is mostly exposed to regulated humidity and temperature, and little ultra violet light. However when wood is used under exterior conditions (e.g. as decks, window frames, roofs, etc.), it is subjected to the harsh weathering factors of nature.

All man-made and natural materials, including wood, are susceptible to environmental degradation. When wood is exposed outdoors, above ground, a complex combination of chemical, mechanical, and light energy factors contribute to what is described as weathering (Feist, 1983). These weathering factors are as follows: solar radiation (ultra violet (UV), infrared and visible light), moisture (rain, dew, snow and changes in relative humidity), abrasion by windblown particles, heat and oxygen. In recent years, an additional weathering influence has arisen with the presence of atmospheric pollutants such as gaseous SO_2, NO_2, and O_3 (Anderson *et al*, 1990). Abrasion of surfaces as a result of human activities such as walking on decks and maintenance such as cleaning surfaces with cleaners and brighteners and power washing cause further modification of weathering effects (Feist, 1990 and Williams, 2005).

The weathering process of wood starts immediately after wood is exposed to sunlight which causes the photo-oxidation or photochemical degradation of the exposed wood surface (Williams, 2005). At first the colour changes and then the combined effect of solar radiation and moisture leads to surface roughening as the grain raises, formation of surface checks which later grow into large cracks, surfaces gather dirt and mildew, the wood loses its surface coherence and becomes friable, splinters and fragments come off (Feist, 1983). If boards contain reaction or juvenile wood, cross-grain checking may develop, the boards may cup and warp and pull away from fasteners, especially in decking applications (Williams, 2005).

Weathering should not be confused with decay, which results from decay organisms acting in the presence of excess moisture and air (Anderson *et al*, 1990). In the absence of decay, wood exposed to the weather only undergoes surface degradation, with the wood a few millimeters under the surface essentially remaining unchanged and unaffected for many years (Feist, 1983). Decay on the other hand is a process that affects the whole thickness or bulk of the wood. Decay fungi can destroy wood in just a few years if the conditions are favourable for their growth (Williams, 2005). The performance of wood exposed to exterior conditions is greatly affected by species, size, shape, construction design which determine the degree of protection from prolonged wetting and finish type (Feist, 1983).

To develop methods to retard or inhibit degradation and to increase the service life of all types of wood products in any type of environment, it is important to understand the mechanisms of weathering that lead to chemical changes and degradation of physical properties.

Balau is a group consisting of 21 *Shorea* species (Pande *et al,* 2005). The timber is widely used for outdoor application and in South Africa, Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of substitute species for decking material. One possible substitute timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India and parts of South America because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors (Sharma *et al*, 2005). These two species were initially utilized as raw material for the pulp and paper industry, but are now gaining importance for commercial and structural uses like furniture, flooring and decking.

The aim of this exploratory investigation was to study the weathering behaviour of Colorado (*Eucalyptus camaldulensis* and *Eucalyptus tereticornis*) and Balau (*Shorea* spp.) and evaluate their suitability as decking material. To achieve this, the study was subdivided under the following objectives:

1. Investigate relevant anatomical, chemical and physical properties of Colorado and Balau
2. Determine the natural weathering performance of Colorado and Balau for decking by evaluating the effect of:
    - environment: Mediterranean inland compared to a Mediterranean marine climate.
    - grain orientation: radial vs. tangentially cut, and
    - surface coating

3. Assess the weathering performance of Colorado and Balau under accelerated weathering conditions.

The structure and experimental layout of this thesis is schematically depicted in Figure 1.1. The results of this investigation are presented in Chapters 3 and 4. Both have been written in article format to enhance later submission for publication in scientific journals. Consequently, for the sake of completeness, a certain amount of duplication of text was unavoidable.

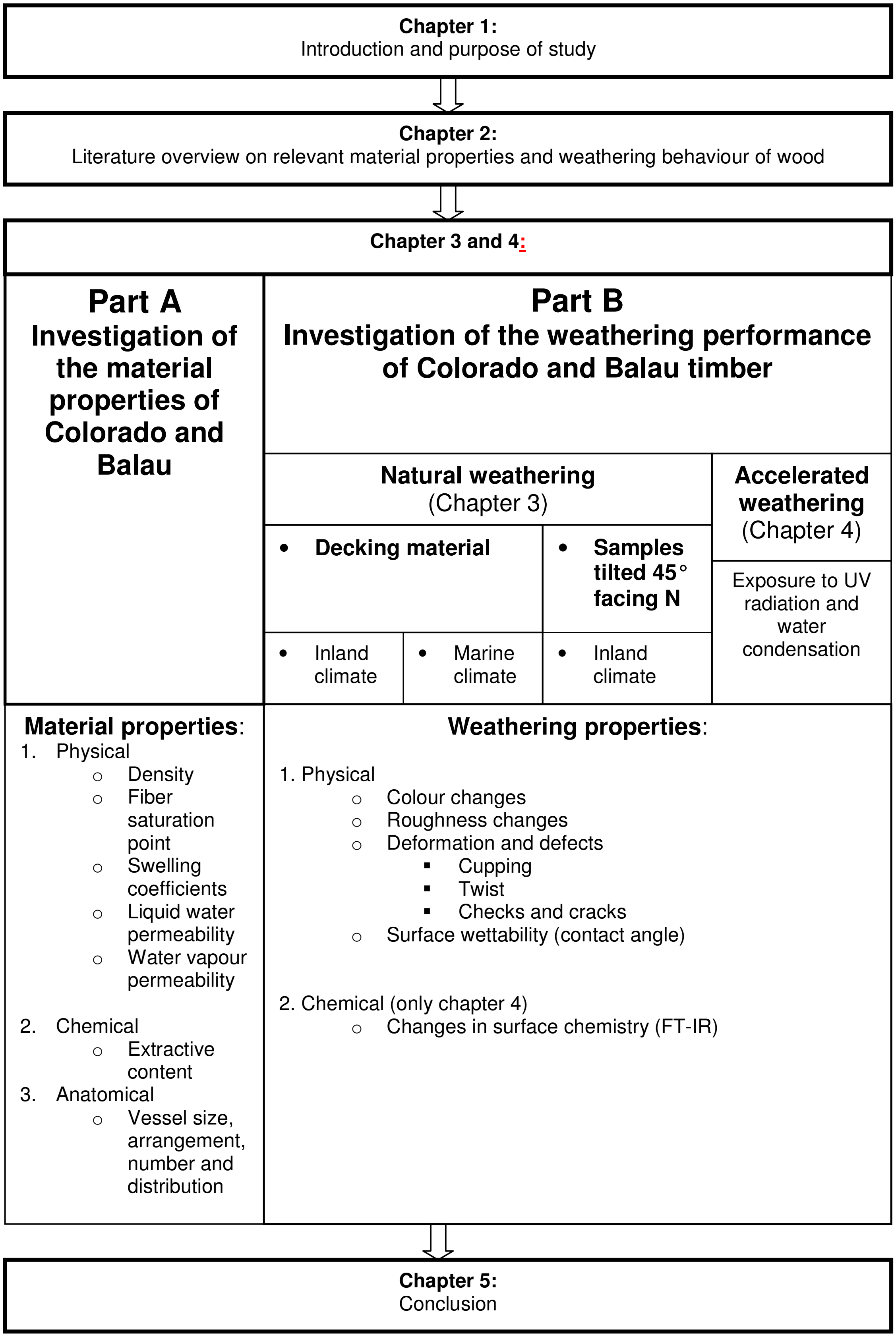

Figure 1.1: Diagram depicting the experimental layout and structure of this thesis.

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Chapter 2: Literature review

The aim of this chapter is to give a general overview on the wood properties and the behaviour of wood during its exposure to weathering, the environmental factors involved in the weathering process of wood and methods of studying the weathering behaviour of wood.

2.1 Wood properties and weathering behaviour

2.1.1 Anatomical structure of wood

Wood cell walls are multilayered and are surrounded by the middle lamella. These layers consist of the primary wall (P) and secondary wall. The secondary wall is further subdivided into three different layers namely the S1 outer layer, S2 middle layer and the S3 inner layer (Figure 2.1). These layers differ from one another with respect to their structure which is determined by the orientation (Figure 2.1), thickness, number of fibrils, as well as their chemical composition (Figure 2.2) (Feist and Hon, 1984). The fibril orientation differs between juvenile and mature wood and between normal and reaction wood. The fibril orientation and the chemical components (Table 2.1) greatly affect the way in which wood weathers (Williams, 2005). The main components of wood are grouped into a number of organic compounds: cellulose, hemicelluloses and lignin. Table 2.1 shows the percentage of each in hardwoods and softwoods.

Table 2.1: Chemical components of wood (Kollmann and Coté, 1968)

	Cellulose	Hemicelluloses *(% of dry weight)*	Lignin
Hardwood	40-44	15-35	18-25
Softwood	40-44	20-32	25-35

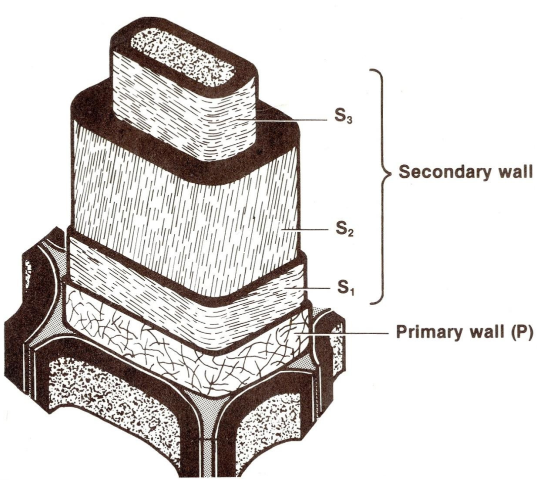

Figure 2.1: Layering of a mature softwood cell wall (Haygreen and Bowyer 1982)

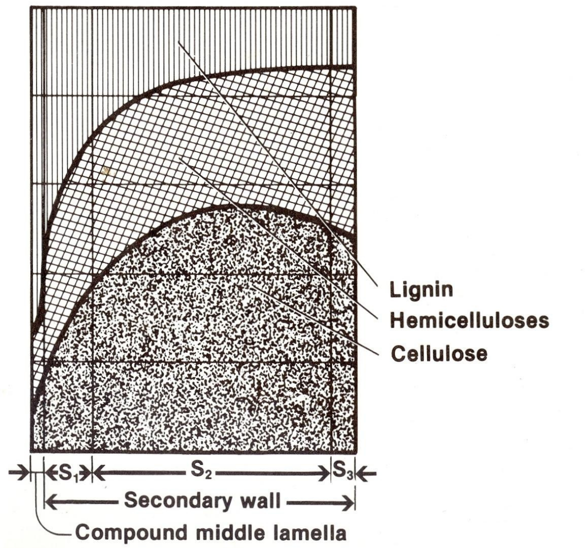

Figure 2.2: Diagram showing the relative amounts of cellulose, hemicelluloses and lignin across a cross section a softwood cell (Haygreen and Bowyer 1982)

Cellulose, a linear and highly crystalline glucan polymer, forms the largest part of the cell wall and is located mainly in the secondary wall. Native cellulose is polydisperse and has a DP of at least 9000 – 10000 and possibly as high as 15000 (Rypstra, 1995). **Hemicelluloses** are polysaccharides mostly formed from glucose, mannose, galactose, xylose, arabinose, 4-O-methylglucoronic acid and galacturonic acid residues. They generally have a lower DP than cellulose and some are branched. **Lignin**, a three-dimensional network of poly-phenols, is distributed throughout and between the cell walls. The relative concentration is the highest in the middle lamella region (Feist and Hon, 1984). These polymeric materials vary widely in their vulnerability to weathering. The variations in stability are caused primarily by differences in chemical structures, particularly in chromophoric functional groups. Metallic ions and other impurities which are introduced when treating wood may also promote deterioration by light (Feist and Hon, 1984).

Besides the polymeric materials there are also extractives in wood. Extraneous components consist of a variety of organic compounds such as fats, waxes, resins, terpenes, simple sugars, starch, pectins, glycosides, gums, simple and complex phenolics, alkaloids, proteins and essential oils. They contribute to the colour, odour and decay resistance of wood (Rypstra, 1995).

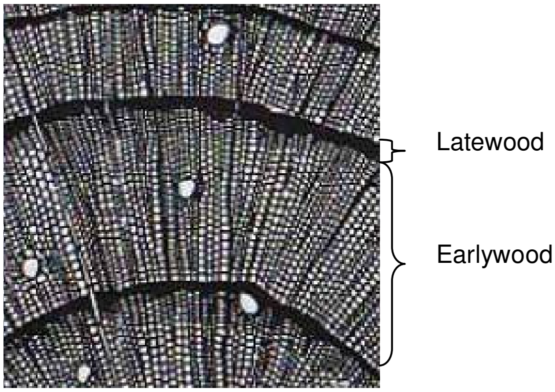

Figure 2.3: Cross-section of a young softwood stem showing the distinction between latewood and earlywood (Adapted from Fritts, 1979)

2.1.2 Earlywood and Latewood

Trees growing in temperate climates normally add one growth increment or ring to their diameter per year. In a summer rainfall area, growth proceeds rapidly in early spring (earlywood), slows down towards the end of summer (latewood) and ceases in the autumn. This kind of growth pattern results in variation of the wood being formed in various seasons of the year (Figure 2.3). Latewood is composed of relatively small diameter cells with thick walls and small lumens and, therefore, has a higher density than earlywood (Haygreen and Bowyer, 1982).

Williams *et al* (2001) studied the erosion rates of various species with regard to the effects of proportion of earlywood to latewood. They found that erosion rates of earlywood and latewood differ when exposed outdoors, with the less dense earlywood eroding significantly faster than dense latewood during the initial phase of weathering (Figure 2.4)

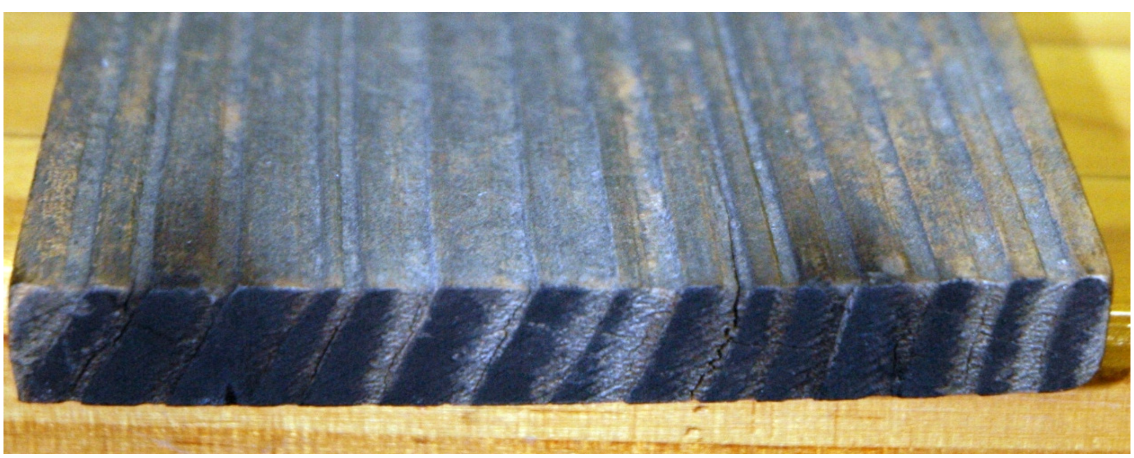

Figure 2.4: Radially sawn SA Pine; after weathering for approximately 3 years shows distinct variation in erosion rates between the earlywood and latewood regions.

2.1.3 Heartwood and Sapwood

Inspection of a tree's cross section often reveals a dark-colored center portion surrounded by a lighter coloured outer zone. The dark center area is heartwood and the lighter area is sapwood. Heartwood and sapwood can be easily distinguished in species such as Colorado (*E. camaldulensis and E. tereticornis*). Sapwood consists of living cells which conduct water and nutrients upward in a living tree. Heartwood no longer functions physiologically but provides mechanical support to the tree (Haygreen and Bowyer, 1982). Heartwood is produced as the individual cells die and are impregnated with extractives, pitch, oil and other extraneous materials. Older trees have a higher percentage of heartwood as compared to younger trees (Williams, 2005). During the early stage of weathering, it is the heartwood that rapidly loses its colour because of leaching of the water soluble extractives.

2.1.4 Juvenile wood

Juvenile wood is formed at every age. In the base of a tree it is formed during the first five to twenty years of a tree's growth. It differs from mature wood, and by most measures is lower in quality e.g. low modulus of rupture. Juvenile wood cells are shorter than mature wood cells (Williams, 2005) and in addition, the cell structure differs as well. There are relatively few latewood cells in the juvenile zone and a high proportion of cells have thin wall layers which results in low density and a corresponding low strength (Haygreen and Bowyer, 1982). Again comparing juvenile and mature wood, there appears to be a greater tendency for spiral grain in juvenile wood (Haygreen and Bowyer, 1982). The microfibril angles of the S2 layer in juvenile wood cells are larger than that of mature wood cells, which causes an increased amount of longitudinal shrinkage and a decrease in transversal shrinkage during weathering. This can cause severe warping, cross grain cracking and surface checking as wood weathers (Williams and Feist, 2001 and Williams, 2005).

2.1.5 Reaction wood

Reaction wood also plays a role in the performance of wood exposed to the weather. Reaction wood formed in softwoods differs from that in hardwoods. In softwoods, it is termed compression wood and in hardwoods, tension wood. Reaction wood properties differ from that of normal wood with many of its properties relating to those of juvenile wood (Haygreen and Bowyer, 1982). Reaction wood in species such as *E. camaldulensis* and *E. tereticornis* tends to produce fuzzy surfaces when sawn or planed. Tension wood also shows an increased amount of longitudinal shrinkage. Warp and twist can result when tension wood is present along only one side or edge of a board and will also lead to cross grain checking as wood weathers (Williams, 2005).

2.1.6 Texture

Texture in general, refers to the coarseness of the individual wood cells and is regularly used in reference to hardwoods. Hardwoods are composed of at least four major kinds of cells namely: fiber (relatively short, small diameter cells), vessel elements (large-diameter pores), longitudinal parenchyma and ray parenchyma. Softwoods, in contrast, consist mainly of longitudinal tracheids which constitute 90-95% of softwood xylem, and ray parenchyma (Haygreen and Bowyer, 1982). The size and arrangement of the vessels, as visible on the cross section, may outweigh the effect of density and grain pattern on weathering. Hardwoods with larger diameter vessels may erode more quickly at the vessels than the surrounding fibers (Williams, 2005).

2.1.7 Density

The density of wood is one of its most important physical characteristics. It is directly related to the porosity of wood. It varies considerably from species to species. The swelling and shrinking behaviour of wood is largely determined by its density; the higher the density the higher the swelling and, therefore, high-density woods tend to warp and check more than the low-density woods (Williams, 2005). The density of wood also determines, to certain extent, the depth by which UV light can penetrate wood. Generally, the higher the density, the smaller the depth of UV penetration, and also the rate of erosion (Feist and Hon, 1984; Moore and Owen, 2001).

2.1.8 Moisture content

Wood is a hygroscopic material because of its polymers containing hydroxyl and other oxygen-containing groups which have a strong affinity for water. This gives wood the ability to remove water vapour from the surrounding air until it is in moisture equilibrium with the air. If it has an open structure, i.e. high porosity, it can also rapidly absorb liquid water. The amount of water that wood can adsorb from the air depends on the wood species. The majority of wood species can adsorb roughly 30% of their ovendry mass in water. When a cell wall of wood reaches its limit to the amount of water that it can adsorb, it is at fiber saturation point (FSP). The FSP of various wood species differs widely from the typical value, i.e. such as Rosewood (15% MC) compared to Ash (24%) and Douglas fir (26%) (Haygreen and Bowyer, 1982). One cause of variation in the FSP is the presence of extractives. Generally, species high in extractives have a relatively low FSP. This could be ascribed to extractives occupying hydroxyl sites in the cell wall which would otherwise attract water (Haygreen and Bowyer, 1982).

Moisture content of interior wood products is primarily controlled by the relative humidity (RH) and temperature of the surrounding air. As the RH changes wood will either loose (desorb) or gain (adsorb) water to reach an equilibrium moisture content (EMC). However, EMC is rarely achieved because of the constant changes in the atmospheric RH and temperature. When wood is exposed outdoors to the weather, the changes in RH can become radical. In addition, wood is subjected to liquid water in the form of rain and dew. Therefore, checking often occurs on decking boards; the fully exposed surface is much drier than the rest of the board. The sudden decrease in RH and associated lower temperatures cause shrinkage of the top of the board which goes beyond the elastic limit of the wood at the surface and checks form parallel to the grain (Williams and Feist, 2001). For this reason wood intended for exterior use should by protected with a finish. However, application of finish to wood does not decrease the EMC of wood but merely decreases the rate of water absorption when exposed to liquid water (e.g. rain, dew and snow). Chemical modification also decreases the FSP of wood, thus decreasing the maximum amount of dimensional changes, and also decreasing the amount of stress the wood would have encountered otherwise.

2.1.9 Grain orientation

Wood is an anisotropic material because of its different properties along its three main anatomical axes. For this reason, several properties of tangentially and radially cut boards differ. These include appearance, strength properties, permeability, dimensional stability, potential grain raising and grain separation, and ability to hold film-forming finishes (Williams and Feist, 2001). The ability of tangentially sawn boards to hold film forming finishes, or the lack thereof, can be attributed to the excessive swelling by the exposed latewood rings, which in effect increases the erosion rate of the finishing film (Figure 2.5). The different sawing patterns generating anatomical surfaces of different sizes are depicted in Figure 2.6.

Figure 2.5: Image of a tangentially cut board, containing a film forming finish which was weathered for 1 year.

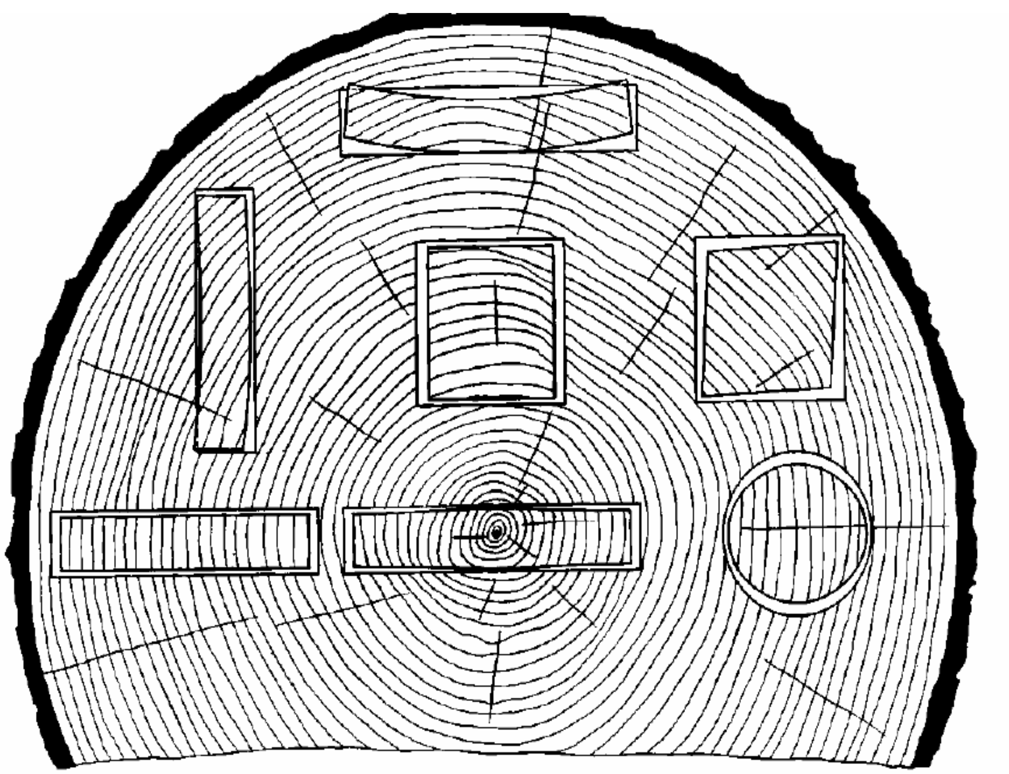

Figure 2.6: Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial (Wood Handbook - Forest Products Laboratory, 1999).

The swelling coefficient of tangentially sawn timber is usually about twice that of radially sawn timber (Williams and Feist, 2001); tangentially sawn timber can thus be expected to swell more across its face than radially sawn timber. Furthermore, tangentially sawn boards tend to swell and shrink unevenly and stresses are set up during the drying process. Because of this, boards start to cup and form checks and ruptures along the grain. The amount of cupping increases with wider boards (Williams, 2005).

Another problem with tangentially cut timber is the increased potential for grain raising and grain separation during exposure. This normally occurs when the harder and denser latewood portion of each annual growth ring is projected above the level of the softer earlywood (Williams and Feist, 2001). The bark side of tangentially sawn products weathers differently than the pith side. Raised or separated grain is much more pronounced on the pith side than on the bark side of tangentially sawn timber, and it is advantageous to orientate the timber, using the bark side as the fully exposed surface (Williams and Feist, 2001).

2.2 Environmental Factors Involved in Weathering

Numerous schemes have been designed to describe and summarize the effects of weathering on wood exposed outdoors. In 1988, Feist developed a scheme (Figure 2.7), where he described the sequential events during natural weathering.

Wood exposed outdoors is subjected to the following weathering factors: sunlight (solar radiation), water (rain, dew, snow, etc.) and gasses such as oxygen. Photodegradation initiates the surface weathering process while water simultaneously gives rise to warping, checking and splitting of the wood material. This leads to micro-structural changes including removal of the middle lamella, destruction of bordered pits and loss of adhesion between cell wall layers. Furthermore, physical changes occur such as surface roughening and preferential removal of lower density tissue. The loosened wood fragments are then washed away by rain, revealing fresh wood tissue on the exposed surface, and the weathering sequence continues.

2.2.1 Moisture

Water is the most erosive force on our planet, sculpting mountains and forming valleys as it finds its way from the clouds back to the ocean. Water's effect on wood has been recognized as one of the principle causes of weathering. It is the frequent exposure of wood surfaces to rapid changes in moisture content below fiber saturation point (FSP) and associated dimensional changes that causes wood to undergo degradation.

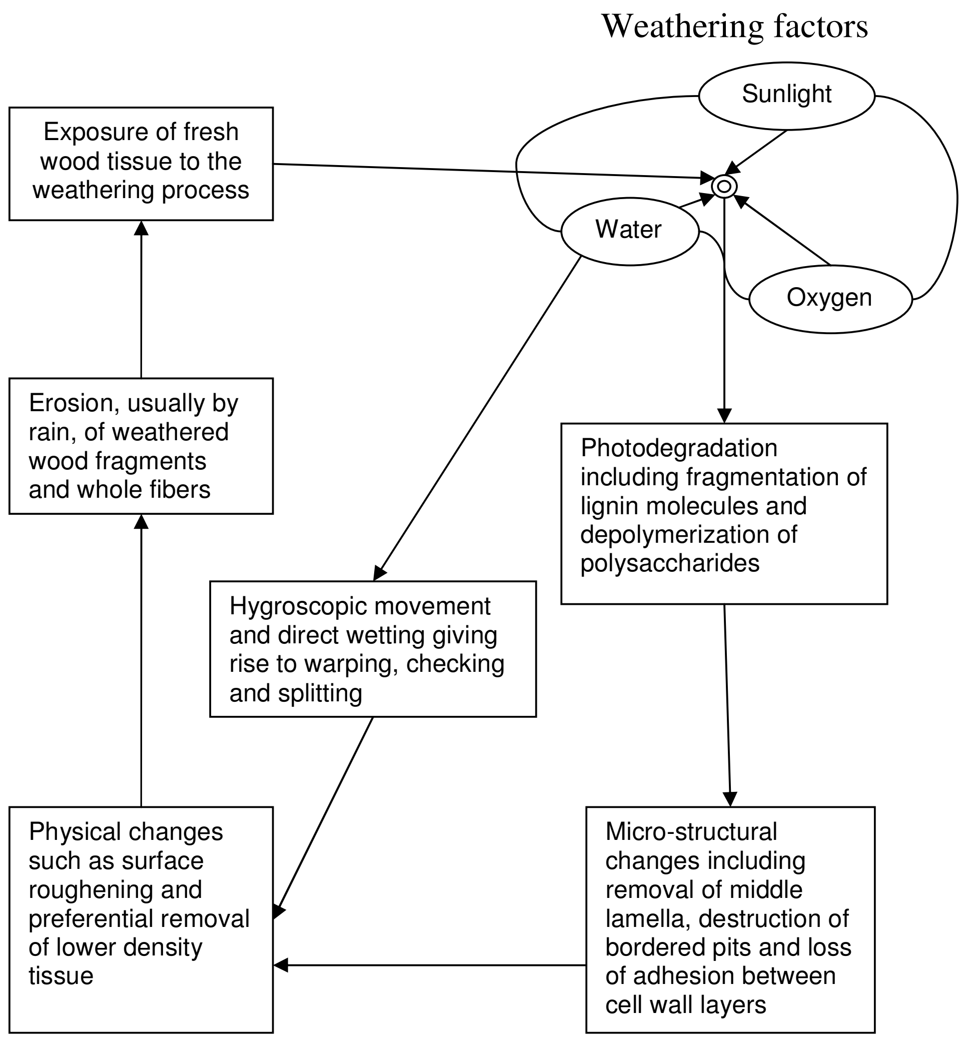

Figure 2.7: A schematic representation of the sequential events during natural weathering (Feist, 1988)

Moisture in the form of rain or dew that falls and precipitates on unprotected wood surfaces is rapidly absorbed by capillary action, followed by adsorption within the wood cell walls until they reach their FSP. Once the wood cell walls are saturated, water is absorbed and kept in liquid form within the cell lumens (Feist and Hon, 1984). Depending on the moisture content (MC) of wood and the relative humidity (RH) of its surroundings, wood will either loose or directly adsorb water vapour from the air to achieve equilibrium moisture content (EMC). It is this change in MC, below fiber saturation point (FSP) which causes wood to swell and shrink, and during this occurrence stresses are set up in the wood due to moisture gradients between the surface and the interior. These induced stresses become greater as the moisture gradient increases and are usually largest near the wood surfaces (Feist, 1983, Feist and Hon, 1984, and Feist, 1988). Unbalanced stresses may result in quality defects such as warping and surface checking, the likelihood of these occurrences increasing with the presence of natural “defects” such as spiral grain, juvenile wood and reaction wood.

2.2.2 Light

Sunlight is the main factor that causes the greatest change in the surface properties of wood during outdoor exposure (Fengel and Wegener, 1984; Tolvaj and Mitsui, 2005). The ultra violet (UV) and visible solar radiation that reaches the earth’s surface used to be limited to the range between 295-800nm (Williams, 2005), but because of the thinning of earth’s ozone layer, nowadays more ultraviolet (UV) radiation reaches the earth’s surface than before. Therefore, the UV B wavelength region (280–315 nm) has to be taken into consideration (Tolvaj and Mitsui, 2005). The radiation from 800 to about 3000nm represents infrared radiation. The radiation from 295-3000nm comprises distinct ranges that affect weathering: UV radiation, visible light and infrared radiation (IR) (Fengel and Wegener, 1984 and Williams, 2005) (see Figure 2.8).

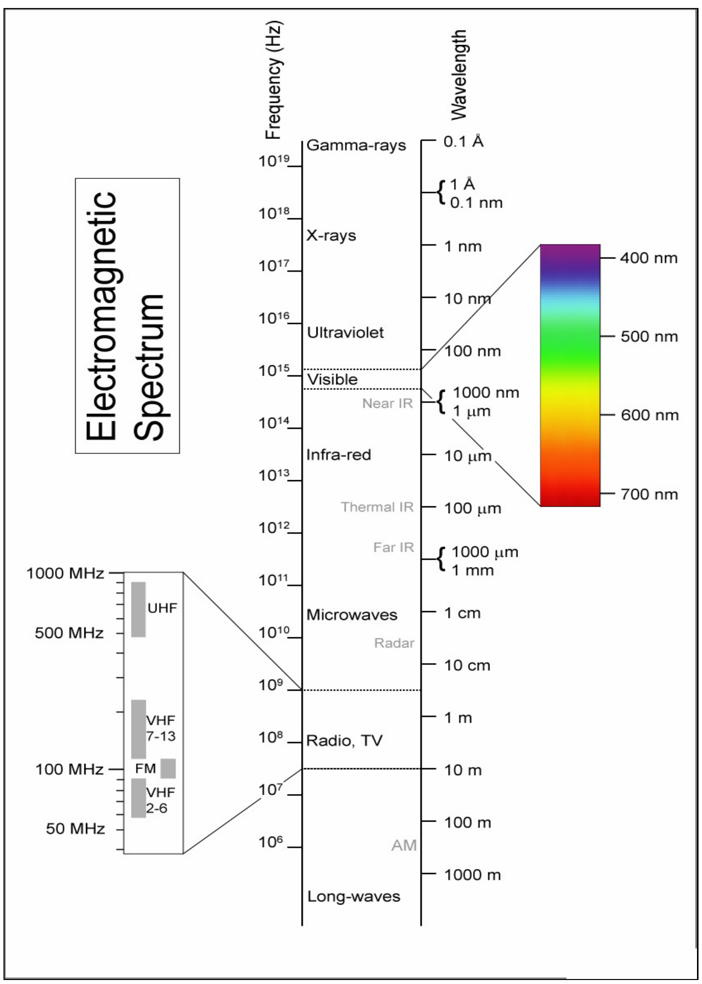

Figure 2.8: Electromagnetic spectrum (Louis E. Keiner – Coastal Carolina University, unknown date)

The intensity of light transmitted through wood decreases exponentially with depth as predicted by the Beer-Lambert equation. Browne and Simonson (1957) determined that short wave, high energy UV light usually penetrates no deeper than 75 µm, visible light only penetrates as deep as 200 µm and infrared rays can penetrate up to 1.5mm into the surface (Fengel and Wegener, 1984). Beyond the zone immediately affected by light, the chemical and physical properties of weathered wood are believed to be largely unchanged (Kataoka *et al*, 2007), which explains why the weathering of wood exposed outdoors is only a surface phenomenon.

Wood's ability to absorb light can be attributed to a wide range of chromophoric groups present in the molecular structure of mainly the polymeric components of wood. The polysaccharides and polyphenolic lignin exhibit varying degrees of sensitivity towards light; the effect is mainly determined by the intensity and energy distribution of light (Feist and Hon, 1984). Absorption of UV light by wood results in the generation of free radicals or singlet oxygen at the chromophoric sites which in turn initiate a series of free radical and oxidative photolytic degradation reactions. For this reason, the concentration, location and nature of chromophores are highly significant in determining the rate of photo-degradation of wood (Feist and Hon, 1984).

Very little UV radiation can penetrate common window glass. Therefore, wood does not undergo UV-catalyzed weathering indoors, although some colour changes can be caused by visible light (Feist and Hon, 1984 and Williams, 2005).

Scientific investigation of the photo-degradation of wood during outdoor exposure is difficult because weather conditions are not repeatable. Therefore, the light-induced degradation of wood is usually investigated under artificial conditions. The artificial light source most frequently used in QUV devices are UVB (medium wavelength UV) and UVA (longer wavelength UV similar to black light).

When conducting an outdoor weathering study it is important to consider the effect that sample orientation has on the amount of solar radiation. Wood samples are normally exposed facing an equatorial direction, tilted either at 45 degrees, or lying in a horizontal manner. In 1995 Rypstra reported the effects that tilt has on solar radiation in Stellenbosch, South Africa. He reported that samples orientated horizontally receive 4.4% less radiation per year than samples tilted at 45 degrees (Figure 2.9) (Rypstra, 1995).

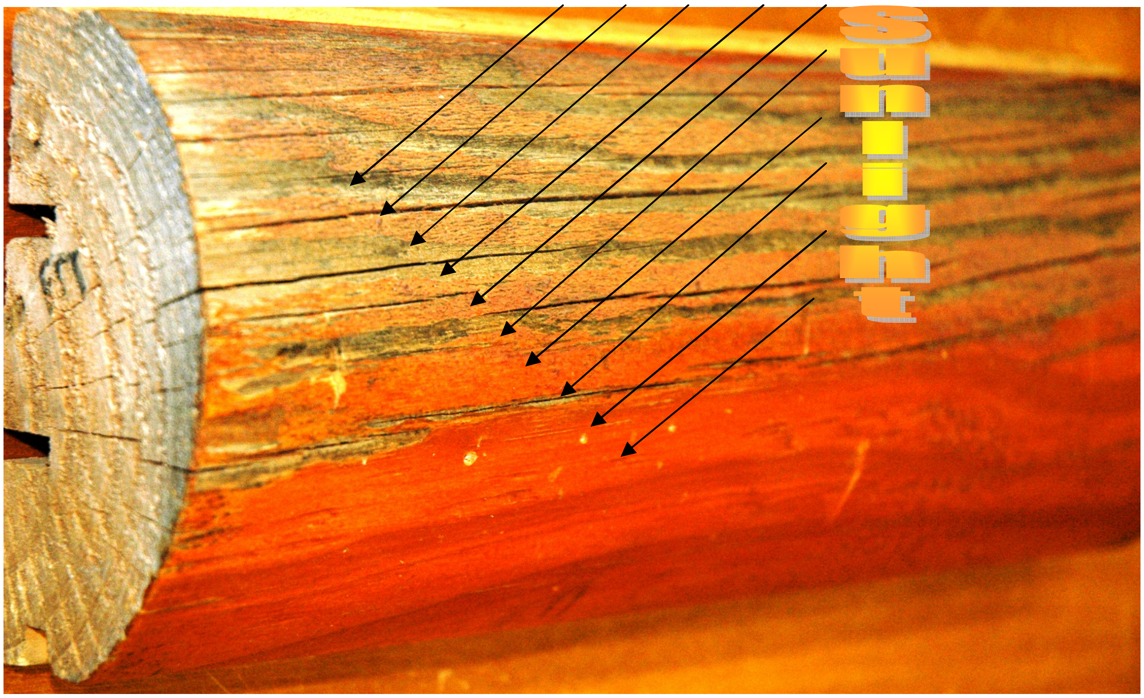

Figure 2.9: Image depicting the effect that sample orientation plays on the amount of degradation during weathering. These effects are visible on this board with the top of the board having been exposed to more solar radiation than the bottom half.

It is important to note that sunlight and water tend to operate at different times. The action of the combined elements can follow different degradation paths, with irradiation accelerating the effect of water or the converse (Feist and Hon, 1984).

2.2.3 Other factors

Even though solar radiation and moisture are the major attributes of weathering, they are accompanied by other weathering factors such as heat, abrasion or mechanical action by wind blown particles, freezing and acid deposition. An increase in temperature causes the acceleration of photochemical and oxidative reactions, and when temperatures decrease to below zero degrees Celsius, water in wood freezes which can then lead to wood checking (Feist and Hon, 1984).

An increasing awareness about the weathering effect of acid rain has developed over the last few decades. It is the increasing amount of sulfur dioxide in the surrounding air that causes acid rain which in effect plays a significant role in the weathering of wood. Acid rain concentrations have been reported in the range of pH 2.0. The effects of acid rain on painted materials are clearly visible in the degradation of the coating and substrate (Feist, 1988).

Solid particles such as sand in combination with wind can have a sandblasting effect on wood, leading to an increased rate of surface degradation and removal of wood. Smaller particles can also become lodged in surface checks and, through swelling and shrinking, weaken fibers in contact with particles (Feist and Hon, 1984).

Products such as decking boards are often used to build features such as marine walks. If wood is exposed to such marine climates, salt deposition is an important weathering factor to consider.

2.3 Biological Degradation

Weathering is not to be confused with decay which results from organisms such as fungi and bacteria performing in the presence of excess moisture and air for an extended period of time (Feist and Hon, 1984). However, it is important to consider the effect brought on by biological attack when studying the deterioration of wood surfaces.

Under circumstances suitable for the development of decay, wood can deteriorate faster and the outcome is far different from that observed for normal outdoor weathering (Figure 2.10) (Feist and Hon, 1984). Under artificial weathering conditions wood turns white due to the predominance of surface cellulose (Xie *et al*, 2008; Ghosh *et al*, 2009). Naturally weathered wood surfaces, however, take on a grey hue, which is practically always due to fungal growth on the surface of the wood (Feist and Hon, 1984). These fungi are able to metabolize photo-

Figure 2.10: Image depicting the effect of brown rot in the middle of a surface coated pine board. The degradation is much different from that observed for normal weathering.

degraded lignin, holocellulose and derived sugars (Ghosh *et al*, 2009, Feist and Hon, 1984, Williams and Feist, 2001 and Xie *et al*, 2008). The most important fungal strain within this specific ecological niche are the ascomycetes *Aureobasidium pullulans* and *Sclerophoma pithyophila*. *Hormonema dematiodes* is another species responsible for blue staining of wood (Xie *et al*, 2008 and Ghosh *et al*, 2009). *Aureobasidium pullulans,* more commonly referred to as mildew, grows on finished as well as unfinished or untreated softwood and hardwood surfaces (Ghosh *et al*, 2009). Mildew does not cause erosion of the surface but it may cause initial graying or an unsightly dark gray and blotchy appearance (Williams and Feist, 2001). Discolouration of wood by mildew is more general than commonly believed (Feist and Hon, 1984) and the surface protection of wood is, therefore, of significant economic importance.

2.4. Property changes during weathering

2.4.1 Chemical changes

Polymers in wood vary widely in susceptibility to photo-degradation because of the differences in their chemical structure, especially chromophoric functional groups (Williams, 2005). The photo-degradation process of wood shows that by absorption of radiation energy, energy is transferred and localized in molecules resulting in splitting reactions such as depolymerization, dehydrogenation and dehydroxymethylation. Degradation of wood surfaces begins at relatively low irradiation intensities with an attack on the middle lamella. Higher intensities also degrade the secondary cell walls (Fengel and Wegener, 1984).

The UV-degradation process is initiated by the formation of free radicals and apparently begins with oxidation of phenolic hydroxyl groups. This process leads to a decrease in methoxyl and lignin content and an increase in acidity and carboxyl concentration (Feist and Hon, 1984). These photochemical changes are largely influenced by moisture and, to a lesser extent, by heat (Fengel and Wegener, 1984; Feist and Hon, 1984). The decomposed products on the surface of weathered wood are mainly organic acids, vanillin, syringaldehyde and higher molecular weight compounds which are all leachable (Feist and Hon, 1984). Most of the decomposed lignin products are washed out by water and the remaining surface fibers are high in cellulose, resulting in the whitish to gray appearance on weathered surfaces (Fengel and Wegener, 1984).

2.4.1.1 Reactions in Cellulose and Hemicelluloses

Cellulose is relatively little affected by degradation factors except for oxidation in the top surface layer. Wood surfaces are rich in cellulose after weathering (Feist and Hon, 1984). The degradation of cellulose by UV light is indicated by a loss of mass, a reduction of α-cellulose content and in the degree of polymerization (Fengel and Wegener, 1984). The loss of mass versus irradiation time is a linear function with the gradient increasing with elevating temperatures (Fengel and Wegener, 1984).

The photo-degradation mechanism of cellulose and hemicelluloses depends on the intensity and energy distribution of the light (Feist and Hon, 1984). Shorter wave lengths cause a hydrolytic chain cleavage which produces aldehyde groups, whereas longer wavelengths cause degradation in the presence of oxygen to produce peroxide groups (Fengel and Wegener, 1984). For the photolytic degradation of cellulose the cleavage of carbon-oxygen or carbon-carbon bonds will require an energy level corresponding to wavelengths of 340nm or shorter. Among the volatile degradation products of cellulose are acetaldehyde, propionaldehyde, methyl formiate, acetone, methanol, ethanol, methane and ethane (Fengel and Wegener, 1984).

It has been suggested that the absorbing chromophores are the hydroxyl, carbonyl, carboxyl or the acetyl groups at the C_1 position of non-reducing glucose units (Fengel and Wegener, 1984).

2.4.1.2 Reactions in Lignin

Lignin is a good UV absorber and is capable of autoxidation. For these reasons, lignin retards the photolytic degradation of cellulose (Fengel and Wegener, 1984). Lignin has an absorption peak at 280 nm with a tail extending to over 400 nm (Figure 2.11) (Feist and Hon, 1984). The absorption occurs at chromophoric structural elements within the molecular network of lignin (Fengel and Wegener, 1984). Hon and Glasser (1979) classified the potential chromophoric groups as follows:

- Chromophoric functional groups: phenolic hydroxyl groups, double bonds, carbonyl groups, etc.
- Chromophoric systems: quinones, quinone methides, biphenyls, etc.
- Leucochromophoric systems: methylenequinones, phenanthrenequinones, etc.
- Intermediates: free radicals
- Complexes: chelate structures with metal ions

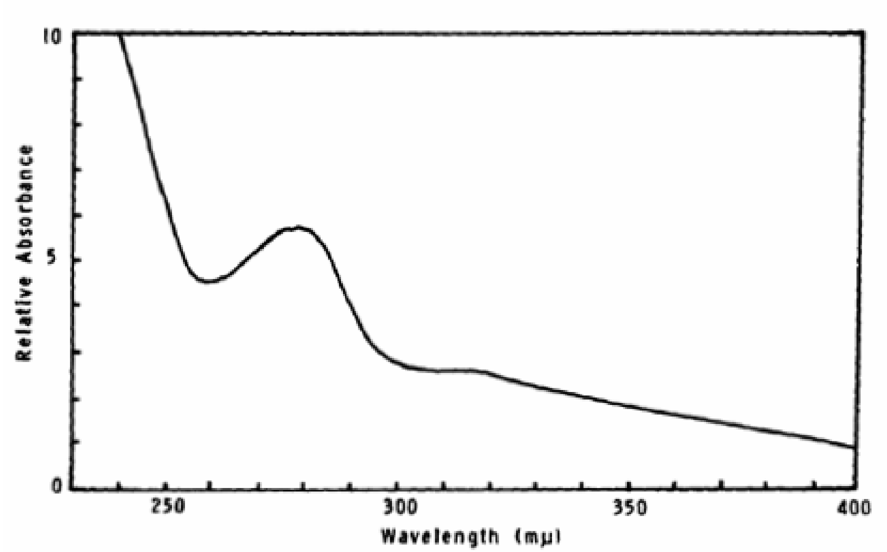

Figure 2.11: UV absorption curve for lignin (Feist and Hon 1984)

Studies on the formation of photo-induced free radicals using model compounds have elicited several facts. Hon (1981) deduced the following:

1. Lignin is easily degraded by light of wavelength shorter than 350nm. Significant colour buildup or formation of chromophoric groups is recognized.
2. Light with a wavelength longer than 350nm has no effect on lignin, but photo-bleaching or whitening of lignin can be observed when it is exposed to light longer than 400nm.
3. Reduction of methoxy content of lignin occurs.
4. Phenoxy radicals are produced readily from phenolic hydroxyl groups.
5. Carbon–carbon bonds adjacent to α-carbonyl groups are photo-dissociated via the Norrish Type I reaction.
6. The Norrish Type I reaction does not occur efficiently in those compounds with ether bonds adjacent to the α-carbonyl group. Photo-dissociation takes place at the ether bond.
7. Compounds bearing benzoyl alcohol groups are not susceptible to photo-dissociation except when photo-sensitizers are present.
8. In addition, Feist and Hon (1984) reported that α-carbonyl groups function as photo-sensitizers in the photo-degradation of lignin.

The rate of radical formation is further influenced by the presence of moisture. Studies have shown that the rate increases from 0 - 6.3% MC, and then decreases with further increases in MC (Rypstra, 1995).

2.4.2 Physical changes

2.4.2.1 Colour changes

Discolouration of wood exposed to the outdoors is initiated rapidly (Feist, 1983, Feist, 1998). The rate and amount of discolouration is dependent on wood species (Schnabel *et al*, 2009). In the early stages of weathering, dark woods tend to become light and light woods, dark. Woods rich in extractives may become bleached before browning is visible. Eventually all wood surfaces become gray if fully exposed to sun and rain (Feist, 1983, Feist and Hon, 1984).

Discolouration of wood is mainly due to UV light (Temiz *et al*, 2005) and to a lesser extent by the visible and infrared light components of sunlight (Schnabel *et al*, 2009). Light acts in combination with moisture, heat, and oxidative agents to depolymerize lignin and cellulose in the wood cell wall (Temiz *et al*, 2005).

Photo-degradation leads largely to the decomposition of lignin. This is due to lignin's capability of absorbing UV light in the range of 300–400 nm (Fabiyi *et al*, 2008 and Temiz *et al*, 2005). Several studies have shown that de-aromatization, a decrease in hydroxyl groups, and an increase in carbonyl groups of lignin were the spectral changes most closely associated with surface discolouration (Fengel and Wegener, 1984, Dirckx *et al*, 1992, Temiz *et al*, 2007, Fabiyi *et al*, 2008). Nevertheless cellulose also yellows under irradiation. The yellowing is attributed to the production of oxygen-containing groups such as carbonyl, carboxyl and hydroperoxide groups (Fengel and Wegener, 1984).

As rain leaches the brown decomposition products of lignin, a silver-gray layer consisting of a disorderly arrangement of loosely matted fibers develops above the brown layer. The gray layer is composed chiefly of the more leach-resistant parts of the partially degraded wood cellulose (Feist, 1983, Feist and Hon, 1984, Feist, 1988). Studies have shown that naturally weathered wood surfaces become gray mostly because of fungal growth. However, Futo (1976) concluded that wood could turn grey without the influence of mould-fungi (Schnabel *et al*, 2009).

2.4.2.2 Surface roughening

Along with chemical and colour changes occurring on wood surfaces exposed outdoors, mechanical damage also occurs. Deterioration of wood surfaces due to the combined effect of water and light leads to the formation of macroscopic to microscopic intercellular and intracellular cracks or checks (Feist, 1983 and Williams, 2005). As weathering continues and surface fibers swell and shrink, the strength of cell wall bonds is lost near the surface. Further erosion occurs as rainwater washes out degraded portions. All these effects lead to the roughening of the surface of wood (Feist and Hon, 1984).

2.4.2.3 Surface wettability

Wettability of a solid surface by a liquid is usually expressed as the contact angle between the solid and the liquid, a smaller contact angle signifying greater wettability. In a study by Kalnins and Feist (1993) on the water repellency of western red cedar surfaces, they found that contact angles reduced from 77° to 55° after four weeks of outdoor weathering. Increased wettability of wood surfaces during weathering is suggested as a contributing factor to the deterioration of wood surfaces. Water readily wets such a surface and is quickly absorbed into the wood.

As mentioned previously, weathering causes gradual deterioration of wood surfaces as wood is converted to volatile and water-soluble degradation products. Lignin and extractives, which are suggested to be the hydrophobic components in wood, are quickly eroded and leached out, leaving the surface with a cellulose-rich layer. Cellulose is a hydrophilic material and with its increased exposure on the surface, leads to an increase in wettability (Kalnins and Feist, 1993).

2.4.2.4 Other physical changes

The physical loss of wood substance from the wood surfaces during weathering depends on the species of wood, density, amount of irradiation, rain action, wind, degree of exposure and, generally, climate (Feist, 1983 and Feist, 1990). Softwoods such as pines generally erode faster than hardwoods such as *E. camaldulensis* and *E. tereticornis.* Studies on the rate of outdoor weathering have indicated that the dense hardwoods erode at a similar rate to that observed for the latewood of softwood species. Hardwoods on average erode at a rate of 3mm/century compared to 6mm for softwoods (Feist and Hon, 1984).

In addition to the slow erosion of wood surfaces, surfaces also develop checks and raised grain. This degradation is caused primarily by stresses which are set up due to MC fluctuations. Checks commonly form at the earlywood/latewood interface. On tangentially cut surfaces, checking occurs predominately on the bark side, however, the raised grain on the pith side can be a more severe problem (Williams, 2005).

Because of wood's anisotropic characteristics, it commonly does not swell and shrink uniformly. This leads to warping of boards, the amount of warping directly related to wood density. Cupping is probably the most common form of warp. Cupping is the distortion of a board that causes a deviation from flatness across the width of the piece. Wide boards cup more than narrow boards (Williams and Feist, 2001 and Williams, 2005). Also, stresses are set up through the alternate shrinking and swelling of wood, which may lead to the development of severe checks or small ruptures along the grain of a board.

2.4.3 Anatomical changes

Microscopic changes accompany the gross physical change of wood during weathering. Lignin is the most photo-sensitive component in wood and because the lignin content is relatively higher in the middle lamella than in the cell wall, the photo-degradation occurs preferentially in this area of the wood surface. Williams (2005) confirmed the latter using micrographs showing the deterioration of the middle lamella in the early stages of weathering.

Through a series of studies, Miniutti (1973) determined changes in softwood surfaces after outdoor exposure. The first sign of deterioration was enlargement of apertures of bordered pits in radial walls of earlywood tracheids. Next, micro-checks occurred. He also showed that these micro-checks enlarge principally as a result of contraction in cell walls. During weathering, the leaching and plasticizing effects of water apparently facilitate enlargement of the micro-checks (Miniutti, 1973).

2.5. Methods of Protecting Wood against Weathering

Many finishing systems have been developed for exterior conditions. These finishes serve to retard the deterioration rate of wood surfaces exposed to UV light and water and help maintain appearance. Protection against these factors is highly important to increase the service life of wood, unfortunately most wood finishes may only last 1-2 years.

The durability of outdoor finishes primarily depends on the wood substrate (Feist, 1988). According to Feist and Hon (1984), important wood properties for finishing are moisture content, density, texture, resin and oil content, width and orientation of growth rings, and defects such as knots, reaction wood and decayed wood. Other contributing factors are the nature and quality of the finish used, application techniques, pretreatment, time between refinishing, extent to which the surfaces are sheltered from the weather and climatic and local weather conditions (Feist and Hon, 1984).

Different finishes give varying degrees of protection from the weather. Usually an increase in pigment concentration offers a higher level of protection i.e. paints provides the highest protection and clear varnish the least (Feist, 1988).

There are two basic types of finishes used for wood protection namely film-forming (those that form a film (layer) or coating on the wood surface) and penetrating finishes (those that penetrate the wood surface and leave no distinct layer or coating).

2.5.1 Film-Forming Finishes

2.5.1.1 Paints

Paint, being pigment rich, provides the highest degree of protection and essentially eliminates photo-degradation of the wood surface. A non-porous paint film retards penetration of moisture and thus reduces discolouration by wood extractives, paint peeling and checking and warping of wood (Feist, 1988). Paint, however, is not a preservative and will not prevent decay if conditions favourable for fungal growth are created. The durability of paint is affected by variables of the wood substrate such as moisture and type of paint (Feist and Hon, 1984).

2.5.1.2 Varnishes

Clear varnishes offer the most natural appearance for wood. Unfortunately, clear varnish finishes exposed to harsh exterior conditions require regular maintenance to maintain a reasonable appearance. The addition of colourless UV light absorbers to clear finishes sometimes helps to retain the natural colour and original surface structure of wood (Feist, 1988). Even with the application of durable, clear, synthetic resin varnishes, the surface protection is still limited because UV light penetrates the clear varnish film and progressively deteriorates the wood underneath. Ultimately the varnish begins to flake and crack off, taking with it loosened wood fibers (Feist, 1988). Semi-transparent varnishes are not as esthetically pleasing as clear varnishes but offer better protection against UV penetration. Besides the retarding effect on UV light penetration, a non-porous varnish film also retards penetration of moisture and thus reduces discolouration by wood extractives, paint peeling and checking as well as warping of wood (Feist, 1988).

2.5.2 Penetrating Finishes

2.5.2.1 Oils

Traditional oils such as linseed, tung and oiticica have been widely used as penetrating wood finishes. These oils unfortunately have a low resistance to UV light and water and do not tend to last longer than a year. Therefore, penetrating oils find limited use as outdoor finishes (Feist and Hon, 1984).

2.5.2.2 Water Repellents

Water, as previously discussed, plays a major role in the deterioration of wood surfaces. In the absence of water repellents, water can readily penetrate wood through open cracks and defects in coated surfaces.

Water repellent preservatives generally comprise a resin (10-20%), solvent, wax (as the water repellent) and preservatives (fungicide) (Feist, 1988). They give wood the ability to repel water thus denying stain and decay fungi the moisture they need to live. They also reduce water damage to wood and help protect applied paint from the blistering, peeling and cracking which often occurs when water excessively penetrates wood (Feist, 1988).

2.5.2.3 Stains

When pigments are added to water-repellent solutions (WRP) or to similar penetrating transparent wood finishes, the mixture is classified as a pigmented, semi-transparent, penetrating stain (Feist and Hon, 1984). The pigment provides colour and greatly increases the durability of the finish because UV light is partially blocked. They do not form a distinct, continuous layer, therefore, they will not blister or peel, even if excessive moisture enters the wood. They are especially useful in applications on tangentially sawn, weathered wood surfaces where paint does not perform well (Feist and Hon, 1984).

According to Feist and Hon (1984), the durability of any stain system is a function of pigment and resin content, preservative, water repellent and the quantity of material (film thickness) applied to the wood surface (Feist and Hon, 1984).

2.5.2.4 Preservatives

According to Feist and Hon (1984) the three main types of preservative are preservative oils (coal-tar creosote), organic solvent solutions and waterborne salts. During the last couple of years however, the use of pentachlorophenol and CCA have mainly been phased out due to an increased environmental awareness. In general, the higher the preservative content of pressure-treated wood, the greater resistance to weathering and the greater surface durability. The chromium-containing preservatives also protect against UV light degradation.

2.5.2.5 Chemical modification

Several studies have shown that it is possible to improve the performance of clear finishes on wood by photo-stabilizing the wood before application of the finish (Feist and Hon, 1984, Evans *et al*, 2002, Ghosh *et al*, 2009). The following chemicals are often used for this purpose: anhydrides, acid chlorides, carboxylic acids, isocyanates, aldehydes, alkyl chlorides, lactones, nitrites and epoxides (Evans *et al*, 2002). These chemicals are capable of forming covalent linkages with the hydroxyl groups of lignin and cellulose and, in certain cases, also bulking the wood cell wall with reacted chemical (Evans *et al*, 2002). These chemical modifications decrease the interaction of water with the polymeric constituents of wood and thus enhance the dimensional stability and decay resistance of wood.

Studies by Hon and Feist (1984) showed that certain inorganic chemicals, when applied as dilute aqueous solutions to wood surfaces, provide the following benefits:

1. Retard degradation of wood surfaces by UV irradiation.
2. Improve durability of UV-light-transparent polymer coatings.
3. Improve durability of paints and stains.
4. Provide a degree of dimensional stability to wood surfaces.
5. Provide fungal resistance to wood surfaces and to coatings on the surface.
6. Serve as natural finishes for wood and obviate further treatment.
7. Fix water-soluble extractives in certain wood species and thereby minimize subsequent staining of applied latex paints.

2.6. Accelerated (Artificial) Weathering

The effect of weathering on wood or surface treatments can be studied using either natural outdoor exposure tests or accelerated laboratory tests. These two major test types are not the same, however, many researchers have found good correlations between erosion rates from natural and accelerated weathering (Feist and Mraz, 1978, Anderson *et al*, 1990, Arnold *et al*, 1991, Tolvaj and Mitsui, 2005). Accelerated tests are conducted with controlled artificial light and water sources, whereas natural weathering is performed on outdoor exposure racks or in field trials with real sunlight and natural moisture conditions. However, accelerated weathering tests do not make provision for the effect of biological degradation, acid deposition and the effects of soil and contaminants (Crewdson, 2008). The main problem with natural weathering tests are that the weather conditions are not repeatable and, therefore, accelerated weathering is more useful when studying the individual or combined effects of water and UV radiation on wood surfaces.

According to Feist and Hon (1984), microscopic changes on wood surfaces during accelerated weathering are closely related to those observed during natural outdoor weathering. These changes include the formation of longitudinal checks between adjacent walls of neighbouring cells that apparently occur in or close to the middle lamella, longitudinal checks in cell walls, and diagonal checks through pits that probably follow the fibril angle of the S2 layer (Feist and Hon, 1984).

2.6.1 Artificial Weathering Apparatuses

2.6.1.1 Water application

The Swiss Federal Laboratories for Materials Testing and Research (EMPA) compared the effects of water-condensation to water-spray systems on wood surface degradation (Arnold *et al*, 1991). Their initial results with water condensation did not show the typical surface erosion of unprotected wood usually observed with carbon arc or xenon arc accelerated-weathering chambers fitted with water-spray systems. The main result observed in the EMPA studies was the usual yellow to brown discolouration of the wood surface which is caused by UV light degradation. They concluded that water-spray systems are most suited for obtaining characteristic wood weathering degradation and significant wood surface erosion as seen with natural weathering, whereas water condensation systems have a smaller effect on wood erosion and roughening but show the same results for discolouration (Arnold *et al*, 1991).

2.6.1.2 Artificial light sources

Tolvaj and Mitsui (2005) studied the effect that light sources have on the photo-degradation of wood surfaces. In their study, wood specimens were irradiated with a xenon lamp and a mercury lamp. They found that xenon light was able to simulate the effect of sunlight during weathering only at long exposure times and that in the short term, the yellowing of wood is faster and greater in the case of xenon light irradiation than in the case of natural sunlight. The acceleration effect by xenon light is about three times that of sunlight. During exposure to xenon light or sunlight, the number of UV light-generated carbonyl groups absorbing the infrared light around $1700cm^{-1}$ appears to be correlated with the yellowing of wood. Furthermore, they found that light emitted by a mercury lamp does not simulate sunlight, and should, therefore, not be used in artificial weathering studies on wood (Tolvaj and Mitsui, 2005).

2.7. Techniques of measuring the weathering characteristics

2.7.1 Fourier Transform Infrared Spectroscopy to study Surface Chemistry

Infrared spectroscopy has a variety of uses as an analytical technique in the wood industry, including quantification and identification of individual components. Fourier transform infrared spectroscopy (FTIR) has also been proven useful in studying the surface degradation of wood samples during weathering (Moore and Owen, 2001).

The infrared region of the electromagnetic spectrum extends from the red end of the visible spectrum to the microwave region (Figure 2.8). The region includes radiation at wavelengths between 0.7 and 500 μm or, in wavenumbers, between 14000 and 20cm^{-1}. The spectrum range used most is the mid-infrared region which covers frequencies from 4000-200cm^{-1} (Willard *et al*, 1988). It is convenient to divide the IR region into three parts: the far-IR (10-200cm^{-1}), the mid IR (200-4000cm^{-1}) and the near IR (4000-12800cm^{-1}) (Griffiths and Haseth, 2007).

2.7.1.1 Vibrational Behaviour of Molecules under IR radiation

Infrared spectroscopy involves examination of the twisting, bending, rotating and vibrational motions of atoms in a molecule (Willard *et al*, 1988). Upon interaction with infrared radiation, portions of the incident radiation are absorbed at specific wavelengths. The multiplicity of vibrations occurring simultaneously produces a highly complex absorption spectrum that is uniquely characteristic of the functional groups that make up the molecule and of the overall configuration of the molecule as well.

2.7.1.2 Correlation of Infrared Spectra with Molecular Structure

The infrared spectrum of a compound is fundamentally the superposition of absorption bands of specific functional groups yet subtle interactions with the surrounding atoms of the molecule impose the stamp of individuality on the spectrum of each compound (Willard *et al*, 1988). For qualitative analysis, one of the best features of an infrared spectrum is that the absorption or the lack of absorption in specific regions can be correlated with specific stretching and bending motions and, in some cases, with the relationship of these groups to the rest of the molecule. Thus, when interpreting the spectrum it is possible to state that certain functional groups are present in the material and certain others are absent (Willard *et al*, 1988).

2.7.1.3 Fingerprint Region

The mid-infrared region is divided into the “group frequency” region, 4000-1300 cm^{-1} and the fingerprint region, 1300 to 650 cm^{-1} (Griffiths and Haseth, 2007). The major factors in the spectrum between 1300 and 650 cm^{-1} are single-bond stretching frequencies and bending vibrations (skeletal frequencies) of poly atomic systems that involve motions of bonds linking a substituent group to the remainder of the molecule. This is the fingerprint region. Multiplicity is too large for assured individual identification of the bands but collectively the absorption bands aid in identifying the material (Griffiths and Haseth, 2007).

2.7.1.4 Assignment of IR absorption spectra bands in wood

Photo-induced degradation of treated and untreated wood causes mainly changes in the absorption intensity at 1720–1740, 1592, 1508 and 1261 cm^{-1} (Temiz *et al*, 2007). The intensity and changes of these bands are related to changes in chemical composition of the functional groups and chemical structure of wood components. The assignments of these characteristic IR absorption peaks in wood are shown in Figure 2.12 below and are listed in Table 2.2.

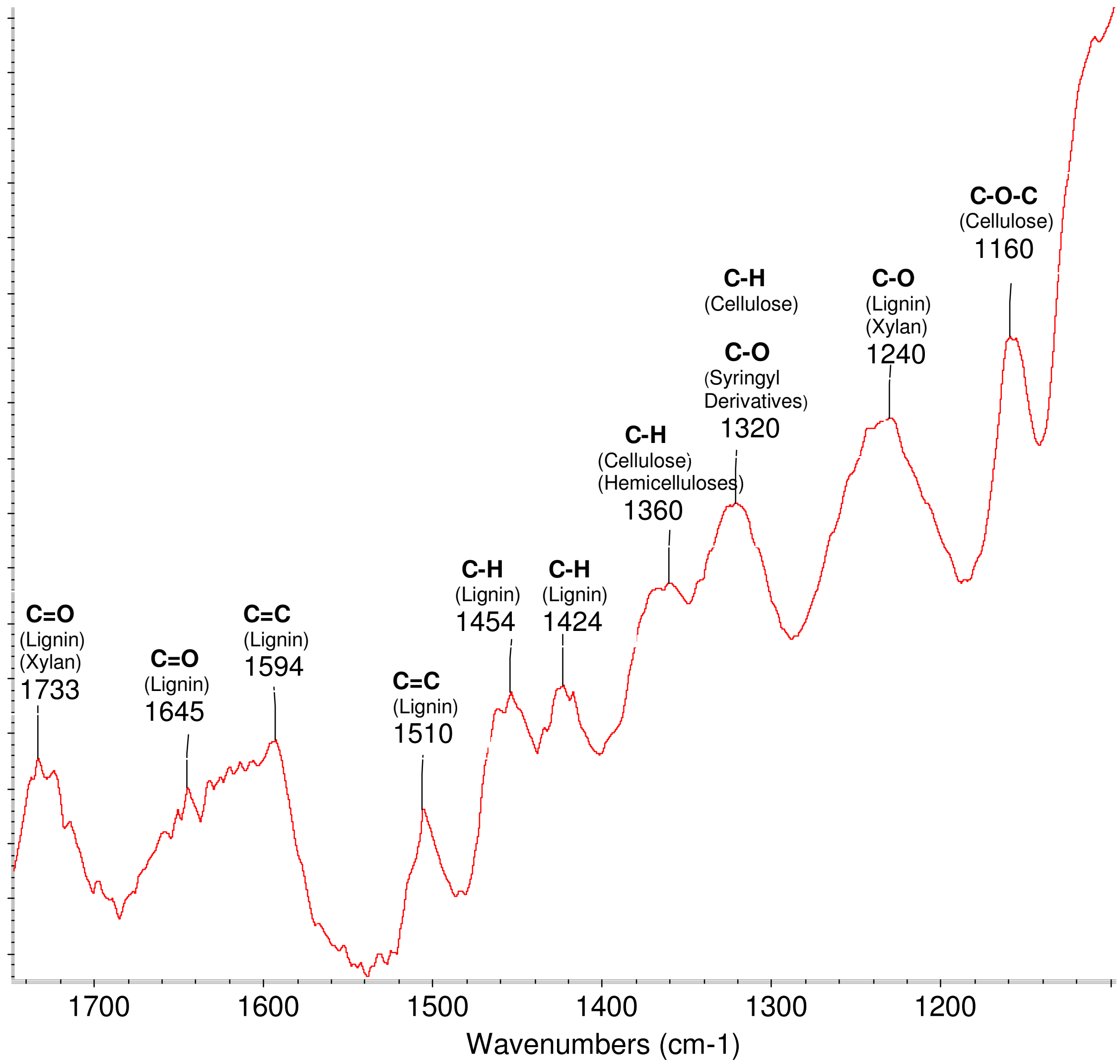

Figure 2.12: Typical FTIR spectrum of a wood sample (Temiz *et al*, 2007).

Table 2.2: Assignment of IR absorption spectra bands in wood (Temiz *et al*, 2007).

Fr (cm^{-1})	Group and class	See Figure
1720–40	• C=O in: - unconjugated ketones - aldehydes - and carboxyl groups	Figure 2.13 - a Figure 2.14 - a Figure 2.14 - b
1645–60	• C=O in: - para-OH substituted aryl ketones - and quinones	Figure 2.13 - b Figure 2.15
1600/1510	• C=C in: - aromatic ring in lignin	
1462 / 1425	• C–H in: - lignin - and carbohydrates	
1375	• C–H in: - cellulose - and hemicelluloses	
1330 / 1320	• C–H in: - cellulose • C–O in: - syringyl derivatives	
1268	• Guaiacyl ring breathing (lignin) • C–O in: - lignin • C–O linkage in guaiacyl aromatic methoxyl groups	Figure 2.13 - c Figure 2.13 - d
1244	• Syringyl ring breathing (lignin) • C–O in: - lignin - xylan	Figure 2.13 - e
1162	• C–O–C in: - cellulose	Figure 2.16

The 1800–1450 cm^{-1} range is of particular importance for the study of processes occurring in wood. The 1720 -1740 cm^{-1} band is characteristic of the unconjugated ketones in lignin (Figure 2.13-a) and aldehydes and carboxyl groups in xylan (Figure 2.14-a and b) (Anderson *et al*, 1990a and Temiz *et al*, 2007).

The absorption at 1645–1660 cm^{-1} is related to the deformation of para-OH substituted aryl ketones (Figure 2.13-b) and quinines (Figure 2.15) present in lignin (Anderson *et al*, 1990, Moore and Owen, 2001, Temiz *et al*, 2007).

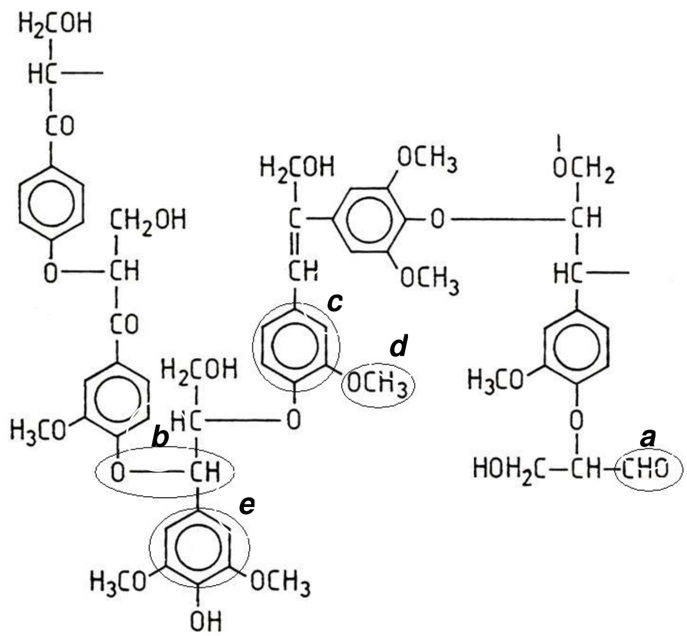

Figure 2.13: Assignment of IR absorption groups in areas of lignin (Adapted from Fengel and Wegener, 1984). a: unconjugated ketone, b: para-OH substituted aryl ketones, c: Guaiacyl ring breathing, d: C–O linkage in guaiacyl aromatic methoxyl groups and e: Syringyl ring breathing.

The absorption at 1600 cm^{-1}, 1510 cm^{-1}, 1268 cm^{-1} and 1244 cm^{-1} are characteristic peaks of lignin due to the C=C stretching vibrations of the aromatic rings present in lignin while the aliphatic part of lignin is characterized by the 1462 cm^{-1} band. It has been reported that the aromatic lignin C=C band (1506/1511 cm^{-1}) disappears within a few hours of exposure to accelerated weathering (Anderson *et al*, 1990, Moore and Owen, 2001, Williams, 2005 and Temiz *et al*, 2007).

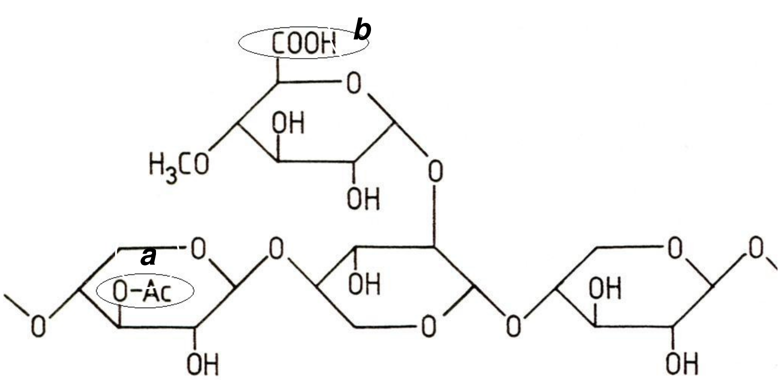

Figure 2.14: Assignment of IR absorption groups in areas of xylan (Adapted from Fengel and Wegener, 1984). a) aldehyde groups and b): carboxyl groups

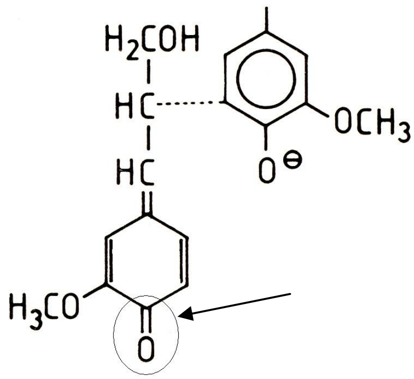

Figure 2.15: Quinone structure present in lignin (Adapted from Fengel and Wegener, 1984).

The absorption at 1268 cm^{-1} is characteristic absorption of guaiacyl ring breathing (Figure 2.13-c), C-O in lignin and C–O linkages in guaiacyl aromatic methoxyl groups (Figure 2.13-d) (Anderson *et al*, 1990a, Moore and Owen, 2001, Temiz *et al*, 2007).

The absorption at 1244 cm^{-1} is characteristic absorption of syringyl ring breathing (Figure 2.13-e), C-O in lignin, and C–O linkages in xylan (Anderson *et al*, 1990, Moore and Owen, 2001 and Temiz *et al*, 2007).

The C–O–C stretching of the pyranose ring of cellulose absorbs at 1162 cm^{-1} in its crystalline and at 1156 cm^{-1} in its amorphous cellulose form (Figure 2.16) (Anderson *et al*, 1990, Moore and Owen, 2001, Temiz *et al*, 2007).

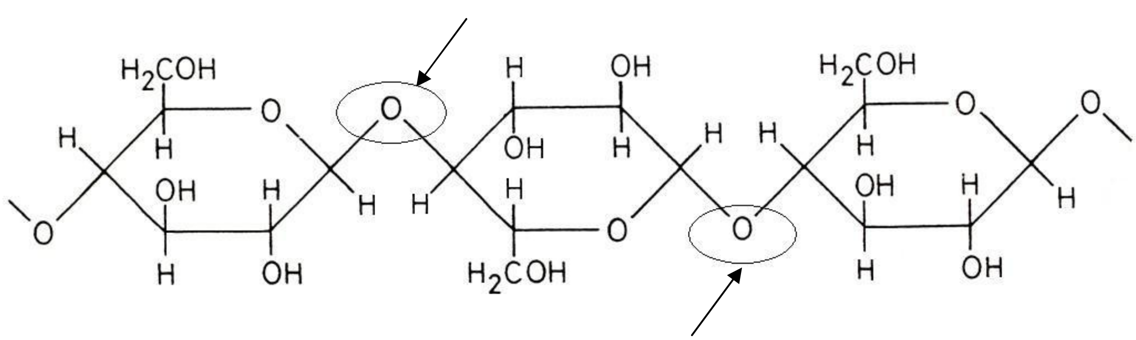

Figure 2.16: C–O–C stretching of the pyranose ring of cellulose (Adapted from Fengel and Wegener, 1984)

2.7.2 Colour

The aesthetic appearance of wood is an important factor concerning wood quality and colour has a significant impact on each individual's perception of this appearance. Unfortunately wood surfaces undergo drastic colour changes when exposed outdoors and mostly turn grey (e.g. Colorado changes from red to grey whereas Balau changes from brown to grey).

In order to compare the quality of different wood products, it is necessary to determine the rate of discolouration that wood surfaces undergo when exposed outdoors. Colour can be measured using a wide range of spectrophotometers. The CIE-lab system is one of the systems used to quantify colour. The colour parameters of this system are as follows: the $L*$ axis is the lightness (ranging from 0 (black) to 100 (white)), the $a*$ and $b*$ axes are the chromaticity coordinates (a positive $a*$ value refers to red and a negative $a*$ value to green while $+b*$ and $-b*$ denote yellow and blue respectively) (see Figure 2.17). $\Delta E*$ is the combined effect of the parameters and can be calculated according to equation 1:

$$\Delta E* = (\Delta L*^2 + \Delta a*^2\ \Delta b*^2)^{1/2} \qquad (1)$$

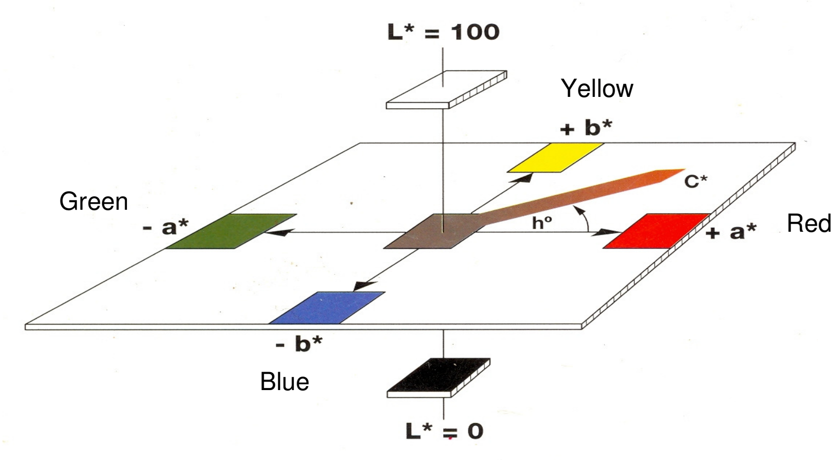

Figure 2.17: Representation of the CIE-lab system (SHEEN – Micromatch Plus: User manual)

2.7.3 Surface Roughness

Different instruments are available for the assessment of surface texture. These instruments either operate on mechanical, mechanical-electrical, pneumatic or optical principles.

Figure 2.18: Example of roughness profiles measured with a stylus tipped roughness meter: (a) roughness profile of Balau before weathering (*Ra* = 6.6, *Rz* = 54.4) and (b) roughness profile of Balau after four weeks of weathering (*Ra* = 10.3, *Rz* = 61.2)

Instruments commonly used in the analysis of wood surfaces are roughness meters containing a cone shaped stylus tip. The tip of the stylus is dragged across the wood's surface, recording the profile curve as it continues. There are normally two modes used to characterize the average roughness namely *Ra* and *Rz* (DIN 4768, 1990). *Ra* represents the average deviation of the roughness profile but it does not differentiate between the peaks and valleys of a surface profile whereas *Rz* considers the mean peak to valley height (Ghosh *et al*, 2009). When using this instrument, its profile filter must be phase-corrected with a cut-off wavelength of 8mm. According to DIN 4768 (1990) wavelengths shorter than this value are considered as roughness and larger wavelengths as waviness.

2.7.4 Substrate defects

During weathering, defects such as surface-checks, checks and cracks may occur in wood. One method of quantifying these defects on a sample is by means of a template. The template is sized according to the surface area of a sample and divided into a number of equally sized blocks e.g. 50 blocks. The percentage of defect free surface can then be calculated by counting the number of blocks which do not contain defects.

2.7.4.1 Surface checks (Hair checks)

Surface checks, as defined by SANS 1783-1 (2007), are very fine checks of width not exceeding 0.5mm.

2.7.4.2 Checks

Checks as defined by SANS 1783-1 (2007) are separations of the wood fibers along the grain of the wood that form a fissure but do not extend through a piece from one face to the opposite face (see Figure 2.19).

2.7.4.3 Crack (split)

A crack/split as defined by SANS 1783-1 (2007) is a separation of the wood fibers along the grain of the wood that forms a crack or fissure that extends through a piece from one face to the opposite face (see Figure 2.19)

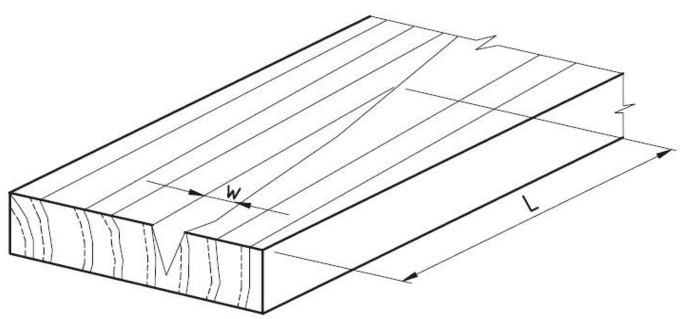

Figure 2.19: Representation of a check (SANS 1783-1: 2007)

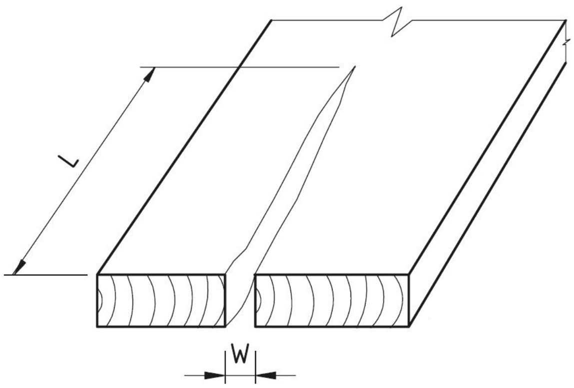

Figure 2.20: Representation of a crack/split (SANS 1783-1: 2007)

2.7.5 Deformation

During weathering a sample may deform from its original state. Different forms of deformation exist namely bow, cup, spring and twist. Any form of these is known as warp and can be measured and quantified as explained in the following section.

2.7.5.1 Bow

Bow as defined by SANS 1783-1 (2007) is the lengthwise curvature, in its own plane, of an edge of a piece. *d* is the variable that is measured as explained in Figure 2.21 below.

2.7.5.2 Cup

Cupping as defined by SANS 1783-1 (2007) is a curvature that occurs in the transverse section of a piece of timber. *C* is the variable that is measured as explained in Figure 2.22.

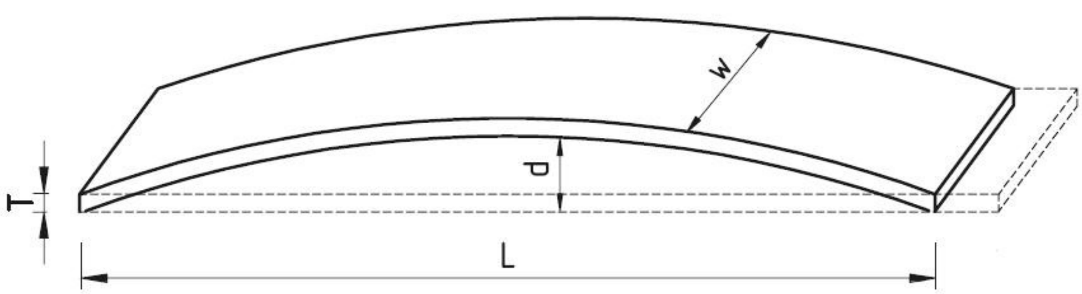

Figure 2.21: Depiction of bow deformation (SANS 1783-1: 2007)

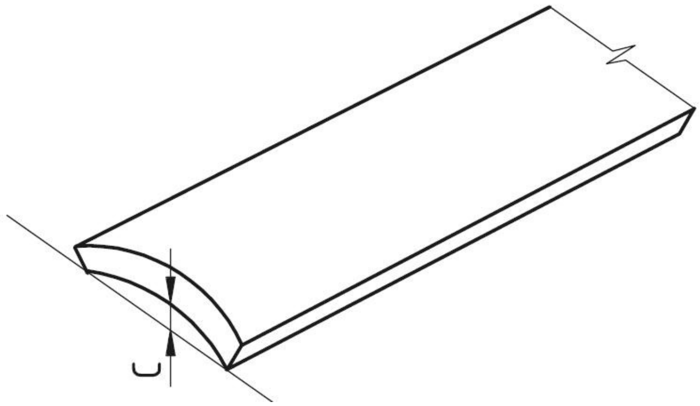

Figure 2.22: Depiction of cup deformation (SANS 1783-1: 2007)

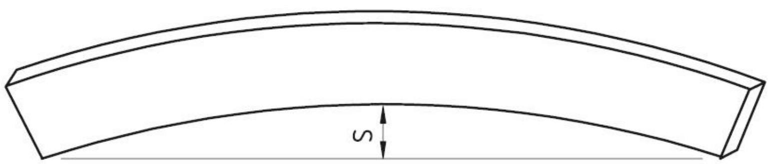

Figure 2.23: Depiction of spring deformation (SANS 1783-1: 2007)

2.7.5.3 Spring

Spring as defined by SANS 1783-1 (2007) is the lengthwise curvature, in its own plane, of the face side of a piece. *S* is the variable that is measured as explained in Figure 2.23

2.7.5.4 Twist

Twist as defined by SANS 1783-1 (2007) is a form of warp that appears as lengthwise spiral distortion in a piece. In order to quantify the amount of twist of a piece, *t* can be measured as the height from a flat surface or angle *α* can be measured as shown in Figure 2.24.

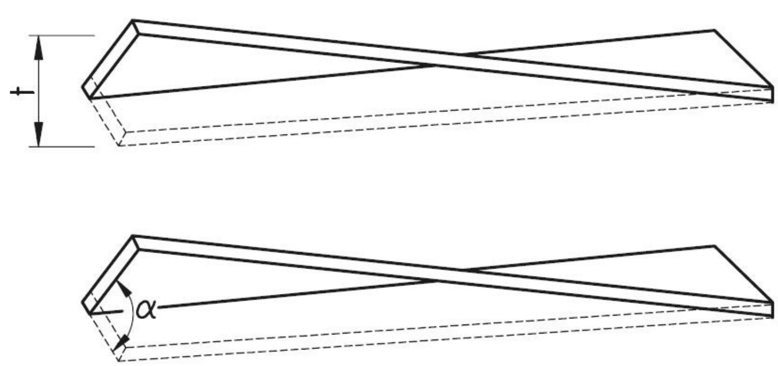

Figure 2.24: Depiction of twist deformation (SANS 1783-1: 2007)

2.7.6 Changes in Surface Wettability

As mentioned previously, weathering causes gradual deterioration of wood surfaces as wood is converted to volatile and water-soluble degradation products. Lignin and extractives which are suggested to be the hydrophobic components in wood are quickly eroded and leached out, leaving the surface with a cellulose-rich layer. Cellulose is a hydrophilic material and with its increased exposure on the surface, leads to an increase in wettability (Kalnins and Feist, 1993). The roughening of the surface also leads to a decrease in topography and thus a smaller contact angle. This increase in contact angle can be explained by the increase of contact area between the liquid and the surface.

Wettability of a solid surface by a liquid is usually expressed as the contact angle between the solid and the liquid (Figure 2.25), a smaller contact angle signifying greater wettability (Kalnins and Feist, 1993).

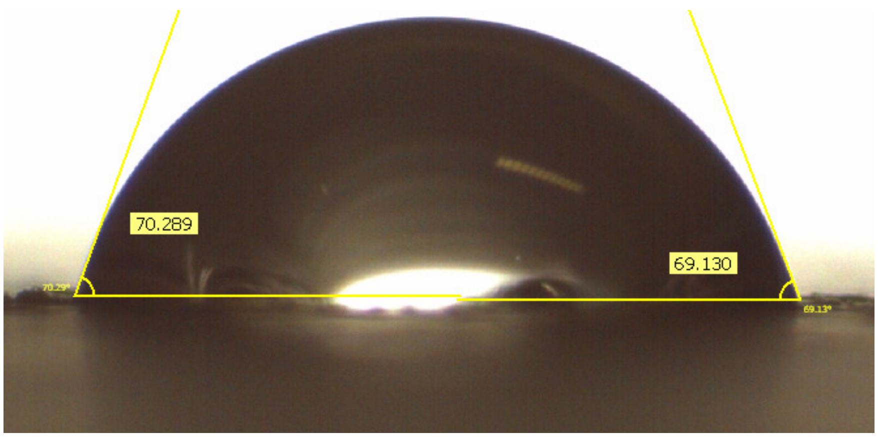

Figure 2.25: Contact angle of a water drop (Image taken with an optical microscope at 25X magnification)

2.8. Conclusion

The properties of all unfinished wood products are degraded by outdoor weathering, the extent of the degradation depending on wood properties and the environmental conditions. The degradation process is slow and only affects the surface of wood. Water, sunlight and oxygen all play a role in wood weathering, the combined effect leading to discolouration, modification of surface texture and formation of checks and cracks, increasing the possibility of fungal attack. The durability of wooden structures is affected by the weatherability of wood. Therefore, it is important to protect wood by applying finishing systems and thus sustain the quality of wood when exposed to the harsh exterior factors of nature.

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Chapter 3: Natural weathering behaviour of Colorado (*Eucalyptus camaldulensis* and *Eucalyptus tereticorni*s) and Balau (*Shorea* spp.)

Abstract

Balau, a group consisting of 21 *Shorea* species, is widely used for outdoor application. In South Africa, Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of a substitute timber for decking material. One possible timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India and parts of South America because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors. The timber was initially utilized as raw material for the pulp and paper industry but is now gaining importance in structural uses like furniture, flooring and decking.

The aim of this exploratory study was to investigate relevant material properties and to examine the natural weathering behaviour of Colorado and Balau to predict Colorado's suitability as decking material.

It was found that Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau and had a higher density than Balau. Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's. The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado's lower swelling anisotropy can result in a lower tendency to twist in service. Colorado had a higher water soluble extractive content than Balau, which can lead to the rapid initial colour changes when the timber is exposed uncoated.

The weathering performance of Colorado and Balau was investigated by exposing samples to natural weathering at inland and marine locations. During weathering for 30 weeks Colorado showed a slightly higher colour change (ΔE^*) than Balau. Balau showed a higher increase in roughness (*Rz*), surface checking and check formation than Colorado. Colorado showed slightly more cup than Balau, however, Balau showed much larger amounts of twisting than Colorado. No statistically significant differences were found between the hydrophobicity of the two timbers. A coating was effective in increasing the initial hydrophobicity of samples and could maintain a relatively hydrophobic surface during weathering. No statistically significant differences were found in the effect of sample cut on timber species surface wettability.

Although only long term natural weathering studies and using substantially more samples can confirm its natural weathering performance, the results of this exploratory, natural weathering study indicated that Colorado can successfully be used as a substitute decking material for Balau.

3.1 Introduction

Wood has been used as a building material for many millennia and despite the invention of new building materials over the last century, the utilization of wood in the construction industry shows little sign of declining. This can be attributed to wood's versatile and attractive engineering and structural properties.

All man-made and natural materials, including wood, are susceptible to environmental degradation. When wood is exposed outdoors, above ground, a complex combination of chemical, mechanical, and light energy factors contribute to what is described as weathering (Feist, 1983). These weathering factors are as follows: solar radiation (ultra violet (UV), infrared and visible light), moisture (rain, dew, snow and changes in relative humidity), abrasion by windblown particles, heat and oxygen. In recent years, an additional weathering influence has arisen with the presence of atmospheric pollutants such as gaseous SO_2, NO_2, and O_3 (Anderson *et al*, 1990). Abrasion of surfaces as a result of human activities such as walking on decks and maintenance such as cleaning surfaces with cleaners and brighteners and power washing, cause further modification of weathering effects (Feist, 1990 and Williams, 2005).

The weathering process of wood starts immediately after wood is exposed to sunlight which causes the photo-oxidation or photochemical degradation of the exposed wood surface (Williams, 2005). At first the colour changes and then the combined effect of solar radiation and moisture leads to surface roughening as the grain raises, formation of surface checks which later grow into large cracks, surfaces gather dirt and mildew, the wood loses its surface coherence and becomes friable, splinters and fragments come off (Feist, 1983). If boards contain reaction or juvenile wood, cross-grain checking may develop, the boards may cup and warp and pull away from fasteners, especially in decking applications (Williams, 2005).

To develop methods to retard or inhibit degradation and to increase the service life of all types of wood products in any type of environment, it is important to understand the mechanisms of weathering that lead to chemical changes and degradation of physical properties. The effect of weathering on wood or surface treatments can be studied using either natural outdoor exposure tests or accelerated laboratory tests. These two major test types are not the same, however, many researchers have found good correlations between erosion rates from natural and accelerated weathering (Feist and Mraz, 1978, Anderson *et al*, 1990, Arnold *et al*, 1991, Tolvaj and Mitsui, 2005). The main problem with natural weathering tests are that the weather conditions are not repeatable and vary from place to place, therefore, artificial weathering is more useful when studying the combined or individual effects of water and UV radiation on wood surfaces.

Balau is a group consisting of 21 *Shorea* species (Pande *et al,* 2005). The timber is widely used for outdoor application and in South Africa, Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of substitute species for decking material. One possible substitute timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India and parts of South America because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors (Sharma *et al*, 2005). These two species were initially utilized as raw material for the pulp and paper industry but are now gaining importance for commercial, structural uses like furniture, flooring and decking.

This paper forms part of a larger study on the weathering characteristics of Colorado (*Eucalyptus camaldulensis* and *Eucalyptus tereticornis*) and Balau (*Shorea* spp.). The objective of this investigation was to determine the physical and chemical changes of Colorado and Balau when subjected to natural weathering at two different (marine and inland) Mediterranean exposure sites. The effect of sample orientation (horizontal vs 45° to the horizontal, north facing), grain orientation (radial vs tangential) and surface coating was also included in the study.

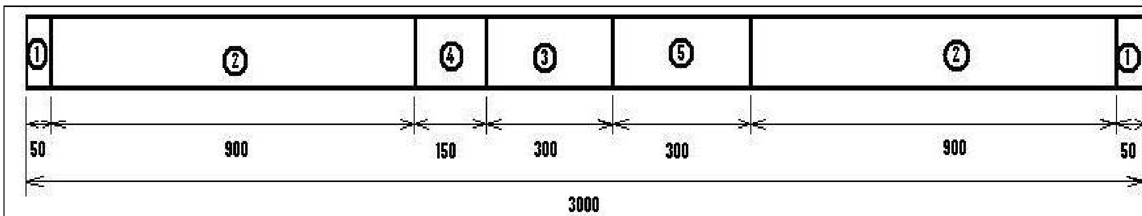
3.2 Materials and methods

3.2.1 Exposure conditions

Weathering was performed under two different Mediterranean climatic (winter rainfall) conditions, i.e. on the Atlantic beach front at Yzerfontein and at Stellenbosch, an inland location. Samples were exposed in a small timber deck erected at each location. A complementary natural weathering study was conducted at Stellenbosch on smaller samples not fixed to a horizontal deck support structure but in exposure racks facing north and at an angle of 45° to the horizontal. Weathering of decks started on 1 May 2009 (late autumn) and periodic evaluation of properties was stopped after 30 weeks on 7 December 2009. The smaller samples were weathered for a shorter period to allow adequate time for permeability measurements on unexposed material. The weathering period started on 24 June 2009 and was terminated after 20 weeks on 9 December 2009.

3.2.2 Sample preparation

Twelve defect free heartwood samples of Colorado and Balau, of which six were radially and six tangentially cut, each measuring 3000 x 19 x 85mm, were obtained from commercial sources. As depicted in Figure 3.1 each 3m board was divided into matched samples required for parallel running natural and accelerated weathering studies.



Sample no and purpose legend:
(1) Density, fiber saturation point (FSP) and swelling coefficient determinations (*50 x 85 x 19mm*)
(2) Natural weathering exposure on decks erected at Stellenbosch and Yzerfontein respectively (*900 x 85 x 19mm*)
(3) Standard panels for permeability determination and natural weathering in north facing exposure racks at Stellenbosch (*300 x 85 x19mm*)
(4) Anatomical studies and extractives determination
(5) Accelerated weathering (*150 x 85 x 5mm*) – not used in this investigation

Figure 3.1: Cutting pattern of 3000mm boards

The 24 small samples (no 3) were sanded with a commercial P100 grit abrasive paper. Half of the wood samples were coated with 3 layers of a commercially available penetrating finish according to manufacturer's specifications. The coating was applied on five of the sample's surfaces (4 edges and 1 face). The solvent borne finish contained a brown ("mahogany") coloured pigment. Samples 1-4 were used in this study, samples 5 were only used in the accelerated weathering study running parallel with this investigation and reported in chapter 4. The samples were conditioned for two weeks before exposure at 20˚C/65%RH.

The deck structures at the two respective sites were constructed using 700mm long, 120 – 139mm top diameter poles (*Eucalyptus* sp.). CCA treated SA Pine was used as bearers. The bearers, of dimensions 2400 x 38 x 114mm, were fastened to the poles using M10 x 180mm bolts. The 900x19x85mm deck samples were fixed onto the bearers using 60mm long galvanized screws and half of the samples were coated in the same manner as the smaller 300x15x85mm panels.

3.2.3 Determination of density, FSP and Swelling coefficients

Two samples (Figure 3.1, no.1) from each 3000mm board were used for density, FSP and swelling coefficient determinations. The samples measuring 50 x 19 x 85mm, were squared on a bench sander and conditioned at 20°C/65%RH for one month. After conditioning, the samples' mass and dimensions of the samples were determined, oven dried at 102°C for 24 hours, and again, the mass and dimensions were measured. The oven dried samples were placed above water inside airtight containers, i.e. exposed to 100%RH at 20°C for three months. After this period, the mass and dimensions at FSP were measured. The following variables were calculated according to SANS 1783-1, 2007: (a) %MC at 20°C/65%RH, (b) FSP, (c) Density at 20°C/65%RH, (d) oven-dry density and (e) the radial, tangential and volumetric swelling coefficients (from 0%MC to FSP).

3.2.4 Anatomical Investigation

10mm (radial) x 10mm (tangential) x 15mm blocks were cut from each sample (Figure 3.1, no. 4). The blocks were softened by boiling them in water for 5 hours. Smoothly cut cross-sections were prepared using a Reichert sliding microtome. Micrographs were taken at 35x magnification with a Leica EZ4D optical microscope. Leica image analysis software was used to analyze the images.

3.2.5 Liquid water and water vapour permeability

Standard panels, measuring 300 x 85 x 15mm, were used for the water vapour permeability (WVP) and liquid water permeability (LWP) tests (Eloff, 1999), following the procedure described in Appendix 1, p.125.

Water vapour permeability (WVP) tests were conducted using an apparatus containing a rectangular basin with a surface area of $200cm^2$ of which the edges were fitted with a rubber O-ring. The basin was filled to 50% of its volume with distilled water. The conditioned samples were weighed and clamped on top of the basin with the O-ring preventing any vapour loss other than through the sample. In effect, the middle $200cm^2$ of the sample's area was exposed to an atmosphere of 100% RH. Samples were clamped in the apparatus for a period of 7 days, and weighed again. The WVP (in $g.m^{-2}.day^{-1}$) of a sample was calculated as follows:

$$WVP = (\text{Final Mass} - \text{Initial Mass}) / (0.2 \times 7\text{days}) \quad (1)$$

Liquid water permeability (LWP) tests were conducted using the same apparatus which was used for the WVP determination but with a different configuration. For LWP measurements the lower water basin was turned upside down. This allowed liquid water to lie on top of the sample's surface, whereby exposing the middle $200cm^2$ of a sample's area to liquid water.

Samples were clamped in the apparatus for a period of 1 day, and weighed again. The LWP (also in $g.m^{-2}.day^{-1}$) of the sample was calculated as follows:

$$LWP = (\text{Final Mass} - \text{Initial Mass}) / (0.2 \times 1\text{day}) \quad (2)$$

WVP and LWP tests were conducted in a conditioned room at 20C°/65%RH.

3.2.6 Ethanol/cyclohexane (E/C) and water soluble extractives content

Solvent ethanol/cyclohexane (E/C) and water extractions were performed on wood powder (Figure 3.1, no 4) according to Tappi standard T 264 om-84.

3.2.7 Colour

Colour measurements on samples no. 2 and 3 (Figure 3.1) were recorded using a Micromatch Plus spectrophotometer, equipped with a standard illuminant D65 (SHEEN) using the CIE-lab system. The colour parameters of this system are as follows; the L^* axis is the lightness (ranging from 0 (black) to 100 (white)), the a^* and b^* axes are the chromaticity coordinates (a positive a^* value refers to red, and a negative a^* value to green, while $+b^*$ and $-b^*$ denote yellow and blue respectively). These values are used to calculate the colour change ΔE^* as a function of the weathering period according to the following equations:

$$\Delta L^* = \Delta L_t^* - \Delta L_i^* \tag{3}$$

$$\Delta a^* = \Delta a_t^* - \Delta a_i^* \tag{4}$$

$$\Delta b^* = \Delta b_t^* - \Delta b_i^* \tag{5}$$

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2}\ \Delta b^{*2})^{1/2} \tag{6}$$

Where i refers to time zero and t indicates measurements at specific times.

Colour measurements were taken at t = 0, and after 4, 8, 12, 20 and 30 weeks of natural weathering exposure. Three measurements were taken per sample and colour changes were always monitored on the same location on the sample.

3.2.8 Surface roughness

Roughness was measured on samples no. 2 and 3 (Figure 3.1) with a MarSurf PS1 surface profilometer. The instrument's needle had a cone shaped stylus tip with an angle of 90°. The measuring length was 17.5mm across the grain. The maximum vertical measuring range of the instrument was -200µm to +120µm. A phase corrected profile filter (Gaussian filter) was used in accordance with DIN 4768. The filter is characterized by a cutoff value. This value is the wavelength of a sinusoidal profile, the amplitude of which will be transmitted by the phase correct filter to a level of 50%. This cutoff defines which elements of the profile will be attributed to roughness or waviness. The Rz mode (mean peak-to-valley height (DIN 4287)) was chosen to characterize the average roughness.

Roughness measurements were also taken at t = 0, and after 4, 8, 12, 20 and 30 weeks of natural weathering exposure. The three measurements taken per sample were also repeated on the same location of the sample's surface.

3.2.9 Deformation

The two forms of warp used to describe deformation of samples are cup and twist. Measurements were taken on samples no. 3 (Figure 3.1) after 20 weeks of natural exposure according to methods described by SANS 1783-1 (2007).

3.2.10 Substrate defects

The substrate defects which were measured on samples no. 2 and 3 (Figure 3.1) include surface checks, checks, cracks and end-cracks as defined in SANS 1783-1 (2007). Perspex templates were used to calculate the percentage of defect containing surfaces. The areas of the Perspex templates were divided into 50 equally sized blocks, and from this, the number of blocks containing defects could be counted and a surface percentage calculated. Measurements were taken after 20 weeks on the 300mm samples and after 30 weeks on both decks.

3.2.11 Surface wettability

Wettability of samples no. 3 (Figure 3.1) surfaces was determined by dispensing a 1-µL drop of distilled water on the wood surfaces with a micropipette. Images of the profile of each drop at 25x magnification were recorded using a Leica EZ4D microscope. Images were taken 4 seconds after drop disposal. Five measurements were taken per sample. Both right and left contact angles were measured on each drop using Leica software. Contact angle measurements were taken at t = 0, and after 4, 10 and 20 weeks exposure.

3.2.12 Mass fluctuations

The mass of the 300mm standard panels were measured every 7 days.

3.2.13 Statistical analysis

The statistical analysis of data was conducted with Statsoft Statistica 9. Interactive effects between multiple variables were analyzed using a factorial ANOVA. A test for normality was performed and an F-test was used with confidence intervals of 95%.

Response variables such as colour change (ΔE) and roughness (Rz), taken at different time intervals, were analyzed using repeated measures ANOVA. An F-test was used with confidence intervals of 95%.

3.3 Results and Discussion

3.3.1 Material Properties

3.3.1.1 Density

The average, and upper and lower density values of Colorado and Balau within the 95% confidence intervals are listed in Table 3.1 and depicted in Figure 3.2.

Table 3.1: Average ovendry density of Colorado and Balau

SPECIES	Average ovendry density (g/cm^3)	Density -95.00%	Density +95.00%	N
Colorado	0.92	0.88	0.96	24
Balau	0.83	0.80	0.87	24

The ovendry density of Colorado (0.922 g/cm^3) was found to be statistically significantly higher than that of Balau (0.836 g/cm^3). The Colorado used in this investigation was thus, on average, 9.3% more dense than Balau.

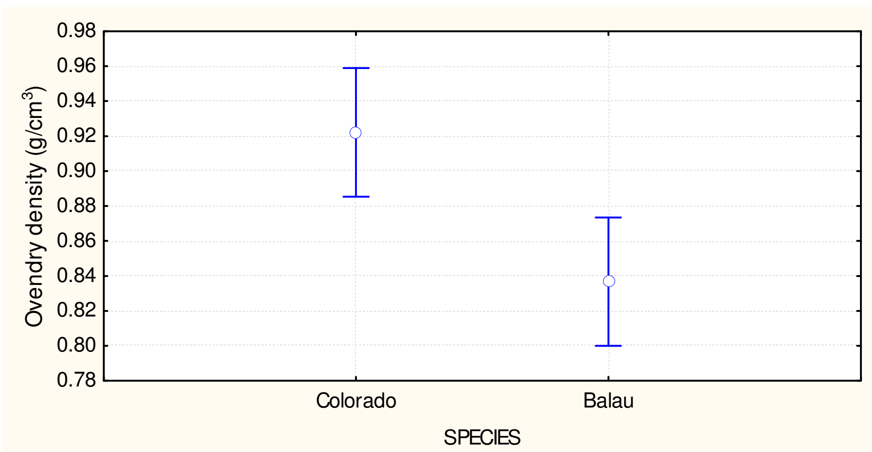


Figure 3.2: Average ovendry density of Colorado and Balau

The following ovendry density results have been reported for Colorado and Balau by other authors whose results are summarized in Table 3.2. From the results reported by Pande *et al.* (2005) it is possible that Balau can have the same density as Colorado.

Table 3.2: Ovendry densities of Colorado and Balau reported by other authors

SPECIES	Density range
Colorado	0.66 - 1.06*
Balau	0.73 - 1.05**

* Veenin *et al* (2005); Doran and Wongkaew (2008); Sharma *et al.* (2005); Brink (2008)
** Pande *et al.* (2005)

3.3.1.2 Fiber saturation point (FSP)

The average, and upper and lower FSP values of Colorado and Balau within the 95% confidence intervals, are listed in Table 3.3 and depicted in Figure 3.3. Both timbers have relatively low FSP when compared to commercially used softwood decking timbers. The difference between Colorado and Balau's average FSP was found to be relatively small but statistically significant. Colorado reached its FSP at 22.1 % MC, which was 2.3 percentage points higher than Balau (an average MC of 19.8%).

Table 3.3: Average fiber saturation point (FSP) of Colorado and Balau

	SPECIES	Average FSP	-95.00%	+95.00%	N
1	Colorado	22.1	21.4	22.8	24
2	Balau	19.8	19.1	20.5	24

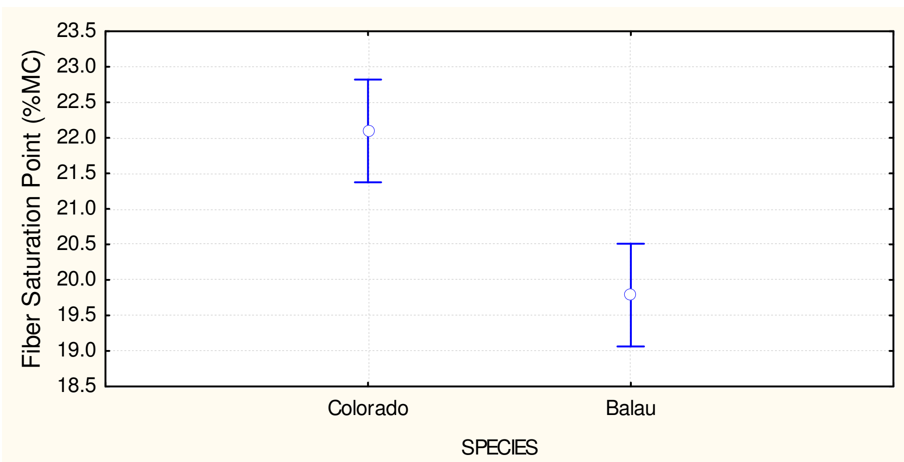


Figure 3.3: Fiber saturation points of Colorado and Balau

Higgins (1957) reported that the FSP of some wood species vary widely from the typical value. He argued that one of the causes of this variation could be attributed to the presence and amount of extractives in a species. Species generally high in extractives have a relatively low FSP. Presumably, the extractives occupy some sites in the cell wall that would otherwise attract water. A low FSP provides the advantage that dimensional changes as a result of moisture fluctuations are comparatively small thereby making these timbers acceptable for outdoor applications.

3.3.1.3 Swelling coefficients

The radial swelling coefficients from ovendry to EMC at 20C°/ 65%RH of Colorado (3.1%) and Balau (2.2%) were found to differ statistically significantly (Table 3.4). The tangential swelling coefficients showed no significant difference (3.69 vs. 3.44%) (Figure 3.4a). However, the radial swelling coefficients from ovendry to FSP of Colorado (6.6%) and Balau (5.2%) were found to differ significantly. The tangential swelling coefficients from ovendry to FSP of Colorado (8.7%) and Balau (7.6%) were also found to differ significantly (Figure 3.4b). Balau has relatively low radial and tangential swelling coefficients but even though Colorado's swelling coefficients are higher than Balau, it has a smaller swelling anisotropy. In decking applications large dimensional changes are not as critical as a high swelling anisotropy. Colorado, having the smaller anisotropy of the two, should warp and twist less than Balau during moisture changes.

Table 3.4: Average swelling coefficients of Colorado and Balau

SPECIES	Swelling range						N
	Average % swelling Ovendry – 12%MC			Average % swelling Ovendry – FSP			
	Radial	Tangential	Tang/Rad	Radial	Tangential	Tang/Rad	
Colorado	3.10	3.69	1.19	6.57	8.68	1.32	24
Balau	2.20	3.44	1.56	5.20	7.58	1.45	24

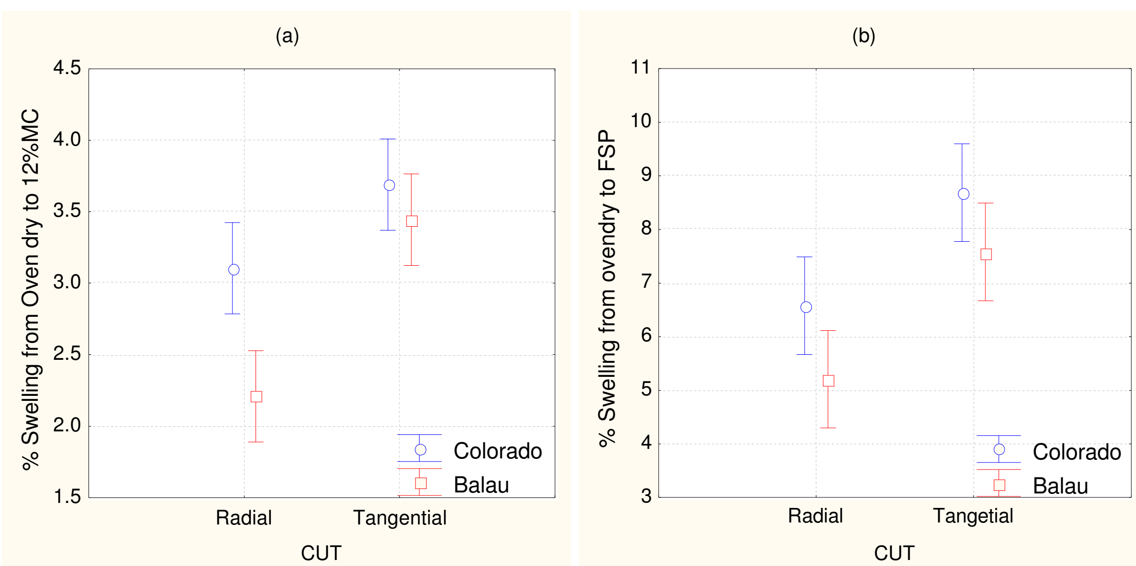


Figure 3.4: Radial and tangential swelling coefficients of Balau and Colorado: (a) from ovendry to 12% moisture, and (b) ovendry to fiber saturation point.

The higher the density of a sample, the more it will swell and shrink. It has also been reported that the lower the FSP of a sample, the less it will swell and shrink (Haygreen and Bowyer, 1982). These could presumably be the reasons why Colorado had a higher swelling coefficient than Balau.

The following results have been reported on Colorado and Balau's ovendry to FSP swelling coefficients and are listed in Table 3.5.

Table 3.5: Average swelling coefficients of Colorado and Balau reported by other authors

SPECIES	**Swelling range**	
	Average % swelling Ovendry – FSP	
	Radial	**Tangential**
Colorado*	4.2 - 9.6	7.4 - 13.5
Balau**	4.0 - 7.9	6.8 – 10.3

* Doran and Wongkaew (2008); Brink (2008)

** Pande *et al.* (2005)

Haygreen and Bowyer (1982) reported that the difference in swelling between the radial and tangential direction of wood can be attributed to several anatomical characteristics, including presence of ray tissue, frequent pitting on radial walls, domination of earlywood in the tangential direction and differences in the amount of cell wall material radially vs. tangentially.

3.3.1.4 Water vapour permeability (WVP) and Liquid water permeability (LWP)

No statistically significant permeability differences existed between the rate at which liquid water and water vapour penetrated uncoated Colorado and Balau, or whether samples were radially or tangentially cut (Figure 3.5, Table 3.6). During exposure to weathering this would mean that penetration of water would be similar for the two timbers irrespective of how they were cut. As expected, surface coating had a significant decreasing effect on both WVP (Figure 3.5a) and LWP (Figure 3.5b); coated samples were thus less permeable than uncoated samples.

Table 3.6: Average water (WVP) and (LWP) values of coated and uncoated Colorado and Balau

	Species							
	Colorado				Balau			
	Radial		Tangential		Radial		Tangential	
	Coated	Uncoated	Coated	Uncoated	Coated	Uncoated	Coated	Uncoated
WVP (g/m^2) (n=3)	0.91	1.12	0.91	1.28	0.66	1.19	0.86	1.26
LWP (g/m^2) (n=3)	3.82	4.90	4.46	5.13	3.34	4.66	3.85	5.09

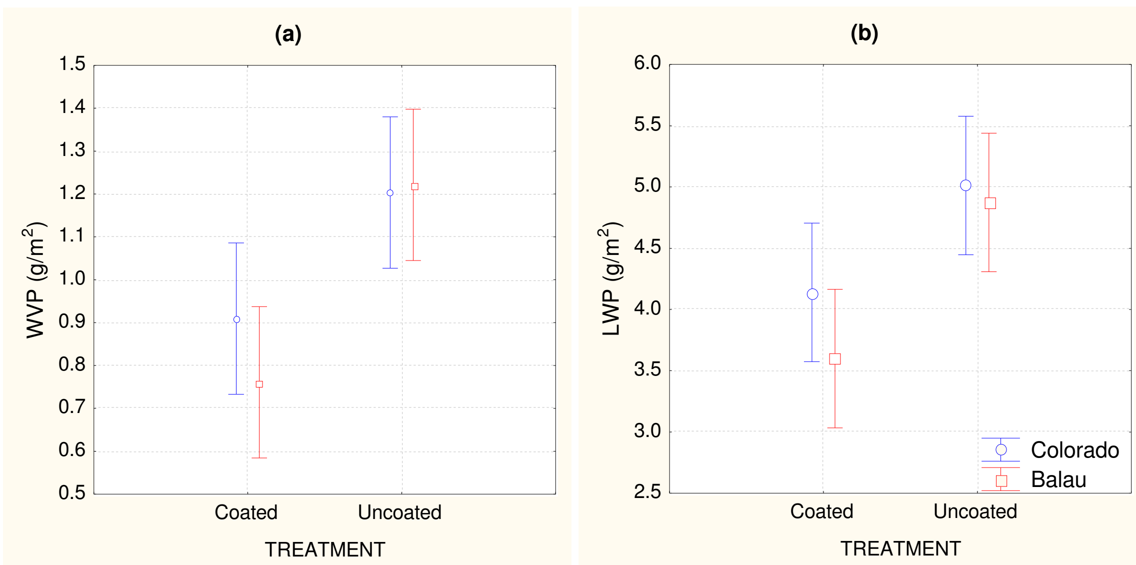


Figure 3.5: (a) water vapour permeability of coated and uncoated Colorado and Balau (b) liquid water permeability of coated and uncoated Colorado and Balau

Even though coated Colorado and Balau showed no statistically significant differences between their WVP and LWP values, their average values differed by nearly 10%. This is due to the relatively small sample size (n = 3) used in this study and the high level of variation within sample groups. Increasing the sample size in future studies should deliver more statistically significant results between coated Colorado and Balau.

Tangentially cut samples showed higher WVP and LWP values than the radially cut samples, this could be attributed to the orientation of rays relative to the exposed surface, causing tangentially cut samples to absorb water more rapidly than radially cut samples.

3.3.1.5 Anatomical Investigation

The results of the anatomical investigation are summarized in Tables 3.7 and 3.8. Two representative micrographs of transverse sections taken at 35x magnifications of Colorado and Balau are shown in Figure 3.6 below.

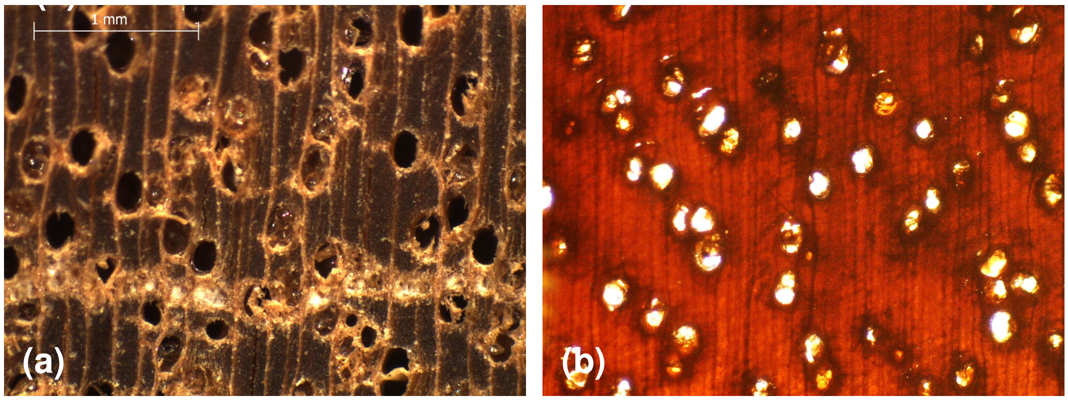


Figure 3.6: Transverse sections of (a) Balau and (b) Colorado. – Micrographs taken at 35X magnification.

Table 3.7: Comparison of general features between Colorado and Balau

	Colorado	**Balau**
Gross features		
Distinction of sapwood and heartwood	Distinct	Distinct
Sapwood colour	Pale red to yellow	Pale brown, whitish yellow
Heartwood colour	Red to brown	Brown
Texture	Moderately coarse	Fairly coarse
Grain	Interlocked	Interwoven or wavy

The sapwood of Colorado had a pale red to yellow colour and Balau's sapwood was brown to white. The heartwood of Colorado was a bright red and sometimes had a slightly brown appearance, whereas the heartwood of Balau was brown. When the face of a tangentially cut Balau sample was inspected, white patterns were observed along the year rings. This characteristic was due to the presence of white resin canals in Balau. The texture of Balau was fairly coarse, slightly more than that of Colorado. Both Colorado and Balau contain interlocked grain which might have given a wavy appearance.

Table 3.8: Comparison of microscopic features between Colorado and Balau

	Colorado	**Balau**
Microscopic structure		
Growth rings	Indistinct or absent	Indistinct or absent
Vessels		
Arrangement	Diffuse-porous	Diffuse-porous
Frequency (mm^2)	11-16	6-9
Size (visibility)	Small	Medium
Distribution	Solitary	Solitary, radial multiples of two or three
Tyloses	Mostly present	Mostly present
Parenchyma	Distinct, vasicentric	Not distinctly visible
Rays	Fine to very fine	Medium to fine, closely spaced
Resin canals	--	Filled with white deposits

When comparing the above microscopic features of Colorado and Balau, it was found that there were many similarities between the two timbers. Both have indistinct growth rings, their vessels were arranged in a diffuse manner and both contained tyloses. Some of the few differences which were found are as follows: Balau had the bigger vessel lumina of the two timbers and slightly bigger rays than Colorado. This could explain Colorado's higher density. Balau also contained resin canals filled with white resin which made it distinguishable from Colorado. This may have compensated for the reduction in the uptake of water associated with the larger vessel lumina.

3.3.1.6 Ethanol/cyclohexane (E/C) and water soluble extractives

The results of the water soluble and ethanol/cyclohexane extraction are listed in Table 3.9, and illustrated in Figure 3.7. Both these timbers contained a high amount of water soluble extractives. Colorado on average contained 5.01% water soluble extractives and Balau 4.08% which is 0.93% less than Colorado. On the other hand, Balau had the highest percentage of E/C extractives, containing 4.8%. Colorado only had 2.03% of E/C extractives, thus containing almost 3% less than Balau.

Table 3.9: Water soluble and ethanol/cyclohexane (E/C) soluble extractives (based on ovendry mass) present in Colorado and Balau

	SPECIES	**% Water soluble extractives**	**% E/C soluble extractives**	**N**
1	Colorado	5.01	2.03	6
2	Balau	4.08	4.80	6

The amount of extractives is one of the important factors when estimating the amount of discolouration which will take place during weathering. During exposure to liquid water, the water soluble extractives can be dissolved and under favorable conditions be leached out of the wood. These extractives usually contribute largely to a wood's initial colour such as the red colour observed in Colorado. When these extractives are eventually leached out, the wood can be left with a pale appearance. E/C extractives on the other hand retard the rapid penetration of water on the surface and thereby also retard the initial discolouration of a wood's surface during weathering. These extractives are also largely responsible for the surface wettability of wood and as they degrade during weathering, the contact angle of a water drop decreases and thus increases surface wettability.

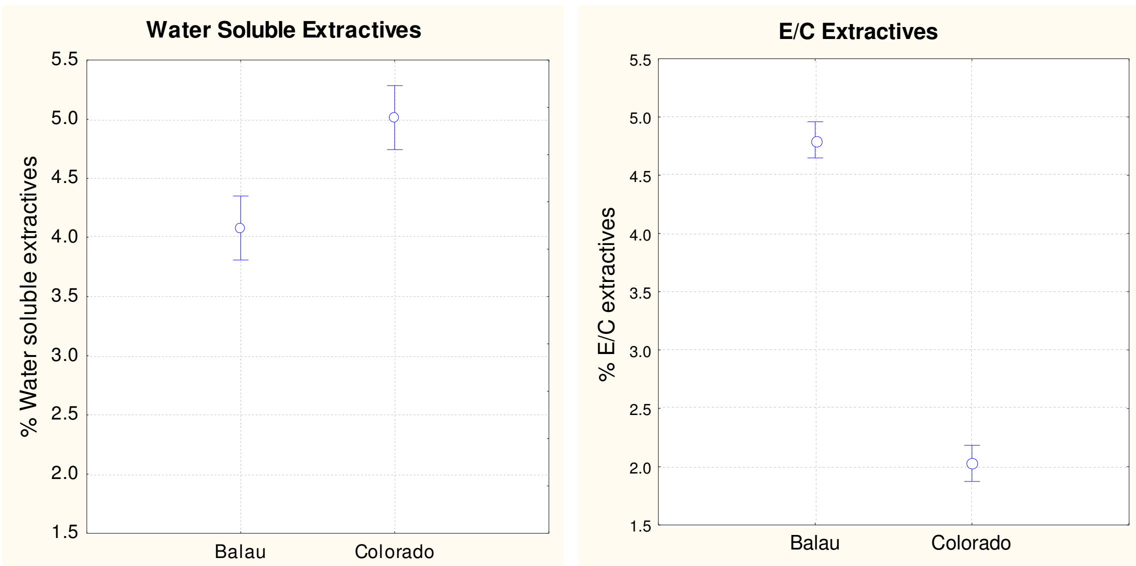


Figure 3.7: Percentage water soluble and E/C extractives (based on ovendry mass) present in Colorado and Balau

3.3.1.7 Summary of material characteristics investigated

- Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau.
- Colorado had a higher density than Balau.
- Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's.
- The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado had a lower swelling anisotropy that would probably result in a lower tendency to twist in service.
- Colorado had a higher water soluble extractive content than Balau which can lead to the rapid initial colour changes of uncoated wood.

3.3.2 Natural weathering characteristics

3.3.2.1 Colour

Colour changes of coated and uncoated exposed Colorado and Balau samples, relative to the colour of unexposed coated and uncoated samples are summarized in Table 3.10 and changes in individual colour parameters L^*, a^* and b^* are shown in Figures 3.8 – 3.16.

As expected the treatment of wood with a pigmented coating changed the colour parameters compared to the uncoated controls. Lightness (L^*) was reduced (Figure 3.8, 3.9 and 3.10, t = 0), and both chromaticity coordinates a^*(Figure 3.11, 3.12 and 3.13) and b^*(Figure 3.14, 3.15 and 3.16) increased. The increase of a^* indicated that the "mahogany" pigmented coating changed the colour of the samples toward a reddish colour, whereas the increase in b^* was associated with a yellowing effect caused by the coating.

3.3.2.1.1 L^* Values

Decks. A statistically significant difference was observed between Stellenbosch and Yzerfontein's lightness values (L^*) of decking samples at the end of the weathering period after 30 weeks. Besides initial differences at t = 0, the only statistically significant difference observed between Colorado and Balau's L^* was after 30 weeks. Uncoated Colorado ended slightly darker than Balau, however, this difference was so small, even though statistically significant, that it could not be distinguished by the human eye (Figure 3.8 and 3.9). The cutting pattern of the samples also contributed no significant effect to changes in L^*. Coating played a significant effect on the change in L^* of samples. Uncoated samples showed the largest decrease in L^* over the first 4 weeks of weathering, thereafter, staying fairly constant up to 30 weeks of weathering. Both Colorado and Balau showed less change in lightness after weathering when coated compared to the uncoated samples. The results found for coated samples agreed with results found by Temiz *et al.* (2007) on the weathering of oil treated wood. According to their research the darkening effect during weathering was the result of the depolymerization of lignin on the exposed surface brought on by photo-degradation.

Table 3.10: Average colour changes relative to t = 0 of coated and uncoated Colorado and Balau after exposure to natural weathering at Stellenbosch (deck and 300mm standard panels) and Yzerfontein (deck)

Exposure site	Species	Treatment	Colour component	Time of exposure (weeks)					
				0	4	8	12	20	30
Stellenbosch - deck	Colorado	Coated	ΔL^*	42.7	33.2	34.3	33.9	44.6	46.0
			Δa^*	22.0	20.6	17.3	14.2	6.8	2.9
			Δb^*	26.8	22.2	19.8	17.8	11.3	9.6
			ΔE^*	0	9.3	10.3	13.0	19.8	24.2
		Uncoated	ΔL^*	53.6	43.9	41.6	39.0	40.7	38.0
			Δa^*	15.1	15.2	9.5	6.4	3.9	2.6
			Δb^*	19.8	22.8	14.8	12.5	5.2	4.9
			ΔE^*	0	11.4	15.7	20.0	24.1	26.5
	Balau	Coated	ΔL^*	37.6	30.7	33.6	33.4	42.4	42.5
			Δa^*	16.3	11.8	10.9	9.7	4.8	2.8
			Δb^*	20.7	17.6	15.8	15.8	9.8	8.6
			ΔE^*	0	7.7	7.4	7.7	16.7	18.3
		Uncoated	ΔL^*	51.7	41.7	42.7	42.6	43.1	40.4
			Δa^*	11.7	10.6	7.2	5.5	2.8	3.2
			Δb^*	19.6	21.8	14.8	13.3	7.0	4.1
			ΔE^*	0	13.7	14.1	15.8	19.8	22.9
Yzerfontein - deck	Colorado	Coated	ΔL^*	40.3	32.7	35.0	36.4	43.7	45.0
			Δa^*	21.0	19.7	17.0	13.3	5.1	2.0
			Δb^*	23.5	19.9	18.9	15.6	10.6	6.5
			ΔE^*	*0*	8.8	7.4	12.7	21.1	26.6
		Uncoated	ΔL^*	52.4	38.9	41.7	42.9	43.4	39.4
			Δa^*	16.5	13.3	7.1	4.7	2.2	1.2
			Δb^*	20.6	19.8	14.2	11.7	6.5	4.2
			ΔE^*	*0*	14.0	15.0	18.8	22.1	26.0
	Balau	Coated	ΔL^*	33.3	29.7	34.9	36.3	45.8	44.0
			Δa^*	12.5	10.7	10.4	7.5	3.7	1.8
			Δb^*	17.2	16.1	15.5	14.4	9.9	6.7
			ΔE^*	*0*	5.9	7.1	10.9	19.6	20.7
		Uncoated	ΔL^*	51.8	35.7	41.1	40.1	45.1	41.9
			Δa^*	10.3	10.8	7.1	5.6	2.4	2.8
			Δb^*	20.9	17.8	12.5	11.3	8.0	5.4
			ΔE^*	*0*	16.7	15.4	15.8	17.4	20.2
Stellenbosch – 300mm standard panels	Colorado	Coated	ΔL^*	40.4	38.3	48.1	*	59.3	*
			Δa^*	21.4	16.4	10.6	*	5.7	*
			Δb^*	24.7	19.1	17.0	*	13.9	*
			ΔE^*	0	9.6	10.7	*	15.7	*
		Uncoated	ΔL^*	56.6	51.3	57.4	*	56.1	*
			Δa^*	16.2	10.5	6.4	*	5.0	*
			Δb^*	20.8	22.9	18.8	*	11.7	*
			ΔE^*	*0*	8.9	17.5	*	27.6	*
	Balau	Coated	ΔL^*	37.7	37.2	45.0	*	55.1	*
			Δa^*	18.1	11.6	7.0	*	5.6	*
			Δb^*	23.3	16.6	16.1	*	14.4	*
			ΔE^*	*0*	9.2	10.1	*	11.2	*
		Uncoated	ΔL^*	55.8	49.8	54.8	*	54.3	*
			Δa^*	10.1	9.7	4.6	*	3.7	*
			Δb^*	20.6	18.2	18.4	*	14.3	*
			ΔE^*	*0*	12.6	17.4	*	24.6	*

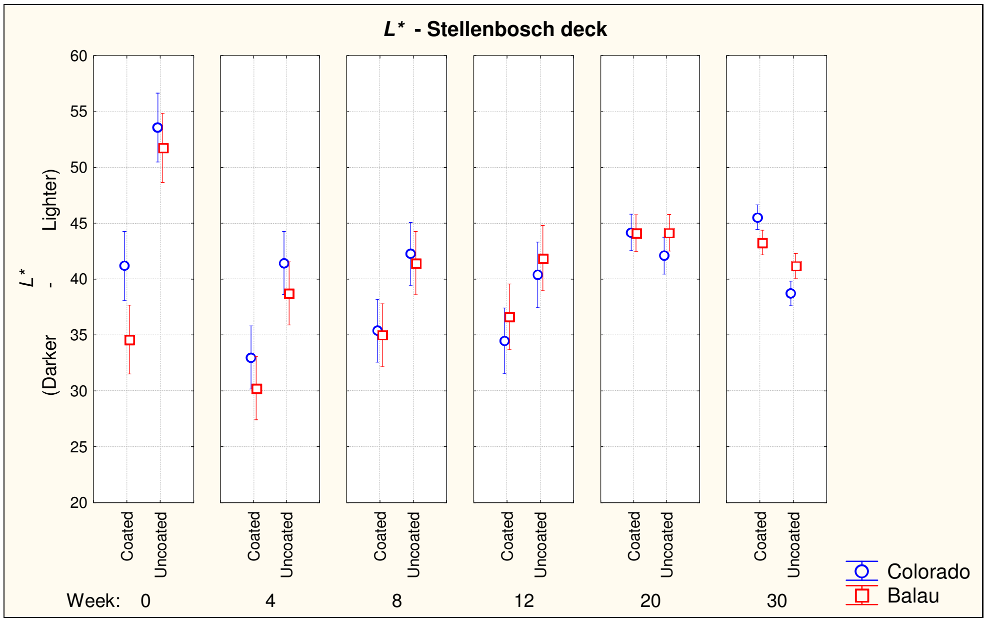


Figure 3.8: Effect of natural weathering on the lightness values (*L**) of coated and uncoated Colorado and Balau - Stellenbosch deck

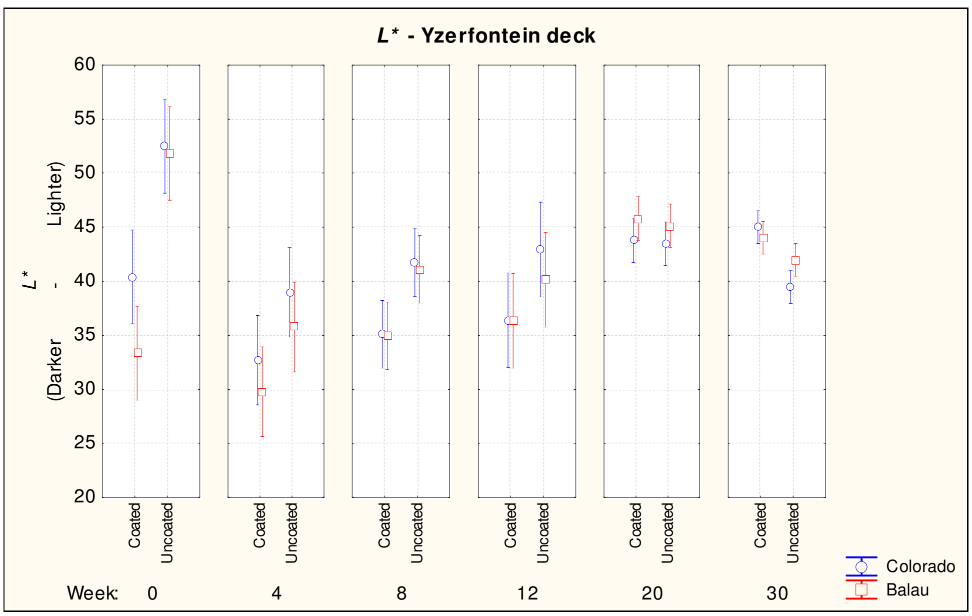


Figure 3.9: Effect of natural weathering on the lightness values (*L**) of coated and uncoated Colorado and Balau - Yzerfontein deck

300mm standard panels. The weathering period of these panels started 10 weeks after the decking samples which allowed time to conduct permeability tests on them. This meant that these panels, in addition to a 45° tilt from the horizontal and north facing, experienced 10 weeks less winter weather than the decking samples. The results found for the standard panels were similar to that of the decking; however, the darkening effect was not as dramatic as on the decking. This could be attributed to less fungal attack on the panels, because of their 45° inclination which allowed water to run of the surface more rapidly when compared to the horizontally positioned decking boards. After 20 weeks of weathering, no statistically significant differences could be observed between the two timbers. Cutting pattern also contributed no significant effect to the amount of change in *L**.

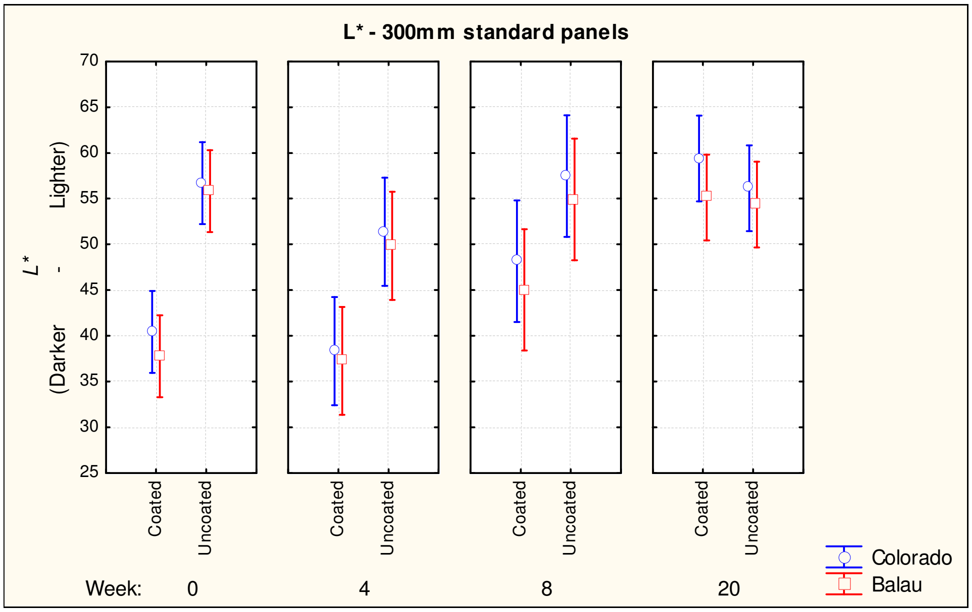


Figure 3.10: Effect of natural weathering on the lightness values (*L**) of coated and uncoated Colorado and Balau - 300mm standard panels at Stellenbosch

3.3.2.1.2 *a** values

Decks. No statistically significant differences were observed between Stellenbosch and Yzerfontein's redness values (*a**) (Figure 3.11 and 3.12) of decking samples throughout the weathering period. A significantly higher change in *a** was found for Colorado compared to that of Balau. Both timbers, coated and uncoated, showed a decrease in *a** over the first 20 weeks of exposure. Thereafter, only a slight decrease was observed up to 30 weeks. After 30 weeks of exposure, no statistically significant difference could be observed between the *a** values of coated and uncoated Colorado and Balau samples surfaces. The decrease in a* indicated a reduction in redness, and consequently resulted in a green appearance. The larger decrease in a* of Colorado could be attributed to Colorado's large quantity of water soluble extractives which leached to the surface and was washed away by rain and dew, leaving the wood with a green appearance similar to that of Balau.

300mm standard panels. The results found for the standard panels (Figure 3.13) were similar to that of the decking and showed similar a* values after 20 weeks of exposure. After exposure no statistically significant differences were found between coated and uncoated Colorado and Balau sample surfaces.

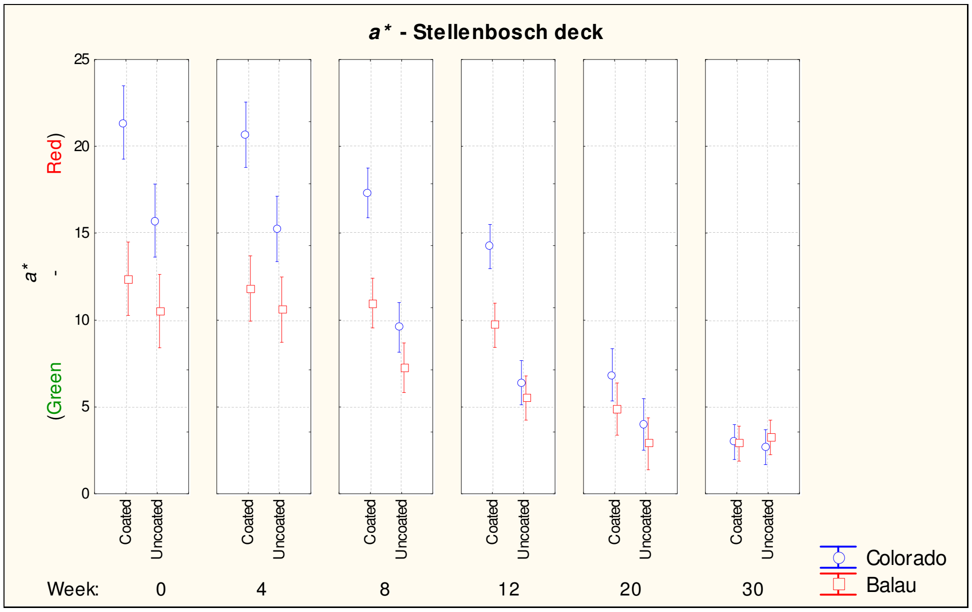


Figure 3.11: Effect of natural weathering on the redness values (*a**) of coated and uncoated Colorado and Balau – Stellenbosch deck

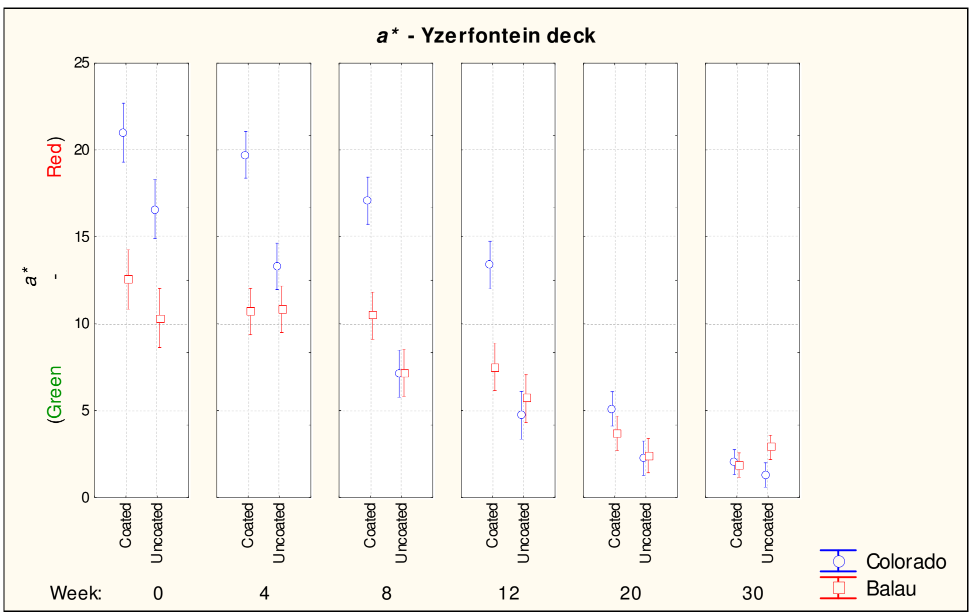


Figure 3.12: Effect of natural weathering on the redness values (*a**) of coated and uncoated Colorado and Balau – Yzerfontein deck

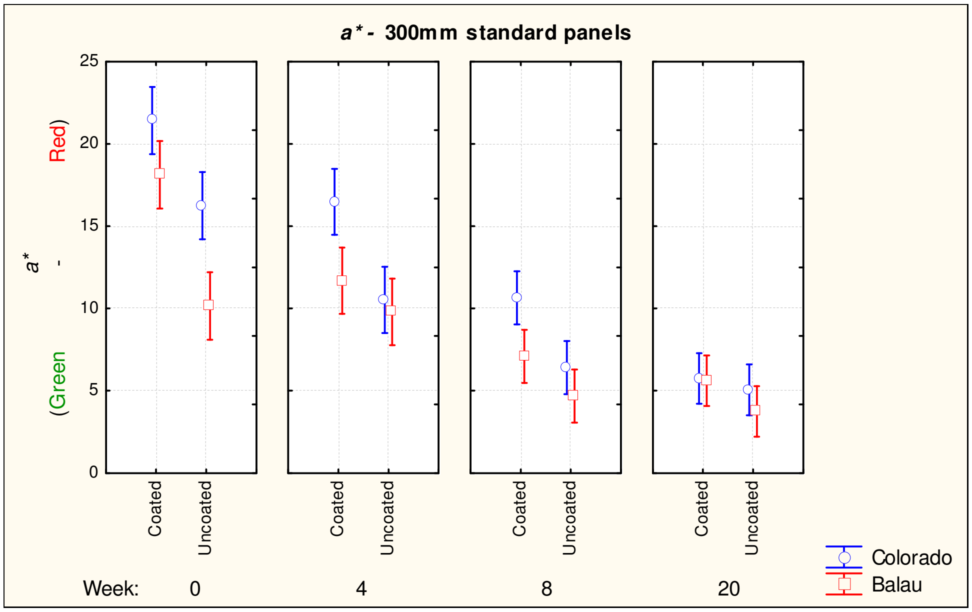


Figure 3.13: Effect of natural weathering on the redness values (*a**) of coated and uncoated Colorado and Balau – 300mm standard panels at Stellenbosch

3.3.2.1.3 *b** Values

Decks. No statistically significant differences were observed between Stellenbosch and Yzerfontein's *b** values (Figure 3.14 and 3.15) for the first 12 weeks of weathering. Thereafter, a difference was observed for the amount of change in *b** between the Colorado samples at Stellenbosch and Yzerfontein. Both coated and uncoated Colorado and Balau showed an increase in *b** over the first 4 weeks of weathering. Thereafter, the *b** values decreased up to 20 weeks of weathering, and stayed constant up to 30 weeks. No significant differences were found between the uncoated Colorado and uncoated Balau's *b** values over the first 12 weeks of weathering, thereafter Balau showed a greater decrease in b* than Colorado at the Stellenbosch site, but decreased similarly at the Yzerfontein site. The initial increase in *b** meant that the uncoated samples turned slightly yellow, and the later decrease meant that samples became slightly blue again. Muller *et al.* (2003) showed that there was a correlation between the yellowing which occurred during weathering and the accumulation of lignin degradation products on the exposed surface of wood. The decrease in *b** value can be attributed to water leaching and washing away the degraded lignin products from the surface and thus leaving the wood slightly blue (Evans *et al.* 2005).

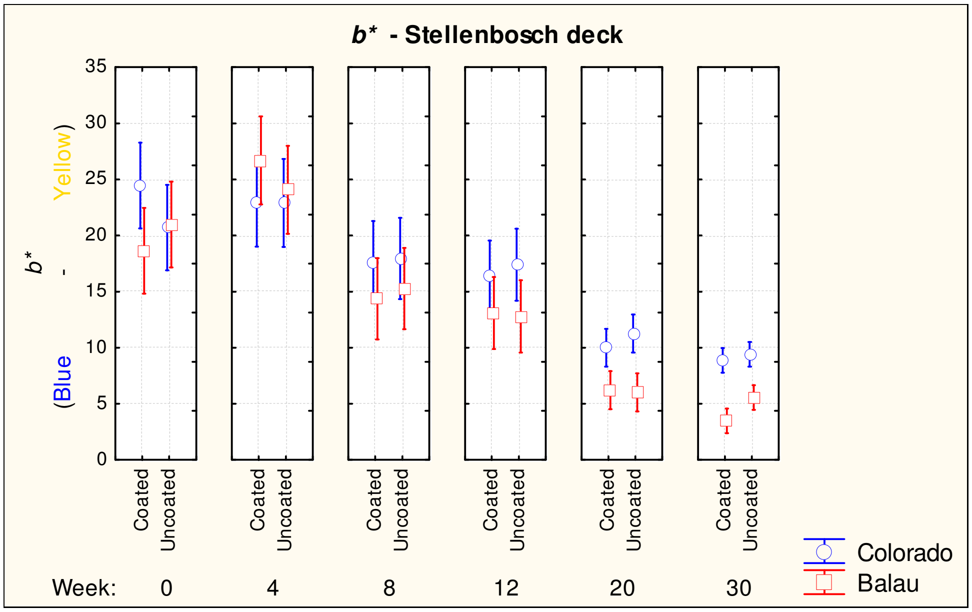


Figure 3.14: Effect of natural weathering on the yellowing (b^*) of coated and uncoated Colorado and Balau – Stellenbosch deck

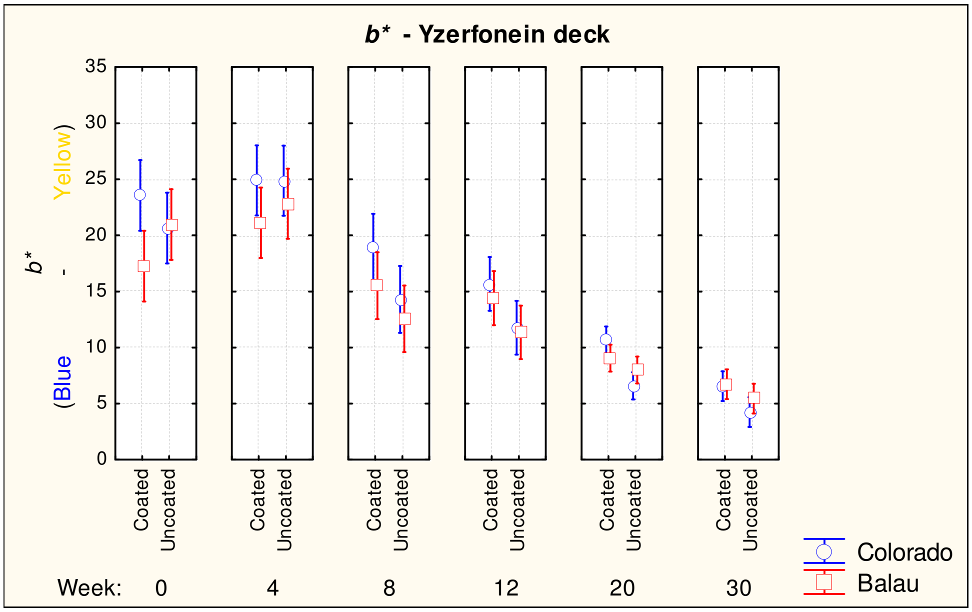


Figure 3.15: Effect of natural weathering on the yellowing (b^*) of coated and uncoated Colorado and Balau – Yzerfontein deck

300mm standard panels. After 4 weeks of weathering, both coated Colorado and Balau showed a decrease in b^* values. Uncoated Balau showed a decrease after 4 weeks, whereas Colorado showed a slight increase in b^*. Thereafter both coated and uncoated Colorado and Balau showed a decrease in b* up to 20 weeks. After 20 weeks there was no statistically significant difference between coated and uncoated Colorado and Balau.

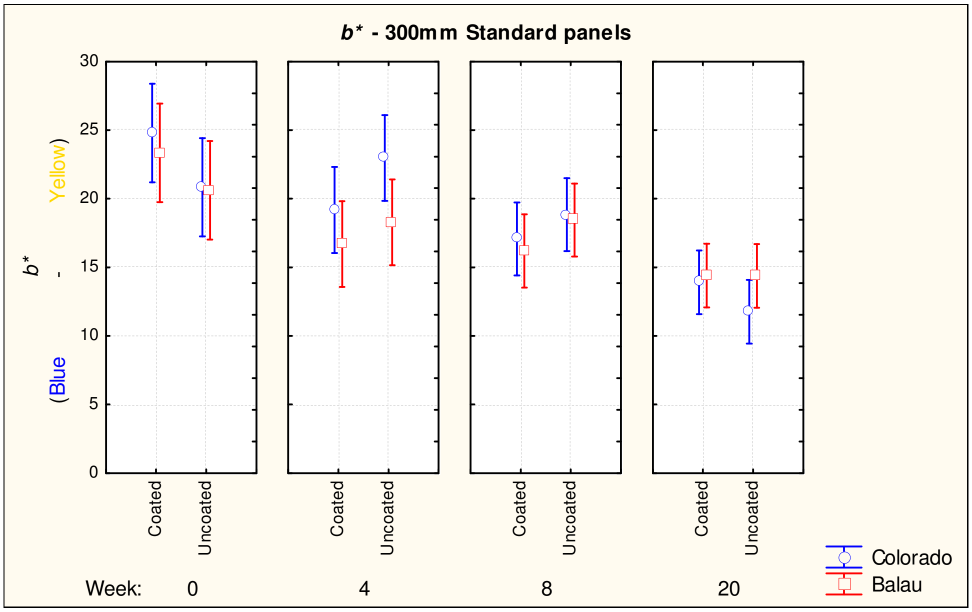


Figure 3.16: Effect of natural weathering on the yellowing (*b**) of coated and uncoated Colorado and Balau – 300mm standard panels at Stellenbosch

3.3.2.1.4 Delta E Values

Decks. No statistically significant differences were found between the *ΔE** values of the sample groups at Stellenbosch (Figure 3.17) and Yzerfontein (Figure 3.18). During the first 4 weeks of weathering a rapid colour change was observed for both uncoated Colorado and Balau samples. Thereafter, no significant differences were found between the overall colour changes of species up to 12 weeks. After 12 weeks Colorado started showing higher *ΔE** values than Balau for both coated and uncoated samples. After 30 weeks of weathering Colorado had undergone the most colour change. Coating had a significant effect on the amount on colour change, however, the difference between coated and uncoated was smaller than expected. According to Feist and Hon (1984) the protection of wood against discolouration should prevent the formation of free radicals induced by UV-irradiation and the access of water to the reaction sites. The results of this study agree with the latter where the coated samples suffered slightly less discolouration than the uncoated samples.

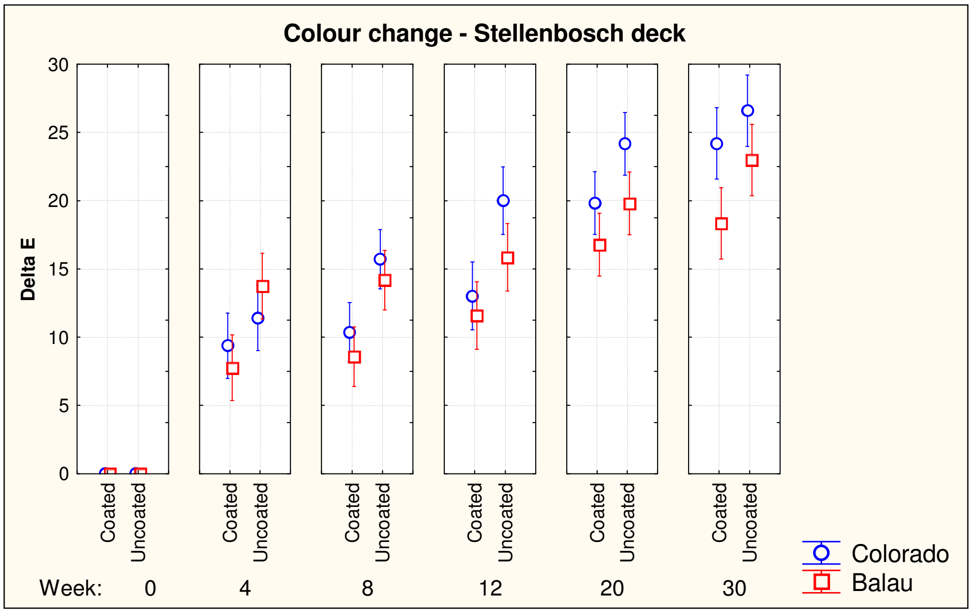


Figure 3.17: Effect of natural weathering on the colour change (*ΔE*) of coated and uncoated Colorado and Balau – Stellenbosch deck

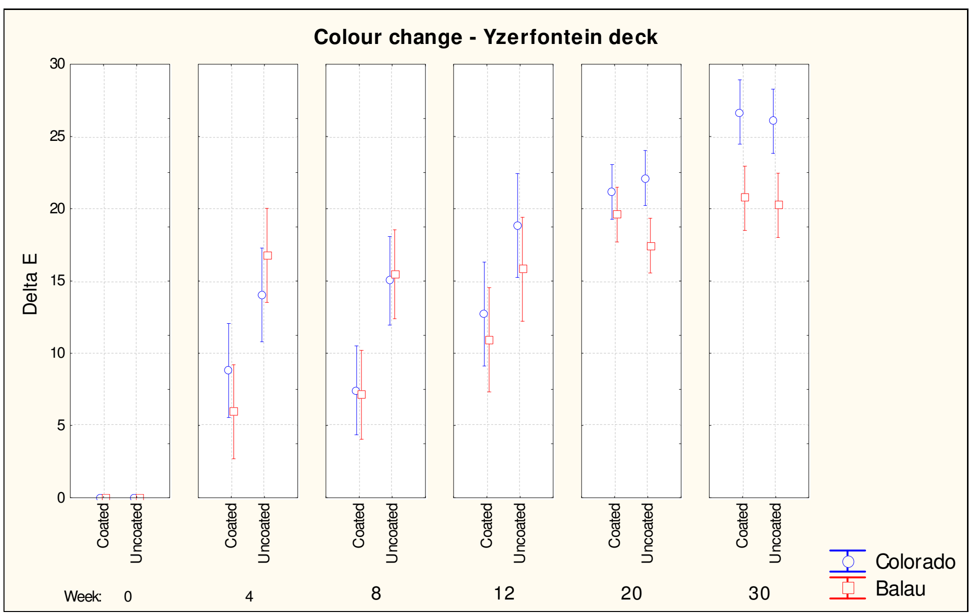


Figure 3.18: Effect of natural weathering on the colour change (*ΔE*) of coated and uncoated Colorado and Balau – Yzerfontein deck

300mm standard panels. Figure 3.19 shows the overall change in colour (*ΔE**) due to natural weathering. During the first 4 weeks of weathering a rapid colour change was observed for both uncoated Colorado and Balau samples. Thereafter, no statistically significant differences were found between the overall colour changes of the two timbers. The total amount of discolouration, after 20 weeks of weathering, observed for uncoated samples was almost double the amount for coated samples.

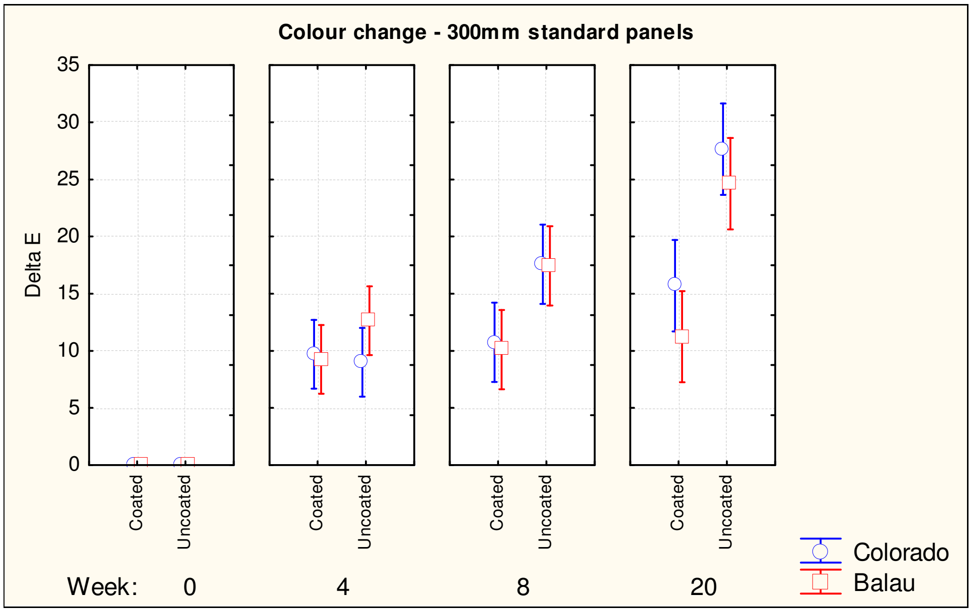


Figure 3.19: Effect of natural weathering on the colour change (*ΔE*) of coated and uncoated Colorado and Balau – 300 mm standard panels at Stellenbosch

3.3.2.2 Roughness

The effect of exposure on the surface roughness of coated and uncoated samples is summarized in Table 3.11. The surface roughness of decking samples at Stellenbosch and Yzerfontein are depicted in Figures 3.20 and 3.21, and standard panels in Figure 3.22.

Deterioration of wood surfaces due to the combined effect of water and light, leads to the formation of macroscopic and microscopic intercellular and intracellular cracks or checks (Feist, 1983 and Williams, 2005). During weathering water also causes the loosening and removal of the surface fibers and particles.

Decks. Figures 3.20 and 3.21 depict the surface roughness values (*Rz*) of coated and uncoated Colorado and Balau decking samples at Stellenbosch and Yzerfontein, respectively. No statistically significant differences were found between the Rz values for these two environments.

Initially no statistically significant differences could be found between the *Rz* values of coated and uncoated samples. Both coated and uncoated samples showed an increase in roughness values as weathering continued. After 12 weeks, differences started showing between uncoated Colorado and Balau samples. The uncoated Balau samples showed significantly higher *Rz* values than the uncoated Colorado sample after 20 weeks of exposure. After 30 weeks of exposure, significant differences were found between coated and uncoated samples of both species. Balau had a significantly higher value than Colorado, which could be explained by the differences in density and anatomical structure of these two timbers, as discussed earlier in this chapter or Chapter 2. According to Hiziroglu *et al*. (2008) species with higher densities generally result in smoother surfaces after weathering, which is in agreement with the results of this study.

No statistically significant differences were found between the roughening of radial and tangentially cut samples throughout the weathering period.

Table 3.11: Average surface roughness (*Rz*) of coated and uncoated Colorado and Balau after exposure to natural weathering at Stellenbosch (deck and 300mm standard panels) and Yzerfontein (deck)

Exposure site	Species	Cut	Treatment	Time of exposure (weeks)				
				4 (*Rz*)	8 (*Rz*)	12 (*Rz*)	20 (*Rz*)	30 (*Rz*)
Stellenbosch - deck	Colorado	Radial	Coated	73.2	83.6	86.9	108.6	120.3
			Uncoated	57.4	63.4	70.0	85	116
		Tangential	Coated	70.6	72.3	70.4	86.3	129.3
			Uncoated	90.2	95.6	87.9	131.7	136
	Balau	Radial	Coated	86.9	94.7	101.6	108	124.6
			Uncoated	88.4	93.3	101.6	113	124.3
		Tangential	Coated	97.4	101.8	107.0	131.6	131.6
			Uncoated	90.5	102.7	108.1	134.3	134
Yzerfontein - deck	Colorado	Radial	Coated	62.5	59.8	74.9	114	118.3
			Uncoated	77.9	80.5	87.2	123	122.6
		Tangential	Coated	57.8	64.7	61.5	109.6	114
			Uncoated	80.2	71.5	78.3	122.6	122.3
	Balau	Radial	Coated	72.1	72.2	83.1	123	127.3
			Uncoated	94.6	97.8	94.8	130	129.6
		Tangential	Coated	90.8	96.5	94.2	129.6	134
			Uncoated	94.0	96.8	113.6	132.3	132
300mm standard panels	Colorado	Radial	Coated	58.8	63.3	*	88.9	*
			Uncoated	97.3	99.2	*	108	*
		Tangential	Coated	67.1	69.9	*	89.3	*
			Uncoated	83.4	105.5	*	113	*
	Balau	Radial	Coated	76.6	78.2	*	96.0	*
			Uncoated	85.0	89.5	*	131.7	*
		Tangential	Coated	75.0	64.6	*	131.6	*
			Uncoated	84.8	91.3	*	134.3	*

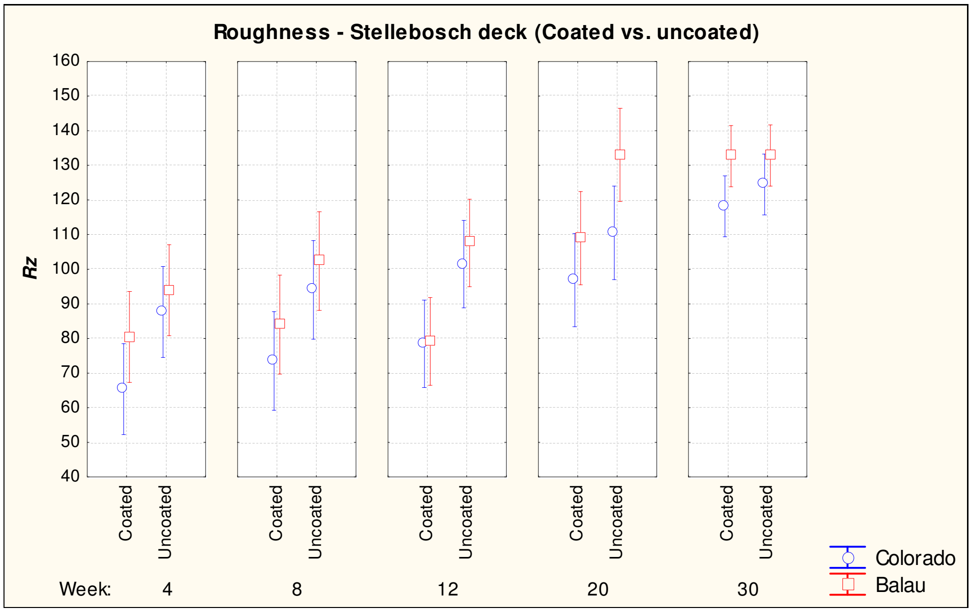


Figure 3.20: Effect of natural weathering on surface roughness (*Rz*) of coated and uncoated Colorado and Balau – Stellenbosch deck

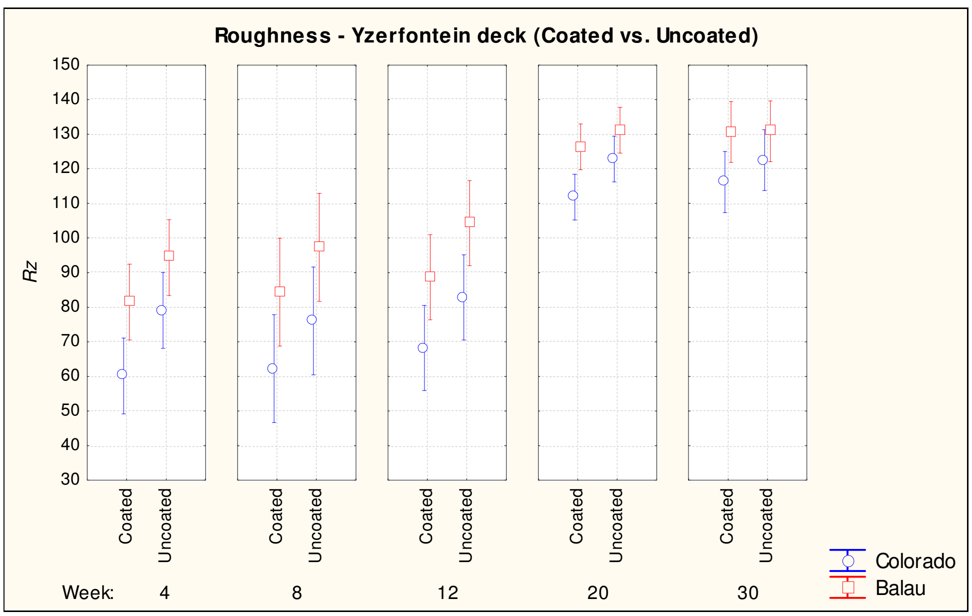


Figure 3.21: Effect of natural weathering on surface roughness (*Rz*) of coated and uncoated Colorado and Balau – Yzerfontein deck

300mm standard panels. Figure 22 depicts the surface roughness (*Rz*) values of coated and uncoated Colorado and Balau 300mm standard panels. After 8 weeks of weathering, no statistically significant differences were observed between the *Rz* values of Colorado and Balau. Coating, however, had a significant effect. After 20 weeks of weathering Balau started showing significantly higher roughness values than Colorado for both coated and uncoated samples.

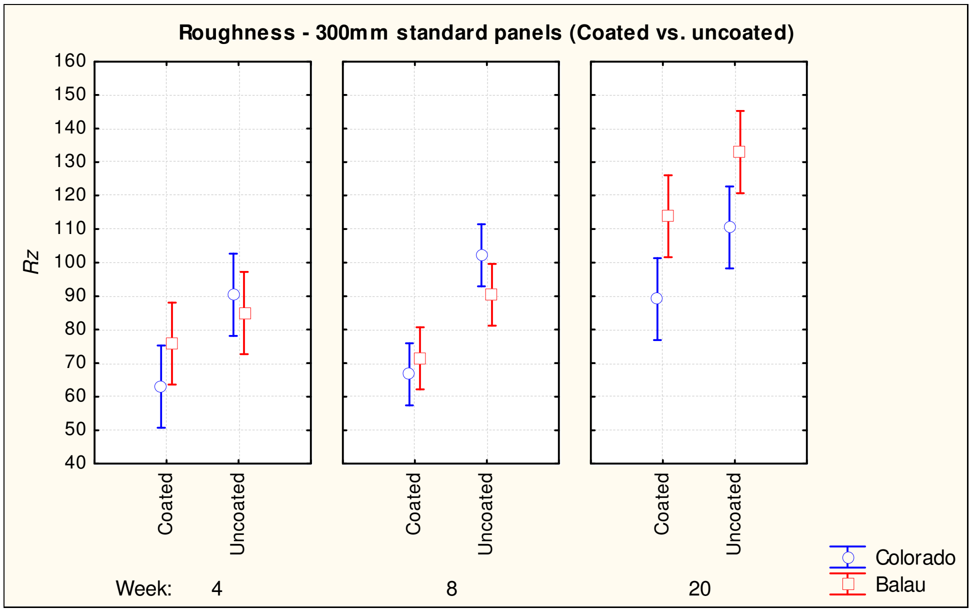


Figure 3.22: Effect of natural weathering on surface roughness (*Rz*) of coated and uncoated Colorado and Balau – 300 standard panels at Stellenbosch

3.3.2.4 Deformation and substrate defects

Table 3.12: Average deformation and % substrate defects after natural weathering

Exposure site	Species	Cut	Treatment	Defects after 20weeks (standard panels) and 30 weeks (decks)*				
				% Surface Checks	% Checks	% Cracks	Cup	Twist
Stellenbosch - deck	Colorado	Radial	Coated	70	10.6	5.3	*	*
			Uncoated	83.3	4	0	*	*
		Tangential	Coated	46	6	1.3	*	*
			Uncoated	100	36	2.6	*	*
	Balau	Radial	Coated	100	7.3	1.33	*	*
			Uncoated	100	17.3	0	*	*
		Tangential	Coated	100	16.6	3.3	*	*
			Uncoated	100	80.6	2.6	*	*
Yzerfontein - deck	Colorado	Radial	Coated	68.6	11.3	0	*	*
			Uncoated	100	0	4.6	*	*
		Tangential	Coated	100	1.3	0	*	*
			Uncoated	59.3	0	0	*	*
	Balau	Radial	Coated	100	0	0	*	*
			Uncoated	100	0	2	*	*
		Tangential	Coated	100	36.6	0	*	*
			Uncoated	100	12.6	1.3	*	*
300mm standard panels	Colorado	Radial	Coated	100.	0.	0	0	0
			Uncoated	100.	28.6	6.6	0	0
		Tangential	Coated	48.6	0	0	0.21	1.85
			Uncoated	100.0	10.0	0	0.88	0.90
	Balau	Radial	Coated	2.6	0.6	0	0	0
			Uncoated	100.0	17.3	0.6	0	0
		Tangential	Coated	68.0	9.3	0.6	0	1.63
			Uncoated	100.0	70.0	2.6	0.75	4.18

The effect of exposure on the deformation, and formation of substrate defects, of coated and uncoated samples is summarized in Table 3.12. Percentage substrate defects of decking samples at Stellenbosch and Yzerfontein after 30 weeks, and standard panels after 20 weeks of exposure are depicted in Figures 3.23 – 3.25. Deformation values of standard panels after 20 weeks of exposure are depicted in Figure 3.26. Even though no cup or twist appeared on decks, prolonged exposure would cause screws to pull away from bearers and samples would start cup and twist.

3.3.2.4.1 Surface Checks

Figure 3.23 (a and b) depicts the average percentage surface checks formed after 30 weeks of exposure on the decking samples at Stellenbosch and Yzerfontein. Figure 3.23(c) depicts the average percentage surface checks formed on the 300mm standard panels at Stellenbosch after 20 weeks of exposure.

Decks. After 30 weeks of weathering, no statistically significant differences were found between the percentage of surface checks present in the uncoated Colorado and Balau decking samples at Stellenbosch. The same applied for the samples at Yzerfontein, with the only exception being the uncoated, tangentially cut Colorado samples which only showed an average of 59.3 % surface checks.

As expected, coated samples formed fewer surface checks than uncoated samples. Coated decking samples at Stellenbosch developed fewer surface checks than the samples at Yzerfontein. The results for the samples at Stellenbosch were as follows: After 30 weeks of weathering, coated, radially cut Balau showed 46 percent surface checks, compared to the 70 percent present in the coated, radially cut Colorado. Tangentially cut Colorado (83.3%) exhibited fewer surface checks than tangentially cut Balau (100%). The results for the coated samples at Yzerfontein were as follows: Radially cut Colorado (68.6%) formed fewer surface checks than the tangentially cut (100%) samples. Both radially and tangentially cut Balau samples developed 100% surface checks.

300mm standard panels: After 20 weeks of weathering, all the uncoated samples contained 100% surface checks. The coating was effective in decreasing most of the surface check formation. The results for the coated samples were as follows: Radially cut Balau (2.6%) contained the least surface checks, followed by tangentially cut Colorado (48.6%), tangentially cut Balau (68%) and radially cut Colorado (100%).

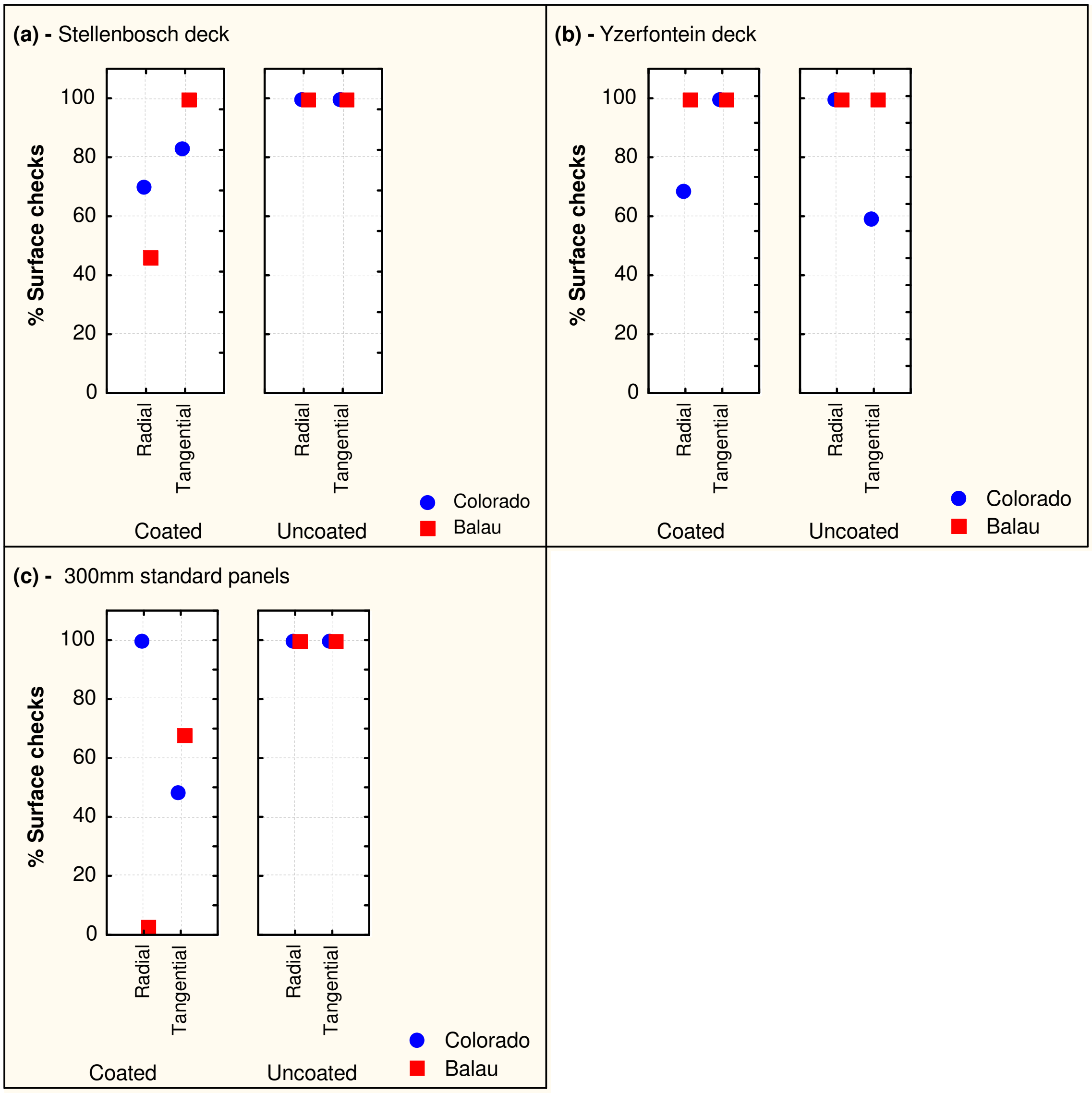


Figure 3.23: Average surface check formation of coated and uncoated, radial and tangentially cut Colorado and Balau – (a) Stellenbosch deck, (b) Yzerfontein deck and (c) 300mm standard panels

3.3.4.2.2 Checks

Figure 3.24 (a and b) depicts the average percentage checks formed after 30 weeks of exposure on the decking samples at Stellenbosch and Yzerfontein. Figure 3.24(c) depicts the average percentage checks formed on the 300mm standard panels at Stellenbosch after 20 weeks of exposure.

Decks. After 30 weeks of weathering, the only statistically significant difference found between the percentages of checks contained by Stellenbosch decking samples compared to Yzerfontein samples was that of uncoated, tangentially cut Balau, which exhibited more checks at the Stellenbosch (80%) than at the Yzerfontein deck (12.6%)

Of the coated samples, tangentially cut Balau (36%) contained the highest amount of checks. No statistically significant differences were found between the other samples groups. When comparing the swelling coefficients of Colorado and Balau, it can be seen that Balau had a larger difference between its radial and tangential swelling coefficients, which could explain the larger amount of checking found in Balau. The coated samples at Stellenbosch showed less checking than the uncoated samples which indicated that the coating was effective in controlling the moisture gradients in samples i.e. decreased the amount of substrate defects, however, the uncoated samples at Yzerfontein showed less checking. This result was unexpected and the reason for it is not clear.

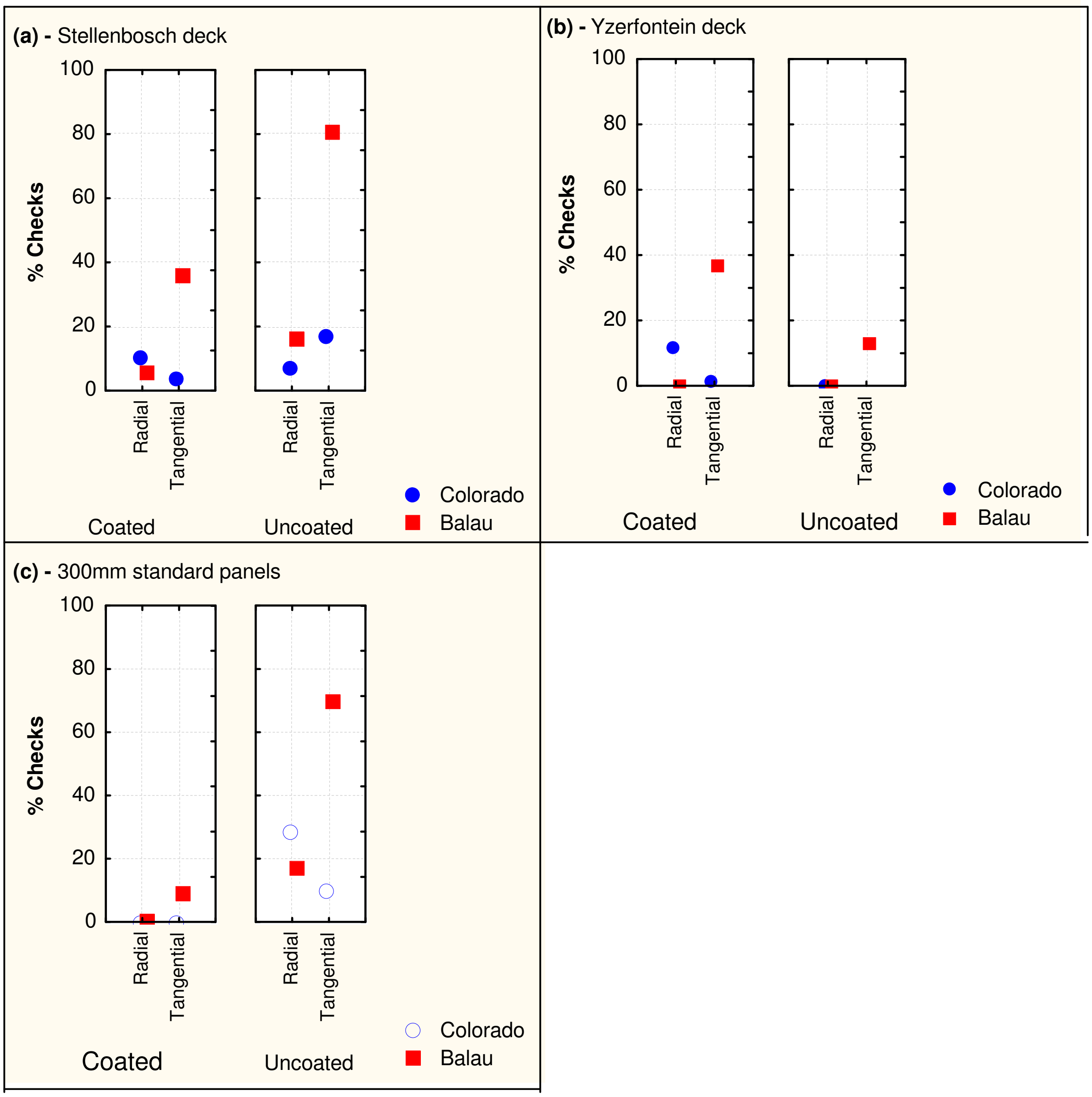


Figure 3.24: Average checking of coated and uncoated, radial and tangentially cut Colorado and Balau – (a) Stellenbosch deck, (b) Yzerfontein deck and (c) 300mm standard panels at Stellenbosch

300mm standard panels: Figure 3.24(c) depicts the average percentage checks formed on the 300mm standard panels at Stellenbosch after 20 weeks of exposure. This result confirmed that the coating was effective in decreasing the amount of check formation as expected. Coated, radial and tangentially cut Colorado and Balau showed no significant differences. Uncoated, tangentially cut Balau (70%) contained the highest amount of checks. None of the other uncoated samples showed any statistically significant differences.

3.3.4.2.3 Cracks

Figure 3.25 (a and b) depicts the average percentage cracks formed after 30 weeks of exposure on the decking samples at Stellenbosch and Yzerfontein. Figure 3.25(c) depicts the average percentage cracks formed on the 300mm standard panels at Stellenbosch after 20 weeks of exposure.

Decks: On average, more crack formation was observed for the decking samples at Stellenbosch than at Yzerfontein, and at both locations radially cut Colorado and Balau, samples displayed more crack formation than the tangentially cut samples.

The results for the coated samples at Stellenbosch were as follows: Radially cut Colorado (5.3%) displayed the highest amount of crack formation, followed by tangentially cut Balau (2.6%) and radially cut Colorado (1.3%). Results for the uncoated samples at Stellenbosch are as follows: Radially cut Balau (3.3%) showed the highest amount of crack formation, followed by tangentially cut Balau (2.6%) and radially cut Colorado (1.3%).

No crack formation was observed for coated Colorado and Balau samples at Yzerfontein. Results for the uncoated samples at Yzerfontein are as follows: Radially cut Colorado (4.1%) showed the highest amount of crack formation, followed by radially cut Balau (2%) and tangentially cut Balau (1.3%). This indicates that the coating was effective in preventing crack formation in the samples at Yzerfontein.

300mm standard panels: Figure 3.25c depicts the amount of crack formation that formed in the standard panels. For the coated samples, tangentially cut Balau (0.6%) was the only group to exhibit any cracks. The results for the uncoated standard panels were as follows: Radially cut Colorado (6.6%) showed the highest amount of crack formation, followed by tangentially cut Balau (2.6%) and radially cut Balau (0.6%). This indicates that the coating was effective in preventing crack formation during the 20 weeks of weathering exposure.

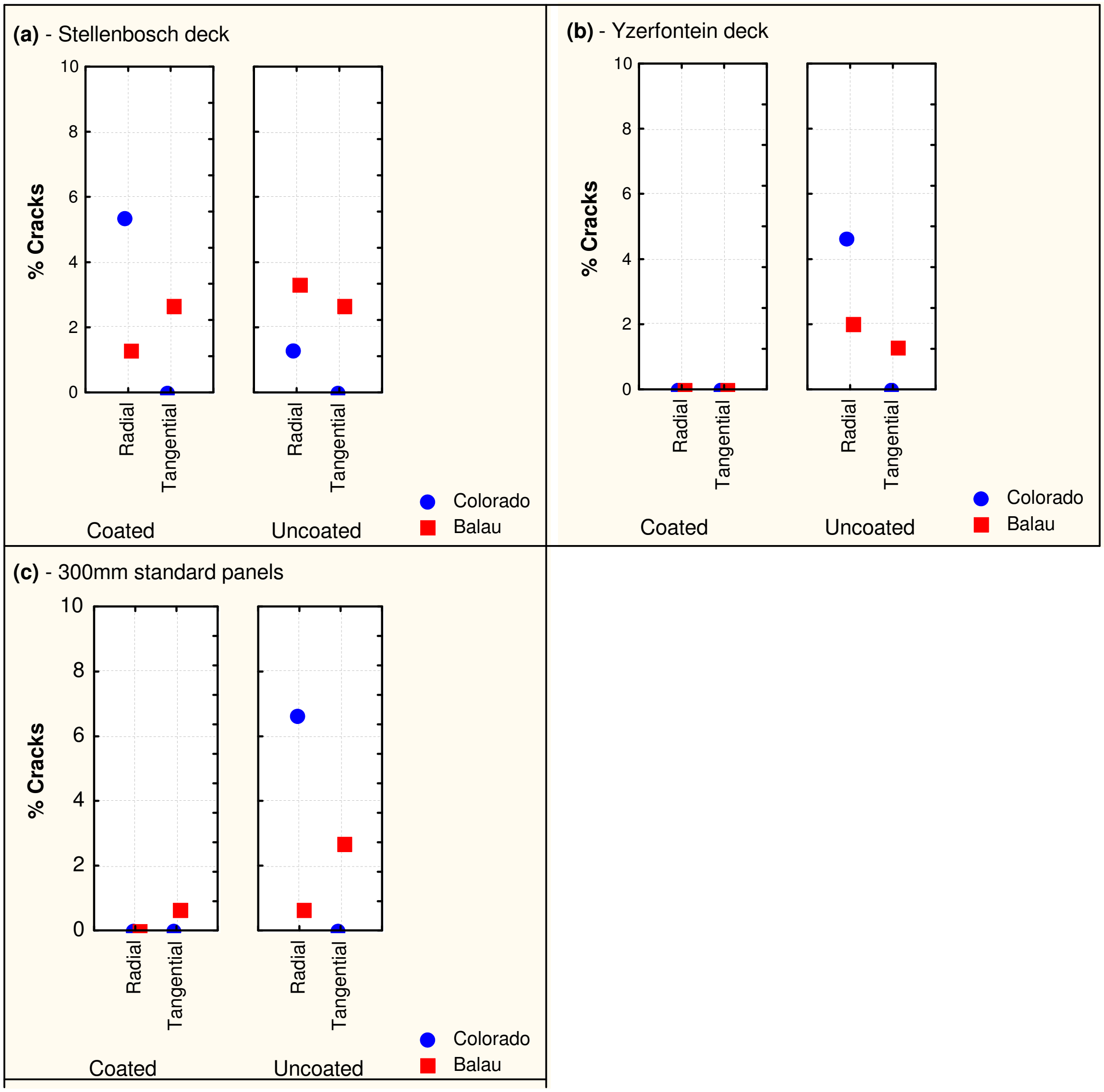


Figure 3.25: Average crack formations of coated and uncoated, radial and tangentially cut Colorado and Balau – (a) Stellenbosch deck, (b) Yzerfontein deck and (c) 300mm standard panels

3.3.2.5 Deformation

The width (85mm) of the smaller samples exposed at Stellenbosch exceeded the thickness (15mm) by more than 5 times which can result in excessive cupping of samples. The average deformation of standard panels are summarized in Table 3.12 and is depicted in Figure 3.26 (a and b)

Cup: After 20 weeks of weathering, coated samples showed significantly less cup than uncoated samples and only cupping of tangentially cut samples occurred. Tangentially cut Colorado samples (0.25mm) were the only coated samples which displayed any cup. Tangentially cut, uncoated Colorado (0.89mm) displayed the highest amount of cup, followed by tangentially cut Balau (0.75mm).

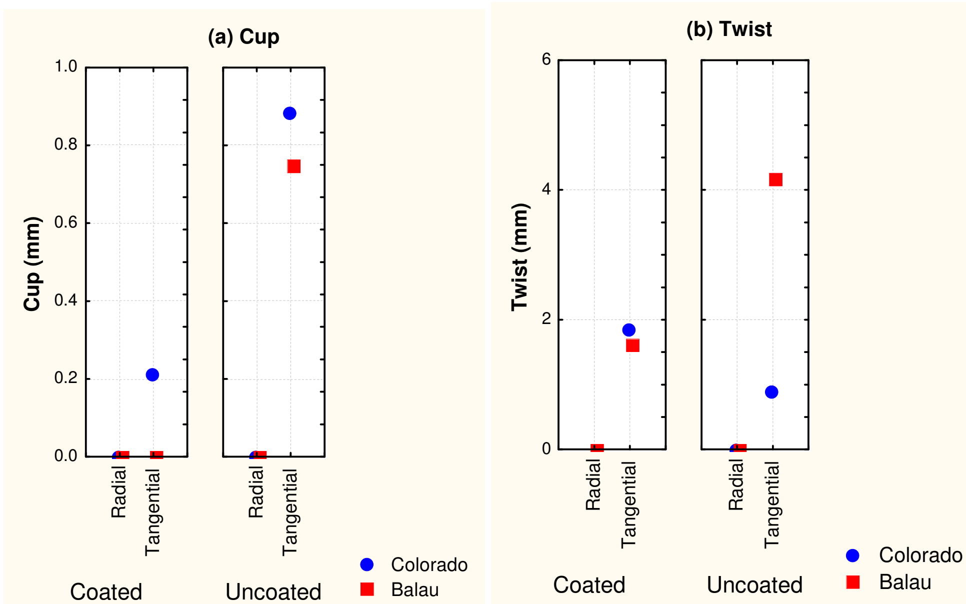


Figure 3.26: Average deformation of radially and tangentially cut, coated and uncoated Colorado and Balau samples after 20 weeks of natural weathering: **(a)** cup and **(b)** twist

Twist: After 20 weeks of weathering, coated samples showed significantly less twist than uncoated samples and twist only occurred in the tangentially cut samples. No significant difference was found between coated, tangentially cut Balau (1.7mm) and Colorado (1.8mm) samples. Tangentially cut, uncoated Balau (4.2mm) displayed the highest amount of twist, followed by tangentially cut Colorado (0.9mm). When comparing the swelling coefficients of Colorado and Balau (Table 3.4), it can be seen that Balau has a larger difference between its radial and tangential swelling coefficients, which could explain the larger amount of twist observed in Balau.

3.3.2.6 Surface wettability

According to Kalnins and Feist (1993) the ability of wood to repel water is decreased as wood weathers. Water readily wets severely weathered surfaces and is quickly absorbed into the wood. The average wettability values of the 300mm standard panels, given as contact angles, are listed in Table 3.12 and shown in Figure 3.27. No statistically significant differences were found between the contact angles of the two timbers during the weathering period.

As expected, the treatment of wood with a coating changed the surface chemistry (wettability) of Colorado and Balau samples' surfaces. The coating increased the initial contact angle of samples. The coating was also effective in maintaining a relatively hydrophobic surface during weathering, meaning that sample surfaces were not easily wettable. After only 4 weeks of weathering, the contact angle of uncoated sample surfaces decreased by half of their original values. After 20 weeks of weathering, the contact angles of uncoated samples were basically zero, meaning that water penetrated the surfaces almost immediately after contact. The decrease in contact angle can be attributed to the degradation of extractives during weathering and with the continuation of weathering, the degraded extractive products were washed away. Besides the reduction of extractives and their water repellent effect, lignin, which is a hydrophobic component of wood was also degraded and removed during weathering. Cellulose, being more resistant to weathering effects became more abundant on the weathered surfaces. This presumably increases the hydroxyl concentration on the surface. Wetting is also assisted by the increase in checks which cause water to rapidly penetrate the surface.

Table 3.13: Average contact angle values of coated and uncoated Colorado and Balau after exposure to natural weathering – 300mm standard panels at Stellenbosch

Species	Cut	Treatment	Time of exposure (weeks)		
			0	4	20
Colorado	Radial	*Coated*	73.9	73.6	77.3
		Uncoated	58.9	34.3	0
	Tangential	*Coated*	69.6	72.3	65.4
		Uncoated	61.4	36	0
Balau	Radial	*Coated*	80.1	73.4	83.8
		Uncoated	60.7	25.8	0
	Tangential	*Coated*	69.5	61.6	64.1
		Uncoated	65.4	27.5	0

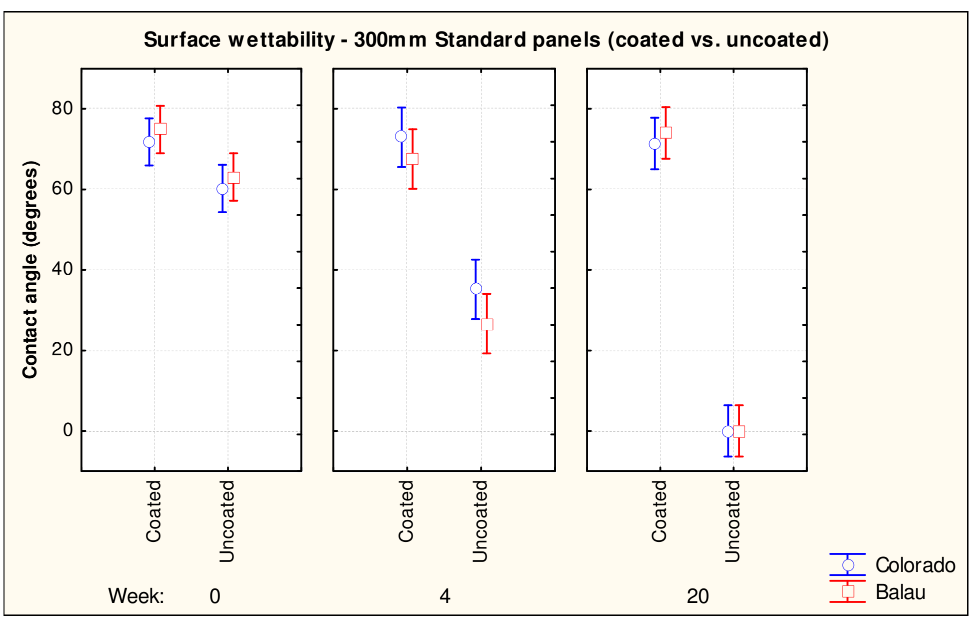


Figure 3.27: Effect of natural weathering on contact angle values of coated vs. uncoated Colorado and Balau

3.3.2.7 Mass

Figure 3.28 depicts the deviation of samples' mass from their original mass measured after conditioning and during exposure. During week 4 and 5 it was observed that the gain in mass of uncoated samples was nearly twice that of the coated samples, the same observation was made for the period weeks 9-10 and 12-15. This indicated that the coating was effective in controlling moisture uptake.

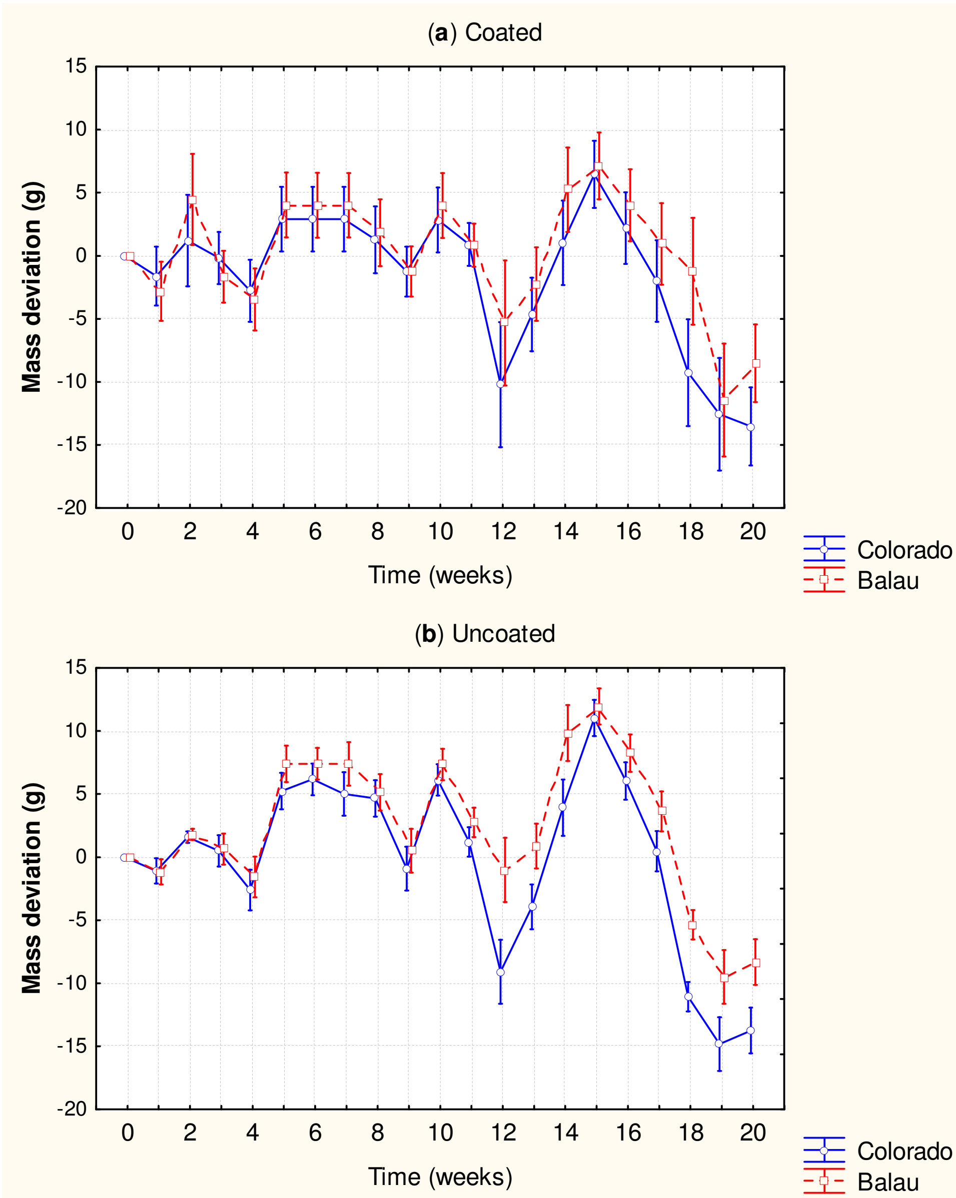


Figure 3.28: Mass deviations of (**a**) coated and (**b**) uncoated 300mm standard panels over 20 weeks at Stellenbosch

After 19 weeks of weathering the driest time of the weathering period was reached. After this period, uncoated Colorado showed significantly higher mass loss than Balau. Colorado contained 1% more water soluble extractives than Balau (Table 3.9). These extractives would have leached out during the weathering period which would explain the higher mass loss.

3.4 Conclusion

A. Comparison of the material (anatomical, physical and chemical) properties of Colorado and Balau:

- Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau.
- Colorado had a higher density than Balau.
- Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's.
- The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's, but it had a lower swelling anisotropy resulting in a lower tendency to twist.
- Colorado had a higher water soluble extractive content than Balau which lead to the rapid initial colour changes of uncoated wood.

Balau is a popular choice when considering a timber for exterior use because of its reputation of performing relatively well during weathering. From the many similarities found between the material properties of Balau and Colorado, one would expect little difference in the weathering behaviour between the two timbers.

B. Comparison of the natural weathering behaviour Colorado and Balau as determined by their material properties, environment and processing (cutting pattern and surface treatment):

Colour: No initial differences were found for the overall colour change (ΔE^*) between Stellenbosch and Yzerfontein. However, after 30 weeks of weathering Colorado had undergone slightly more colour change than Balau. Coating had a significant effect on the amount on colour change, however, the difference between coated and uncoated was smaller than expected.

A significant difference was observed between Colorado and Balau's change in redness (a^*). Colorado experienced a larger overall decrease in redness (a^*) than Balau. This could be attributed to Colorado's large quantity of water soluble extractives which were leached out and washed of the surface during weathering. Coating had no significant effect in decreasing the amount of change in redness (a^*).

After 30 weeks of weathering Balau showed a greater decrease in b^* than Colorado at the Stellenbosch site but the two timbers' b^* values decreased similarly at the Yzerfontein site.

No statistically significant differences were observed between the lightness values (L^*) samples at Stellenbosch and Yzerfontein. Both Colorado and Balau showed less change in lightness after weathering when coated compared to the uncoated samples. Uncoated Colorado ended slightly darker than Balau. However, this difference was so small, even though statistically significant, that it could not be distinguished by the human eye.

Surface roughness: No statistically significant differences were observed between the roughness values of decking samples at Stellenbosch and Yzerfontein. During weathering Balau showed a significantly higher increase in roughness than Colorado. This could be explained by the lower density and higher swelling anisotropy of Balau. Radially cut samples showed a larger increase in roughness than tangentially cut samples. The increase in roughness observed for coated samples was lower than observed for uncoated samples, the coating was thus effective in retarding the roughening of surfaces.

Substrate defects:

Balau showed larger amounts of surface checking than Colorado at Stellenbosch and Yzerfontein. Environment played a role; the samples at Yzerfontein experienced more surface checking. As expected, coating decreased the amount of surface checks on Colorado and Balau.

Balau showed larger amounts of checking than Colorado at Stellenbosch and Yzerfontein. Environment played a role; the samples at Stellenbosch experienced more checking. Coating also decreased the amount of checks on Colorado and Balau.

Radially cut Colorado showed slightly higher amounts crack formation at Stellenbosch than Balau. Crack formation was more severe at Stellenbosch than at Yzerfontein. Coating was not able to decrease the amount of cracks formed.

Deformation: Colorado showed slightly more cup than Balau, however, Balau showed much larger amounts of twist than Colorado. This could also be attributed to the higher swelling anisotropy of Balau. Both these defects were mostly only observed for the uncoated, tangentially cut samples.

Wettability: No statistically significant differences were found between the hydrophobicity of the two timbers. The contact angle of the uncoated timber decreased towards zero after 20 weeks of exposure. The coating was effective in increasing the initial hydrophobicity of samples and maintained a relatively hydrophobic surface during weathering. No differences were found concerning the effect of sample cut on sample surface wettability.

C. Final comment

From the results of this study it can be concluded that both timbers performed better at Yzerfontein than at Stellenbosch. This can be attributed to Stellenbosch's lower and more fluctuating humidity levels in the summer time, causing excessive check and crack formation. Colorado is comparable with Balau as a decking material. Based on aesthetics considerations (colour change and surface defects), Colorado performed similar to Balau and twisted less.

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Chapter 4: Artificial weathering behaviour of Colorado (*Eucalyptus camaldulensis* and *Eucalyptus tereticornis*) and Balau (*Shorea* spp.)

Abstract

Balau, a group consisting of 21 *Shorea* species, is widely used for outdoor application. In South Africa, Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of a substitute timber for decking material. One possible timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India and parts of South America because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors. The timber was initially utilized as raw material for the pulp and paper industry but is now gaining importance in structural uses like furniture, flooring and decking. The aim of this exploratory study was to investigate relevant material properties and to examine the accelerated weathering behaviour of Colorado and Balau to predict Colorado's suitability as decking material. In this investigation it was found that Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau and had a higher density than Balau. Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's. The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado's lower swelling anisotropy can result in a lower tendency to twist in service. Colorado had a higher water soluble extractive content than Balau, which can lead to the rapid initial colour changes when the timber is exposed uncoated. The accelerated weathering performance was investigated in a QUV fluorescent UV/condensation weatherometer equipped with UVB-313 type lamps. Properties of samples were evaluated after 92h, 200h, 432h and 912h of exposure. FT-IR analysis showed that there were no statistically significant differences between the chemical changes which occurred on the uncoated surfaces of Colorado and Balau after 912 hours of weathering. A penetrating coating was not effective in preventing the photo-degradation of the aromatic rings present in lignin (1509 $cm^{-1}$and 1597 cm^{-1}). However, the coating was effective in preserving the 1461 cm^{-1} peak, which is characteristic of the C-H vibrations found in lignin, the 1229cm^{-1} which is characteristic of syringyl ring breathing in lignin, and C-O stretching vibration in lignin and xylan. The rest of the weathering characteristics of these timbers were similar to results found in a parallel running, natural weathering study conducted over 30 weeks. Balau showed a higher increase in roughness (*Rz*), surface checking and check formation than Colorado. Colorado showed slightly more cup than Balau, however, Balau showed much larger amounts of twisting than Colorado. No statistically significant differences were found between the surface hydrophobicity (measured as contact angle) of the two timbers. The coating was effective in increasing the initial hydrophobicity of samples and could maintain a relatively hydrophobic surface during weathering. No statistically significant differences were found when the effect of grain orientation on surface wettability was assessed Although only long term natural weathering studies and using substantially more samples can confirm its natural weathering performance, the results of this exploratory, accelerated weathering study indicated that Colorado can successfully be used as a substitute decking material for Balau.

4.1 Introduction

Wood has been used as a building material for many millennia and despite the invention of new building materials over the last century, the utilization of wood in the construction industry shows little sign of declining. This can be attributed to wood's versatile and attractive engineering and structural properties.

All man-made and natural materials, including wood, are susceptible to environmental degradation. When wood is exposed outdoors, above ground, a complex combination of chemical, mechanical, and light energy factors contribute to what is described as weathering (Feist, 1983). These weathering factors are as follows: solar radiation (ultra violet (UV), infrared and visible light), moisture (rain, dew, snow and changes in relative humidity), abrasion by windblown particles, heat and oxygen. In recent years, an additional weathering influence has arisen with the presence of atmospheric pollutants such as gaseous SO_2, NO_2, and O_3 (Anderson *et al*, 1990). Abrasion of surfaces as a result of human activities such as walking on decks, and maintenance such as cleaning surfaces with cleaners and brighteners and power washing cause further modification of weathering effects (Feist, 1990 and Williams, 2005).

The weathering process of wood starts immediately after wood is exposed to sunlight which causes the photo-oxidation or photochemical degradation of the exposed wood surface (Williams, 2005). At first the colour changes and then the combined effect of solar radiation and moisture leads to surface roughening as the grain raises, formation of surface checks which later grow into large cracks, surfaces gather dirt and mildew, the wood loses its surface coherence and becomes friable, splinters, and fragments come off (Feist, 1983). If boards contain compression or juvenile wood, cross-grain checking may develop, the boards may cup and warp and pull away from fasteners, especially in decking applications (Williams, 2005).

To develop methods to retard or inhibit degradation, it is important to understand the mechanisms of weathering that lead to chemical changes and degradation of physical properties, to increase the service life of all types of wood products in any type of environment.

The effect of weathering on wood or surface treatments can be studied using either natural outdoor exposure tests or indoor accelerated laboratory tests. These two major test types are not the same, however, many researchers have found good correlations between erosion rates from natural and accelerated weathering (Feist and Mraz, 1978, Anderson *et al*, 1990, Arnold *et al*, 1991, and Tolvaj and Mitsui, 2005). The main problem with natural weathering tests are that the weather conditions are not repeatable and vary from place to place, therefore, artificial weathering is more useful when studying the combined or individual effects of water and UV radiation on wood surfaces, and allows one to study these effects in a shorter period of time.

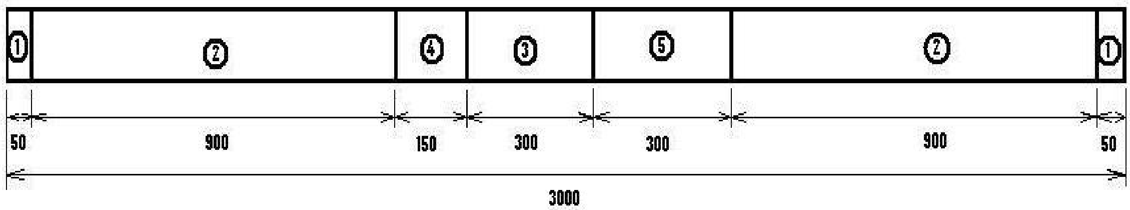
Balau is a group consisting of 21 *Shorea* species (Pande *et al,* 2005). The timber is widely used for outdoor application, and in South Africa Balau is one of the most popular materials used for decking. Due to the increasing scarcity of Balau, it is of economic importance to investigate the possibility of a substitute species for decking material. One possible substitute timber could be Colorado, a mixture containing one or more of the following: *Eucalyptus camaldulensis, Eucalyptus tereticornis* and their hybrids. These two species and their hybrids are extensively cultivated in countries such as Australia, India, and parts of South America, because of their short rotation period and easy adaptability to a wide variety of soil and climatic factors (Sharma et al, 2005). These two species were initially utilized as raw material for the pulp and paper industry, but are now gaining importance for commercial, structural uses like furniture, flooring and decking.

This paper forms part of a larger study on the weathering behaviour and associated wood characteristics of Colorado and Balau. The objective of this investigation was to determine the physical and chemical changes of these timbers when subjected to accelerated weathering. Practical aspects such as the effect of grain orientation (radial vs tangential) and surface coating were also included in the study.

4.2 Materials and methods

4.2.1 Materials

Twelve Colorado and Balau, defect free heartwood samples of which six were radially and the other six tangentially cut, each measuring 3000 x 19 x 85mm, were obtained from commercial sources. As depicted in Figure 4.1 each 3m board was divided into matched samples required for parallel running natural and accelerated weathering studies.



Sample no and purpose legend:
(1) Density, fiber saturation point (FSP) and swelling coefficient determinations (*50 x 85 x 19mm*)
(2) Natural weathering exposure on decks erected at Stellenbosch and Yzerfontein respectively (*900 x 85 x 19mm*) – not used in this investigation
(3) Standard panels for permeability determination and natural weathering in north facing exposure racks at Stellenbosch (*300 x 85 x19mm*) – not used in this investigation
(4) Accelerated weathering (*150 x 85 x 5mm*)
(5) Anatomical studies and extractives determination

Figure 4.1: Cutting pattern of 3000mm boards

The 24 small samples (Figure 4.1, no 4) were sanded with a commercial P100 grit abrasive paper. Half of the wood samples were coated with 3 layers of a commercially available penetrating finish according to manufacturer's specifications. The coating was applied on five of the sample's surfaces (4 edges and 1 face). The solvent borne finish contained a brown coloured ("mahogany") pigment. Samples 1, 4 and 5 were used in this study, samples 2 and 3 were only used in the natural weathering study running parallel with this investigation and reported on in Chapter 3. The samples were conditioned for two weeks before exposure.

4.2.2 Accelerated weathering chamber

Samples were placed in a QUV fluorescent UV/condensation weatherometer (Q Panel, Cleveland, Ohio, USA). The lamps used were of the type UVB-313, which gives the highest irradiation at a wavelength of 313nm. These lamps are the most widely used light source in ASTM G-53 devices. Each 12h weathering cycle consisted of 8 hours UV exposure at 45°C, followed by a 4 hour condensation period at 50°C. Properties of all samples were evaluated after 92h, 200h, 432h and 912h of exposure. Measurements were taken at the lowest moisture conditions in a cycle, i.e. directly after completion of the radiation period to ensure repeatable moisture conditions and to maximize possible surface checking phenomena.

4.2.3 Determination of Density, FSP and Swelling coefficients

Two samples (Figure 4.1, no.1) from each 3000mm board were used for density, FSP and swelling coefficient determinations. The samples measuring 50 x 19 x 85mm, were squared on a bench sander and conditioned at 20°C/65%RH for one month. After conditioning, the samples' mass and dimensions were determined, oven dried at 102°C for 24 hours, and again, the mass and dimensions were measured. The oven dried samples were placed above water inside airtight containers, i.e. exposed to 100%RH at 20°C for three months. After this period, the mass and dimensions at FSP were measured. The following variables were calculated according to SANS 1783-1, 2007: (a) %MC at 20°C/65%RH, (b) FSP, (c) Density at 20°C/65%RH, (d) oven-dry density and (e) the radial, tangential and volumetric swelling coefficients (from 0%MC to FSP).

4.2.4 Anatomical Investigation

10mm (radial) x 10mm (tangential) x 15mm blocks were cut from each sample (Figure 4.1, no. 5). The blocks were placed in water, and softened by boiling them for 5 hours. Smoothly cut cross-sections were prepared using a Reichert sliding microtome. Micrographs were taken at 35x magnification with a Leica EZ4D optical microscope. Leica image analysis software was used to analyze the images.

4.2.5 Liquid water and water vapour permeability

Standard panels, measuring 300 x 85 x 15mm, were used for the water vapour permeability (WVP) and liquid water permeability (LWP) tests (Eloff, 1999), following the procedure described in Appendix 1.

Water vapour permeability (WVP) tests were conducted using an apparatus containing a rectangular basin with a surface area of 200cm^2 of which the edges were fitted with a rubber O-ring. The basin was filled to 50% of its volume with distilled water. The conditioned samples were weighed and clamped on top of the basin with the O-ring preventing any vapour loss other than through the sample. In effect, the middle 200cm^2 of the sample's area was exposed to an atmosphere of 100% RH. Samples were clamped in the apparatus for a period of 7 days, and weighed again. The WVP (in g.m^{-2}.day^{-1}) of a sample was calculated as follows:

$$\text{WVP} = (\text{Final Mass} - \text{Initial Mass}) / (0.2 \times 7\text{days}) \quad (1)$$

Liquid water permeability (LWP) tests were conducted using the same apparatus which was used for the WVP determination but with a different configuration. For LWP measurements the lower water basin was turned upside down. This allowed liquid water to lie on top of the sample's surface, whereby exposing the middle 200cm^2 of a sample's area to liquid water.

Samples were clamped in the apparatus for a period of 1 day, and weighed again. The LWP (also in g.m^{-2}.day $^{-1}$) of the sample was calculated as follows:

$$LWP = (Final\ Mass - Initial\ Mass)/\ (0.2 \times 1day) \quad (2)$$

WVP and LWP tests were conducted in a conditioned room at 20C°/65%RH.

4.2.6 Ethanol/cyclohexane (E/C) and water soluble extractives content

Solvent ethanol/cyclohexane (E/C) and water extractions were performed on wood powder (Figure 4.1, no 5) according to Tappi standard T 264 om-84.

4.2.7 Colour

Colour measurements were recorded using a Micromatch Plus spectrophotometer, equipped with a standard illuminant D65 (SHEEN) using the CIE-lab system. The colour parameters of this system are as follows; the *L** axis is the lightness (ranging from 0 (black) to 100 (white)), the *a** and *b** axes are the chromaticity coordinates (a positive *a** value refers to red, and a negative *a** value to green, while *+b* and *–b* denote yellow and blue respectively). These values are used to calculate the colour change *ΔE** as a function of the weathering period according to the following equations:

$$\Delta L^* = \Delta L_t^* - \Delta L_i^* \quad (3)$$

$$\Delta a^* = \Delta a_t^* - \Delta a_i^* \quad (4)$$

$$\Delta b^* = \Delta b_t^* - \Delta b_i^* \quad (5)$$

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2}\ \Delta b^{*2})^{1/2} \quad (6)$$

Where *i* refers to time zero and *t* indicates measurements at specific times.

Colour measurements were taken at $t = 0$, and after 92, 200, 432 and 912 hours of accelerated weathering exposure. Three measurements were taken per sample and colour changes were always monitored on the same location on the sample.

4.2.8 Surface roughness

Roughness was measured with a MarSurf PS1 surface profilometer. The instrument's needle had a cone shaped stylus tip with an angle of 90°. The measuring length was 17.5mm across the grain. The maximum vertical measuring range of the instrument was -200µm to +120µm. A phase corrected profile filter (Gaussian filter) was used in accordance with DIN 4768. The filter is characterized by a cut-off value. This value is the wavelength of a sinusoidal profile, the amplitude of which will be transmitted by the phase correct filter to a level of 50%. This cut-off defines which elements of the profile will be attributed to roughness or waviness. The *Rz* mode (mean peak-to-valley height (DIN 4287)) was chosen to characterize the average roughness.

Roughness measurements were also taken at $t = 0$, and after 92, 200, 432 and 912 hours of accelerated weathering exposure. The three measurements taken per sample were also repeated on the same location of the sample's surface.

4.2.9 Deformation

The two forms of warp used to describe deformation of samples are cup and twist. Measurements were taken after 912h of exposure according to methods described by SANS 1783-1 (2007).

4.2.10 Surface wettability

Wettability of the sample surfaces was determined by dispensing a 1-µL drop of distilled water on the wood surfaces with a micropipette. Images of the profile of each drop at 25x magnification were recorded using a Leica EZ4D microscope. Images were taken 4 seconds after drop placement. Five measurements were taken per sample. Both right and left contact angles were measured on each drop using Leica software. Contact angle measurements were also taken at t = 0, and after 92, 200, 432 and 912 hours of accelerated weathering exposure.

4.2.11 FT-IR

All spectra were recorded at $4cm^{-1}$ resolution with the use of a NEXUS model FT-IR instrument, custom made by Thermo Nicolet instruments. The IR spectra were recorded in reflectance mode using a Golden Gate Smart Performer Attenuated Total reflectance (ATR) from Thermo, equipped with ZnSe lenses. Shavings, taken from the exposed surface of each sample, were placed on the ZnSe horizontal ATR, and 16 scans performed. Three accumulated spectra for each sample were obtained at t = 0, and after 92, 200, 432 and 912 hours of accelerated weathering exposure. From each treatment group, six samples were scanned, their spectra accumulated and transformed into absorbance spectra averaged before baseline correction (1800-1850cm^{-1}), and normalized to 1 absorbance unit for the highest peak at 1030cm^{-1}. Instrument operation and data manipulation was performed using the available basic OMNIC software.

4.2.12 Statistical analysis

The statistical analysis of data was conducted with Statsoft Statistica 9. Interactive effects between multiple variables were analyzed using a factorial ANOVA. A test for normality was performed and an F-test was used with confidence intervals of 95%.

Response variables such as colour change (ΔE) and roughness (Rz), taken at different time intervals, were analyzed using repeated measures ANOVA. An F-test was used with confidence intervals of 95%.

4.3 Results and discussion

4.3.1 Material Properties

4.3.1.1 Density

The average, and upper and lower density values of Colorado and Balau within the 95% confidence intervals, are listed in Table 4.1, and depicted in Figure 4.2.

Table 4.1: Average ovendry density of Colorado and Balau

SPECIES	Average ovendry density (g/cm^3)	Density -95.00%	Density +95.00%	N
Colorado	0.92	0.88	0.96	24
Balau	0.83	0.80	0.87	24

The ovendry density of Colorado (0.922 g/cm^3) was found to be statistically significantly higher than that of Balau (0.836 g/cm^3). Colorado was thus, on average, 9.3% more dense than Balau.

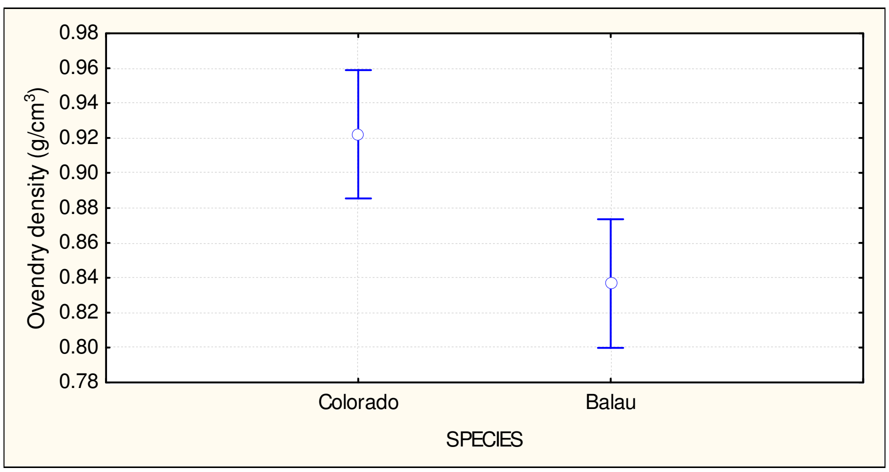


Figure 4.2: Average ovendry density of Colorado and Balau

The following ovendry density results have been reported for Colorado and Balau by other authors whose results are summarized in Table 4.2.

Table 4.2: Ovendry densities of Colorado and Balau reported by other authors

SPECIES	Density range
Colorado	0.66 - 1.06*
Balau	0.73 - 1.05**

* Veenin *et al* (2005); Doran and Wongkaew (2008); Sharma *et al.* (2005); Brink (2008)
** Pande *et al.* (2005)

4.3.1.2 Fiber saturation point (FSP)

The average, and upper and lower FSP values of Colorado and Balau within the 95% confidence intervals, are listed in Table 4.3, and depicted in Figure 4.3. Both timbers have relatively low FSP when compared to commercially used softwood decking timbers. The difference between Colorado and Balau's average FSP was found to be relatively small, but was statistically significant. Colorado reaches its FSP at 22.1 % MC, which is 2.3 percentage points higher than Balau which reached FSP at an average MC of 19.8%.

Table 4.3: Average fiber saturation point (FSP) of Colorado and Balau

	SPECIES	Average FSP	-95.00%	+95.00%	N
1	Colorado	22.1	21.4	22.8	24
2	Balau	19.8	19.1	20.5	24

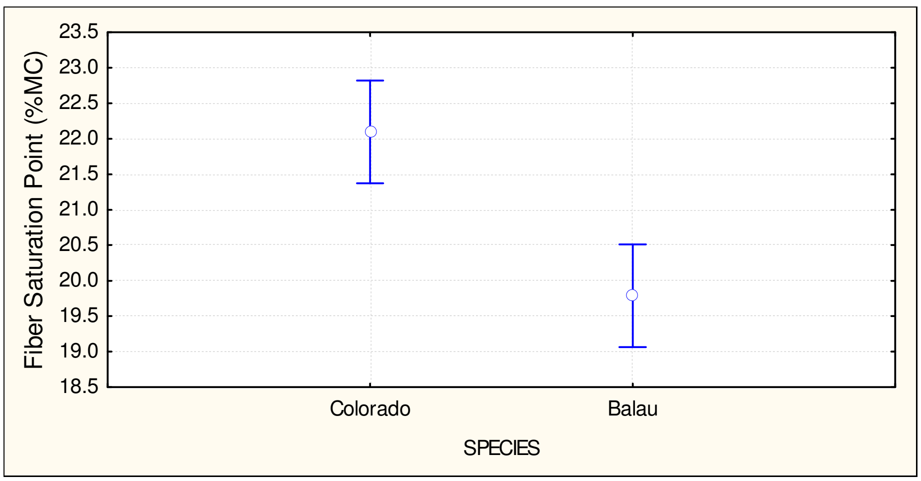


Figure 4.3: Fiber saturation points of Colorado and Balau

Higgins (1957) reported that the FSP of some wood species vary widely from the typical value. He argued that one of the causes of this variation could be attributed to the presence and amount of extractives in a species. Species generally high in extractives have a relatively low FSP. Presumably, the extractives occupy some sites in the cell wall that would otherwise attract water. A low FSP provides the advantage that dimensional changes as a result of moisture fluctuations are comparatively small thereby making these timbers acceptable for outdoor applications.

4.3.1.3 Swelling coefficients

The radial swelling coefficients from ovendry to EMC at 20C°/ 65%RH of Colorado (3.1%) and Balau (2.2%) were found to differ statistically significantly (Table 4.4), whereas the tangential swelling coefficients showed no significant difference (3.69 vs. 3.44%) (Figure 4.4a).

The radial swelling coefficients from ovendry to FSP of Colorado (6.6%) and Balau (5.2%) were found to differ significantly. The tangential swelling coefficients from ovendry to FSP of Colorado (8.7%) and Balau (7.6%) were also found to differ significantly (Figure 4.4b). Balau has relatively low radial and tangential swelling coefficients, but even though Colorado's swelling coefficients are higher than Balau, it has a smaller swelling anisotropy. In decking applications large dimensional changes are not as critical as a high swelling anisotropy. Colorado, having the smaller anisotropy of the two, should warp and twist less than Balau during moisture changes.

Table 4.4: Average swelling coefficients of Colorado and Balau

SPECIES	Swelling range				N
	Average % swelling Ovendry – 12%MC		Average % swelling Ovendry – FSP		
	Radial	Tangential	Radial	Tangential	
Colorado	3.10	3.69	6.57	8.68	24
Balau	2.20	3.44	5.20	7.58	24

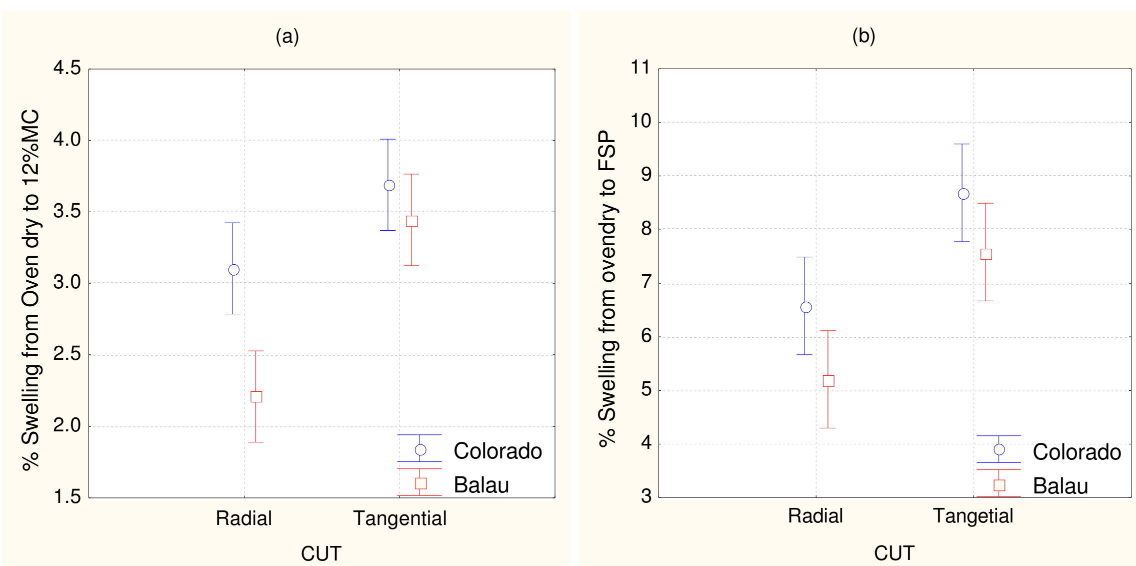


Figure 4.4: Radial and tangential swelling coefficients of Balau and Colorado: (a) from ovendry to 12% moisture, and (b) ovendry to fiber saturation point.

The higher the density of a sample, the more it will swell and shrink. It has also been reported that the lower the FSP of a sample, the less it will swell and shrink (Haygreen and Bowyer, 1982). These could presumably be the reasons why Colorado had a higher swelling coefficient than Balau.

The following results have been reported on Colorado and Balau's ovendry to FSP swelling coefficients, and are listed in Table 4.5.

Table 4.5: Average swelling coefficients of Colorado and Balau reported by other authors

SPECIES	Swelling range Average % swelling Ovendry – FSP	
	Radial	Tangential
Colorado*	4.2 - 9.6	7.4 - 13.5
Balau**	4.0 - 7.9	6.8 – 10.3

* Doran and Wongkaew (2008); Brink (2008)

** Pande *et al.* (2005)

Haygreen and Bowyer (1982) reported that the difference in swelling between the radial and tangential direction of wood can be attributed to several anatomical characteristics, including presence of ray tissue, frequent pitting on radial walls, domination of earlywood in the tangential direction and differences in the amount of cell wall material radially vs. tangentially.

4.3.1.4 Water vapour permeability (WVP) and Liquid water permeability (LWP)

No statistically significant permeability differences existed between the rate at which liquid water and water vapour penetrated Colorado and Balau, as well as whether samples were radially or tangentially cut (Figure 4.5, Table 4.6). During exposure to weathering this would mean that penetration of water would be similar for the two timbers irrespective of how they were cut. As expected, surface coating had a significant decreasing effect on both WVP (Figure 4.5a) and LWP (Figure 4.5b); coated samples were thus less permeable than uncoated samples.

Table 4.6: Average water (WVP) and (LWP) values of coated and uncoated Colorado and Balau

	Species							
	Colorado				Balau			
	Radial		Tangential		Radial		Tangential	
	Coated	Uncoated	Coated	Uncoated	Coated	Uncoated	Coated	Uncoated
WVP (g/m^2) (n=3)	0.91	1.12	0.91	1.28	0.66	1.19	0.86	1.26
LWP (g/m^2) (n=3)	3.82	4.90	4.46	5.13	3.34	4.66	3.85	5.09

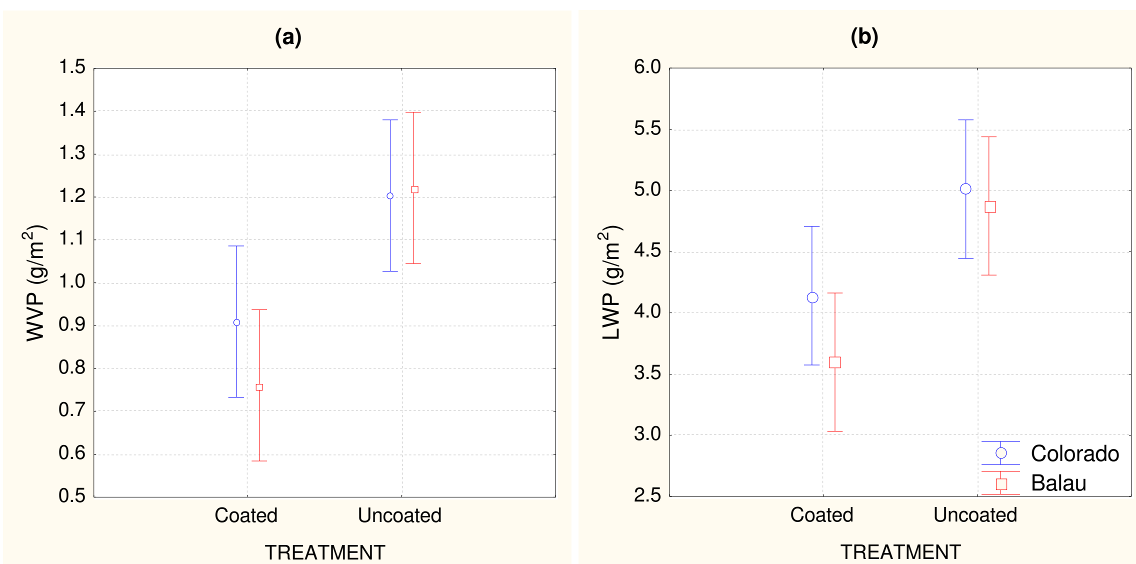


Figure 4.5: (a) water vapour permeability of coated and uncoated Colorado and Balau (b) liquid water permeability of coated and uncoated Colorado and Balau

4.3.1.5 Anatomical Investigation

The results of the anatomical investigation are summarized in Tables 4.7 and 4.8. Two representative micrographs of transverse sections taken at 35x magnifications, of Colorado and Balau are shown in Figure 4.6 below.

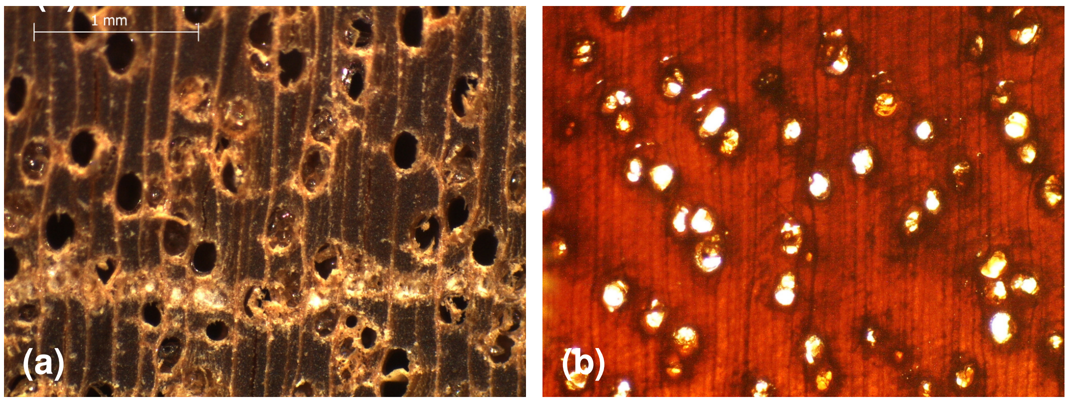


Figure 4.6: Transverse sections of (a) Balau and (b) Colorado. – Micrographs taken at 35X magnification.

Table 4.7: Comparison of general features between Colorado and Balau

	Colorado	**Balau**
Gross features		
Distinction of sapwood and heartwood	Distinct	Distinct
Sapwood colour	Pale red to yellow	Pale brown, whitish yellow
Heartwood colour	Red to brown	brown
Texture	Moderately coarse	Fairly coarse
Grain	Interlocked	Interwoven or wavy

The sapwood of Colorado had a pale red to yellow colour, and Balau's sapwood was brown to white. The heartwood of Colorado was a bright red, and sometimes had a slightly brown appearance, whereas the heartwood of Balau was brown. When the face of a tangentially cut Balau sample was inspected, white patterns were observed along the year rings. This characteristic was due to the presence of white resin canals in Balau. The texture of Balau was fairly coarse, slightly more than that of Colorado. Both Colorado and Balau contain interlocked grain, which might have given a wavy appearance.

Table 4.8: Comparison of microscopic features between Colorado and Balau

	Colorado	**Balau**
Microscopic structure		
Growth rings	Indistinct or absent	Indistinct or absent
Vessels		
Arrangement	Diffuse-porous	Diffuse-porous
Frequency (mm^2)	11-16	6-9
Size (visibility)	Small	Medium
Distribution	Solitary	Solitary, radial multiples of two or three
Tyloses	Mostly present	Mostly present
Parenchyma	Distinct, vasicentric	Not distinctly visible
Rays	Fine to very fine	Medium to fine, closely spaced
Resin canals	--	Filled with white deposits

When comparing these microscopic features of Colorado and Balau, it was found that there were many similarities between the two timbers. Both have indistinct growth rings, their vessels were arranged in a diffuse manner and contained tyloses. Some of the few differences which were found are as follows: Balau had the bigger vessel lumina of the two timbers and slightly bigger rays than Colorado. This could explain Colorado's higher density. Balau also contained resin canals filled with white resin, which made it distinguishable from Colorado. This may have compensated for the reduction in water uptake associated with the larger vessel lumina.

4.3.1.6 Ethanol/cyclohexane (E/C) and water soluble extractives

The results of the water soluble and ethanol/cyclohexane extraction are listed in Table 4.9, and illustrated in Figure 4.7. Both these timbers contained a high amount of water soluble extractives. Colorado on average contained 5.01% water soluble extractives, and Balau 4.08%, which is 0.93% less than Colorado. On the other hand, Balau had the highest percentage of E/C extractives, containing 4.8%. Colorado only had 2.03% of E/C extractives, thus containing 2.77% less than Balau.

Table 4.9: Water soluble and ethanol/cyclohexane (E/C) soluble extractives (based on ovendry mass) present in Colorado and Balau

	SPECIES	**% Water soluble extractives**	**% E/C soluble extractives**	**N**
1	Colorado	5.01	2.03	6
2	Balau	4.08	4.80	6

The amount of extractives is one of the important factors when estimating the amount of discolouration which will take place during weathering. During exposure to liquid water, the water soluble extractives can be dissolved, and under favorable conditions be leached out of the wood. These extractives usually contribute largely to a wood's initial colour, such as the red colour observed in Colorado. When these extractives are eventually leached out, the wood is left with a pale appearance. E/C extractives on the other hand retard the rapid penetration of water on the surface, and thereby also retard the initial discolouration of a wood's surface during weathering. These extractives are also largely responsible for the surface wettability of wood, and as they degrade during weathering, the contact angle of water drops decreases, and thus increases surface wettability.

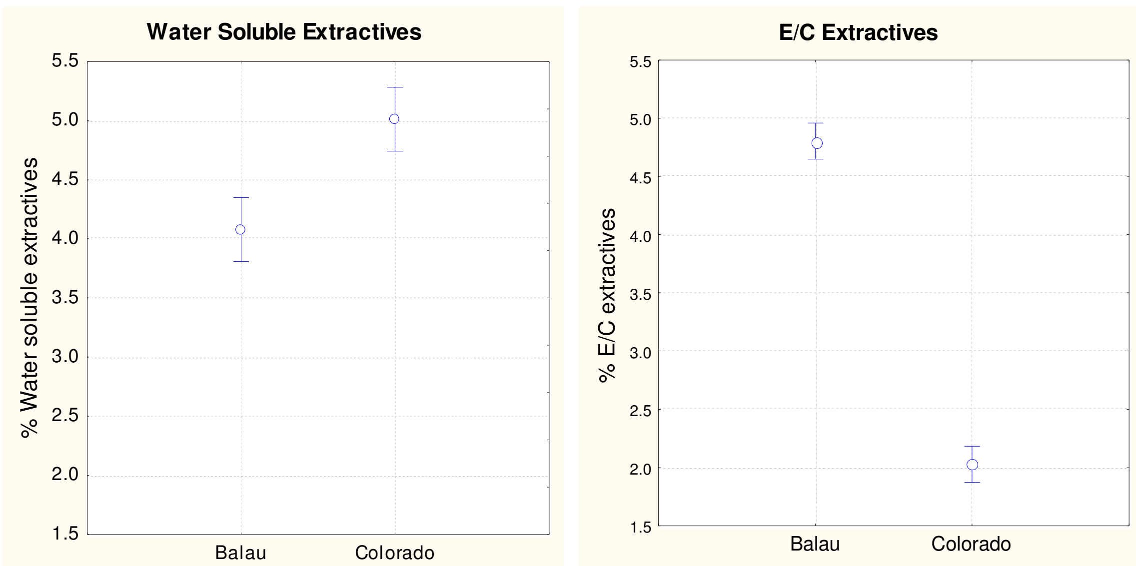


Figure 4.7: Percentage water soluble and E/C extractives (based on ovendry mass) present in Colorado and Balau

4.3.1.7 Summary of material characteristics

- Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau.
- Colorado had a higher density than Balau.
- Although both timbers had a relatively low FSP, Colorado's FSP is 2.3 percentage points higher than Balau's.
- The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's, but Colorado had a lower swelling anisotropy that would probably result in a lower tendency to twist in service.
- Colorado had a higher water soluble extractive content than Balau, which can lead to the rapid initial colour changes when the wood is exposed uncoated.

4.3.2 Artificial weathering characteristics

4.3.2.1 Colour

Colour changes of coated and uncoated exposed Colorado and Balau samples, relative to the colour of unexposed coated and uncoated samples are summarized in Table 4.10 and changes in individual colour parameters *L**, *a** and *b** are shown in Figure 4.8, 4.9 and 4.10 respectively.

L* **- Values**

As expected the treatment of wood with a pigmented coating changed the colour parameters compared to the uncoated controls. Lightness (*L**) was reduced (Figure 4.8, t = 0), and both chromaticity coordinates *a**(Figure 4.9) and *b**(Figure 4.10) increased. The increase of *a** indicated that the coating changed the colour of the samples toward a reddish colour, whereas the increase in *b** was associated with a yellowing effect caused by the coating.

Table 4.10: Average colour changes relative to *t* = 0 of coated and uncoated Colorado and Balau after exposure to accelerated weathering

Species	Treatment	Colour component	Time of exposure			
			92h	**200h**	**432h**	**912h**
Colorado	Coated	ΔL^*	-4.53 (2.63)	-5.22 (2.65)	-5.66 (2.15)	-6.88 (2.41)
		Δa^*	3.46 (2.00)	3.16 (2.05)	0.79 (1.69)	-1.98 (2.31)
		Δb^*	1.03 (2.38)	-1.48 (2.67)	-2.92 (3.48)	-3.22 (2.49)
		ΔE^*	6.77 (1.37)	6.98 (2.68)	7.13 (2.83)	8.30 (2.95)
	Uncoated	ΔL^*	-11.36 (3.83)	-13.03 (4.68)	-13.76 (4.13)	-16.14 (4.04)
		Δa^*	5.89 (1.62)	6.15 (1.54)	3.12 (1.89)	-1.38 (2.61)
		Δb^*	5.01 (3.04)	4.43 (2.72)	6.47 (3.13)	4.10 (4.36)
		ΔE^*	14.20 (3.35)	15.46 (4.23)	16.14 (2.60)	17.43 (3.54)
Balau	Coated	ΔL^*	-1.51 (1.49)	-2.05 (2.60)	-1.41 (3.99)	-1.92 (7.31)
		Δa^*	0.86 (0.79)	1.62 (1.02)	0.73 (1.73)	-0.62 (1.90)
		Δb^*	-1.58 (2.23)	-2.16 (3.75)	-2.58 (6.29)	-2.84 (6.52)
		ΔE^*	3.31 (1.14)	5.35 (1.13)	6.94 (3.43)	8.63 (4.96)
	Uncoated	ΔL^*	-8.88 (4.05)	-11.83 (5.13)	-12.89 (5.40)	-15.70 (5.94)
		Δa^*	2.85 (2.50)	4.30 (4.09)	4.82 (3.45)	2.06 (4.60)
		Δb^*	6.15 (4.75)	6.28 (1.33)	2.16 (3.68)	2.83 (7.37)
		ΔE^*	11.75 (5.41)	14.46 (5.61)	14.49 (5.94)	17.76 (6.54)

Values in parentheses are standard deviations

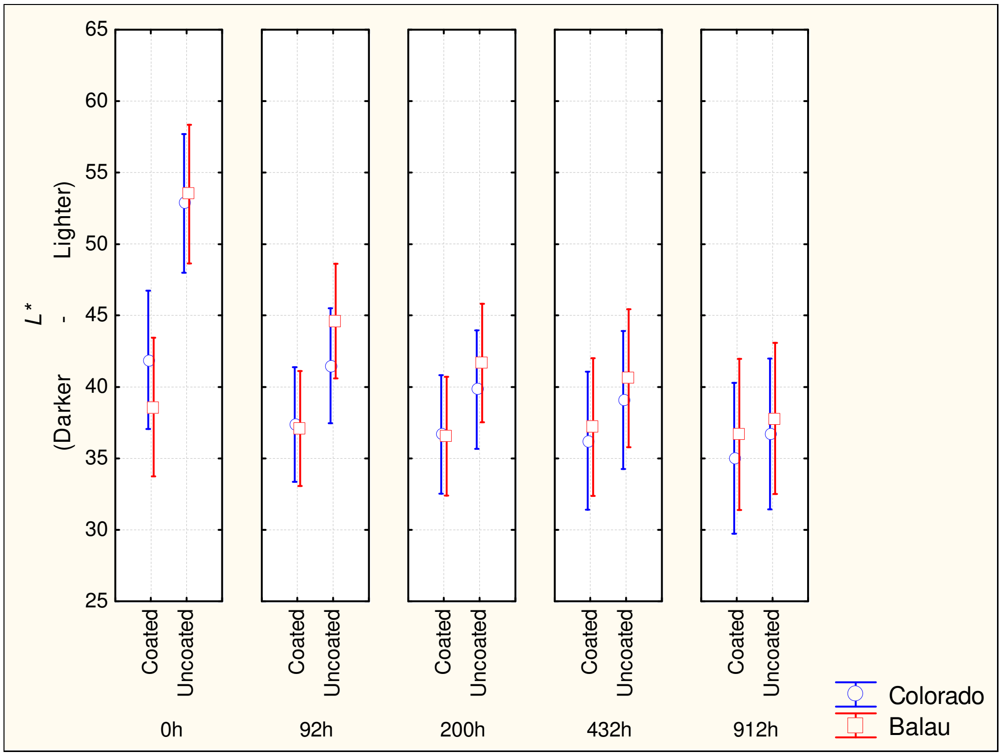


Figure 4.8: Effect of accelerated weathering on the lightness (L^*) of coated and uncoated Colorado and Balau

No statistically significant differences were observed between Colorado and Balau's lightness values (L^*) at t = 92h, 200h, 432 and 912h (Figure 4.8). The cutting pattern of the samples also contributed no significant effect to changes in L^*. Uncoated samples showed a significant decrease in L^* for the first 200h of weathering, eventually becoming equal in value to that of the coated samples after 912h. Both Colorado and Balau showed less change in lightness after weathering when coated compared to the uncoated samples. The results obtained for coated samples agree with results found by Temiz *et al.* (2007) on the weathering of oil treated wood. According their research the darkening effect during weathering was the result of the depolymerization of lignin on the exposed surface brought on by photo-degradation.

*a** - values

A significant difference was found between the change in a^* of Colorado compared to that of Balau. Both species showed an initial increase in a^* for the first 200h of weathering, and thereafter a decrease, with Colorado showing a much larger change in a^* than Balau. The increase in a* meant that the samples turned reddish, and the later decrease indicated that the samples returned towards its initial green colour. The reddening of Colorado could be attributed to its large quantity of water soluble extractives which leached to the surface when exposed to water and radiation. As weathering continued, these extractives were washed of the surface and the wood faded back to a greener colour.

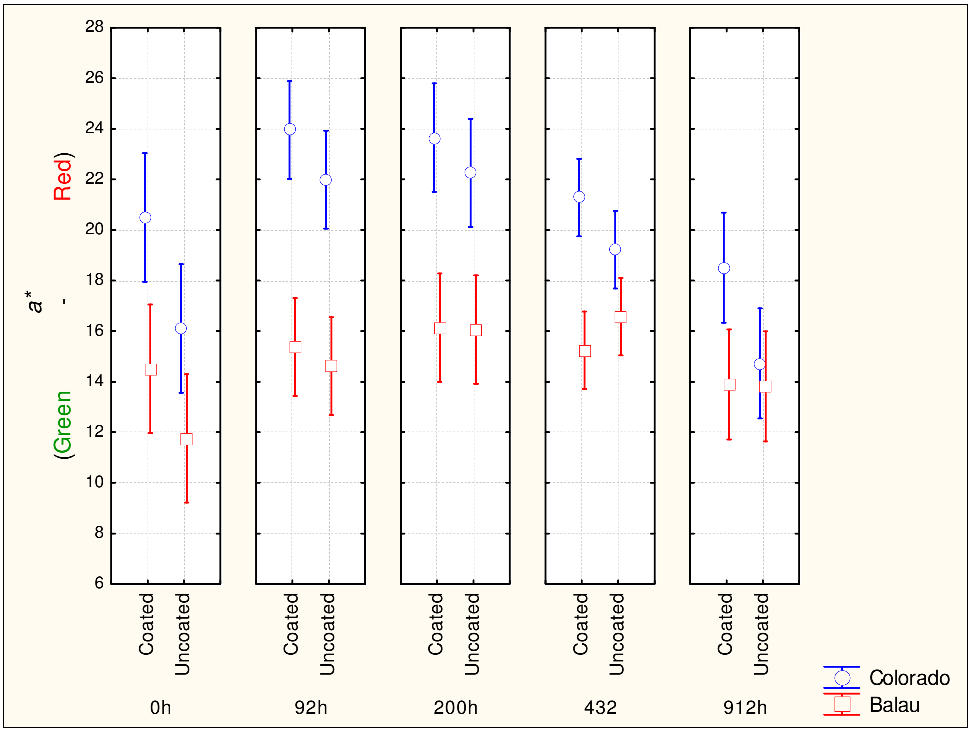


Figure 4.9: Effect of accelerated weathering on the redness (a^*) of coated and uncoated Colorado and Balau

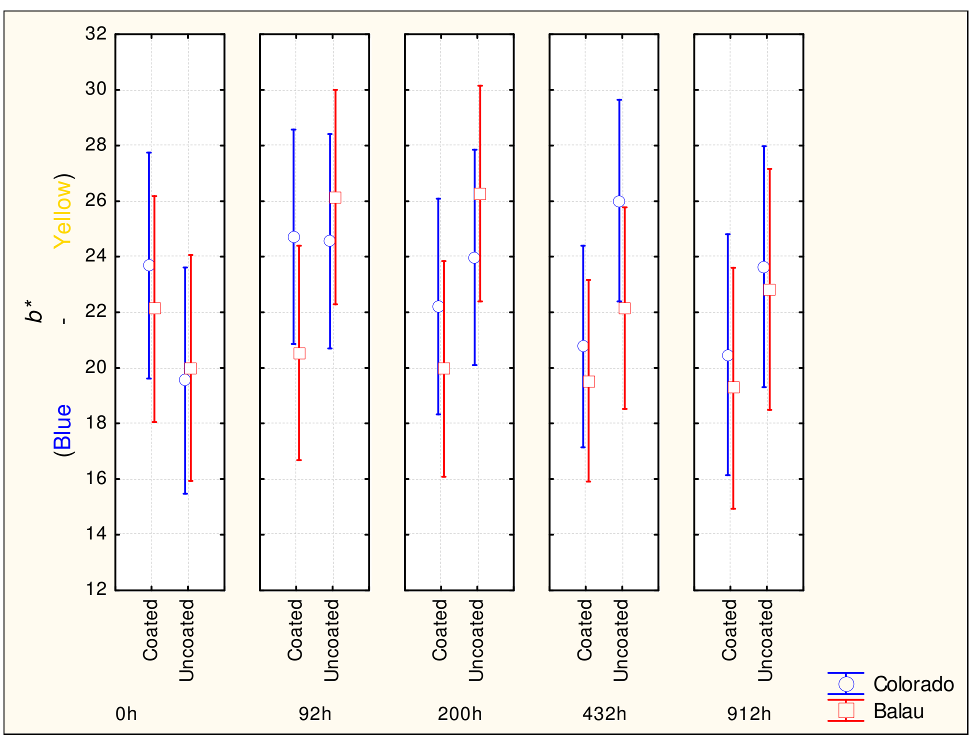


Figure 4.10: Effect of accelerated weathering on the yellowing (b^*) of coated and uncoated Colorado and Balau

b* - values

Uncoated Colorado and Balau showed a steep increase in *b** over the first 92h of weathering (Figure 4.10). The *b** values stayed constant up to 200h of weathering, and thereafter a slight decrease was noted up to 912h of weathering. The initial increase in *b** meant that the uncoated samples turned slightly yellow, and the later decrease meant that samples became slightly blue again. No significant differences were found between the uncoated Colorado and uncoated Balau's *b** values. Muller *et al*. (2003) showed that there was a correlation between the yellowing which occurred during weathering and the accumulation of lignin degradation products on the exposed surface of wood. The decrease in *b** value can be attributed to water leaching and washing away the degraded lignin products from the surface and thus leaving the wood slightly blue (Evans *et al*. 2005).

Coated Colorado showed a slight increase in *b** values over the first 92h of weathering, whereas Coated Balau showed a slight decrease. Thereafter both species showed a decrease in *b** up to 912h of weathering. No significant differences were found between Colorado and Balau's final *b** values.

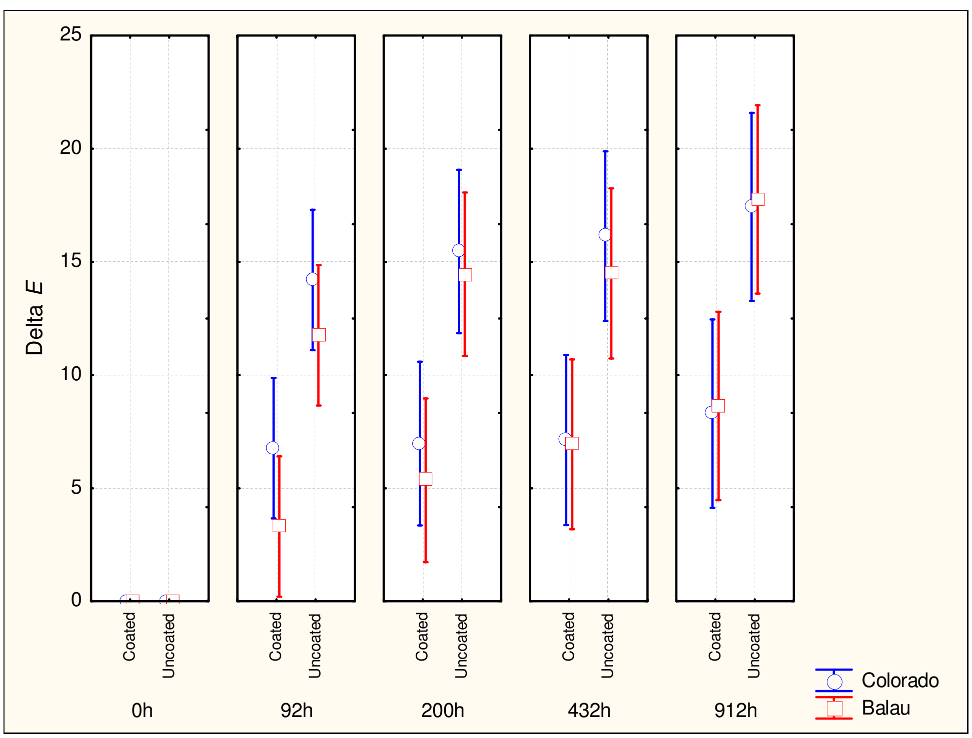


Figure 4.11: Effect of accelerated weathering on the colour change (ΔE) of coated and uncoated Colorado and Balau

***ΔE** – Values**

Figure 4.11 shows the overall change in colour due to artificial weathering (*ΔE**). During the first 92h of weathering a rapid colour change was observed for both uncoated Colorado and Balau samples. Thereafter, no significant differences were found between the overall colour changes of species. The initial rate (0-92h) of discolouration of uncoated samples (*ΔE** = 14.2 for Colorado and 11.75 for Balau) was double that of the coated samples (*ΔE** = 6.77 for Colorado and 3.31 for Balau). Later on discolouration rates declined down to approximately ¼ of the initial slope for both the uncoated and coated samples. The total amount of discolouration, after 912h of weathering, observed for uncoated samples was more than double the amount for coated samples. According to Feist and Hon (1984) the protection of wood against discolouration should prevent the formation of free radicals induced by UV-irradiation and the access of water to the reaction sites. The results of this study agree with the latter where the protected samples suffered only half the amount of discolouration.

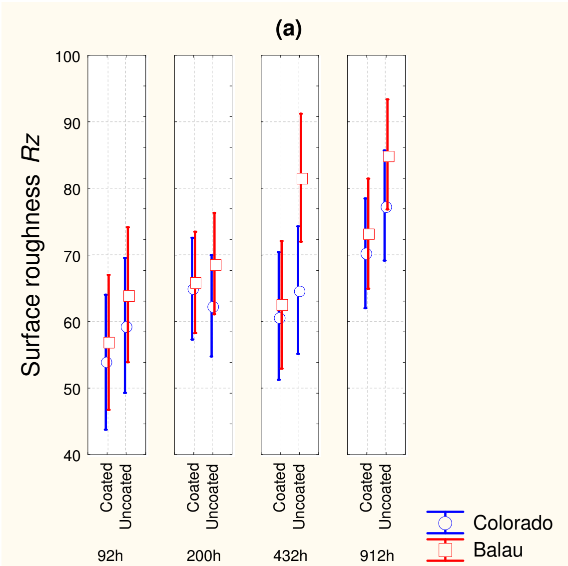
4.3.2.2 Roughness

The effect of exposure on the surface roughness of coated and uncoated samples is summarized in Table 4.11 and depicted in Figure 4.12. Deterioration of wood surfaces due to the combined effect of water and light, leads to the formation of macroscopic and microscopic intercellular and intracellular cracks or checks (Feist, 1983 and Williams, 2005). During weathering water also causes the loosening and removal of the surface fibers and particles. The amount of erosion and roughening on the surface was also dependent on the grain orientation of the wood (Figure 4.12b). As reported by Williams *et al.* (2001), radially sawn surfaces tend to erode and roughen slightly faster than tangentially sawn surfaces.

Table 4.11: Average surface roughness (*Rz*) of coated and uncoated Colorado and Balau after exposure to accelerated weathering

Species	Cut	Treatment	Time of exposure			
			92h ***(Rz)***	**200h** ***(Rz)***	**432h** ***(Rz)***	**912h** ***(Rz)***
Colorado	Radial	*Coated*	57.2(8.5)	61.1(4.9)	64.8(10.3)	74.4(12.4)
		Uncoated	63(13.8)	63.5(6.1)	68.7(15.1)	79.2(12.3)
	Tangential	*Coated*	50.7(5.5)	68.8(9.0)	56.8(3.7)	66.2(7.5)
		Uncoated	55.8(13.8)	61.3(10.3)	60.7(12.3)	75.7(10.3)
Balau	Radial	*Coated*	56.2(10.8)	67.8(11.0)	65.6(13.3)	80.0(11.2)
		Uncoated	61.1(14.8)	66.6(13.8)	87.7(19.8)	92.0(15.6)
	Tangential	*Coated*	57.5(11.6)	63.9(7.5)	59.4(10.0)	66.4(10.8)
		Uncoated	66.9(10.2)	70.9(5.5)	75.5(5.5)	78.2(7.5)

Values in parentheses are standard deviations



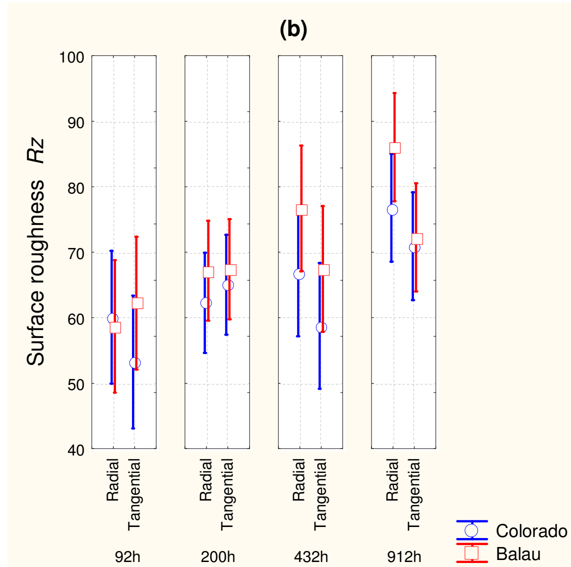


Figure 4.12: Effect of accelerated weathering on surface roughness (*Rz*) of Colorado and Balau (a) coated vs. uncoated samples (b) radial vs. tangentially cut samples

Figure 4.12a depicts the surface roughness values (*Rz*) of coated and uncoated Colorado and Balau samples. Initially no statistically significant differences could be found between the *Rz* values of coated and uncoated samples. Both coated and uncoated samples showed an increase in roughness values as weathering continued.

After 432h, differences started showing between uncoated Colorado and Balau samples. The uncoated Balau samples showed significantly higher *Rz* values than the uncoated Colorado sample after 432h of exposure. After 912h of exposure, significant differences were found between coated and uncoated samples of both species. Balau had a significantly higher value than Colorado, which could be explained by the differences in density and anatomical structure of these two species, as discussed earlier in this chapter. According to Hiziroglu *et al*. (2008) species with higher densities generally result in smoother surfaces after weathering, which is in agreement with the results of this study.

Figure 4.12b shows the differences which occurred between the *Rz* values of radially and tangentially cut Colorado and Balau samples after weathering for 912h. It can be seen that radially cut samples roughened more during weathering than tangentially cut samples. After 432h of weathering a decrease in roughness was observed for the tangentially cut samples, the reason for this is not quite clear, however, after 432h of exposure, resin which had leached out onto the surface appeared hardened, which could possibly have decreased the roughness temporarily. Thereafter it is assumed that the resin was degraded and washed away after further weathering exposure. After 912h of exposure, radially cut Balau had the highest Rz value followed by radially cut Colorado. No difference was observed between the final roughness values of tangentially cut Colorado and Balau. These results are in agreement with the results found by Williams *et al.* (2001) on the rate of roughening between radially and tangentially cut samples.

4.3.2.3 Surface wettability

According to Kalnins and Feist (1993) the ability of wood to repel water is decreased as wood weathers. Water readily wets severely weathered surfaces and is quickly absorbed into the wood. The average wettability values, given as contact angles, are listed in Table 4.13, and shown in Figure 4.13.

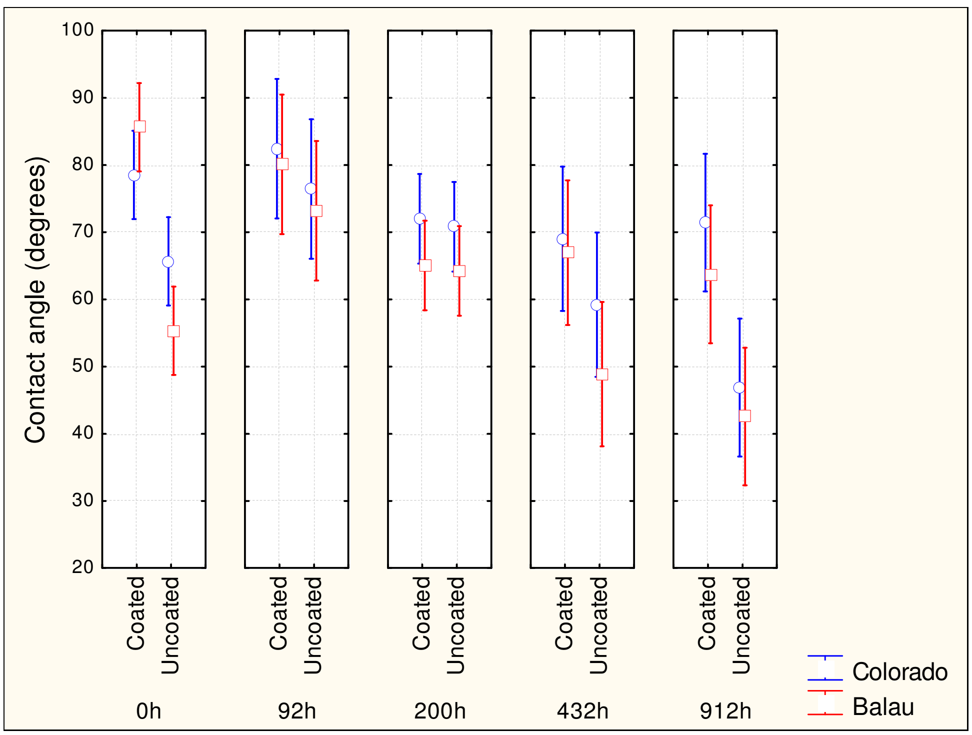


Figure 4.13: Effect of accelerated weathering on contact angle values of coated vs. uncoated Colorado and Balau

Table 4.12: Average contact angle values of coated and uncoated Colorado and Balau after exposure to accelerated weathering

Species	Cut	Treatment	Time of exposure				
			0h Angle (°)	**92h Angle (°)**	**200h Angle (°)**	**432h Angle (°)**	**912h Angle (°)**
Colorado	Radial	*Coated*	77.6(9.3)	79.5(11.1)	64.1(13.8)	69.6(18.5)	68.8(18.2)
		Uncoated	59.5(10.2)	82.4(15.2)	63.1(11.3)	58.8(8.0)	42.9(17.9)
	Tangential	*Coated*	78.4(14.7)	85.4(19.4)	79.9(14.1)	68.5(19.1)	74.3(9.9)
		Uncoated	71.8(12.8)	83.5(10.4)	78.5(9.5)	59.6(6.4)	50.8(10.1)
Balau	Radial	*Coated*	74.3(8.1)	78.7(14.9)	55.6(10.8)	75.5(12.8)	62.6(9.4)
		Uncoated	57.2(10.3)	71.9(5.7)	56.9(8.2)	45.8(12.8)	32.8(5.5)
	Tangential	*Coated*	96.9(13.0)	81.6(15.9)	75.8(13.4)	58.4(12.2)	64.8(10.8)
		Uncoated	53.5(8.5)	75.1(14.8)	75.2(7.8)	53.2(16.0)	51.2(10.1)

Values in parentheses are standard deviation

Up to 92h of exposure a remarkable increase in contact angle was found for uncoated samples. According to Kalnins and Feist (1993) this initial increase can be attributed to the following factors: 1) the migration of extractives to the surface and 2) the initial roughening of the surfaces both increase the hydrophobicity of surfaces. With the continuation of weathering exposure, however, the leached extractives are further degraded and washed away; this decreases the hydrophobicity of the surface. Besides the reduction in the amount of extractives and their water repellent effect, lignin, which is a hydrophobic component of wood, is also degraded and removed during weathering. Cellulose, being more resistant to weathering effects, becomes more abundant on the weathered surfaces. This presumably increases the hydroxyl concentration on the surface. These effects were visible in this study and can be seen in Figure 4.13 where the contact angle of both coated and uncoated samples decreased between 92h and 200h of exposure.

As expected, the treatment of wood with a coating changed the surface chemistry (wettability) of Colorado and Balau samples surfaces. Treatment increased the initial contact angle of the samples before weathering (see Figure 4.13, t = 0), i.e. causing an increase in the hydrophobicity of the surface. After 200h of exposure, the contact angle of the coated samples stayed constant up 912h, whereas uncoated samples showed a decrease in contact angle up to 912h. This shows that the coating was effective in sustaining the hydrophobicity of the samples. No statistically significant differences were found between the two timbers after 912h.

4.3.2.4 Deformation and cracks

Deformation values were measured after 912h of accelerated weathering. The width (85mm) of the samples exceeded the thickness (5mm) by 17 times which can allow excessive cupping within samples to occur. Results are summarized in Table 4.13, and shown in Figure 4.14.

Table 4.13: Average deformation of Colorado and Balau after 912 hours of accelerated weathering

Species	Cut	Treatment	Defects after 912h of exposure		
			Cup(mm)	Twist (mm)	Cracks (mm)
Colorado	Radial	*Coated*	1.08	1.37	0
		Uncoated	0.49	1.33	0
	Tangential	*Coated*	0.86	0.82	0
		Uncoated	0.90	1.42	34
Balau	Radial	*Coated*	0.63	0.57	0
		Uncoated	0.68	0.97	0
	Tangential	*Coated*	0.58	1.63	42
		Uncoated	1.48	6.33	87

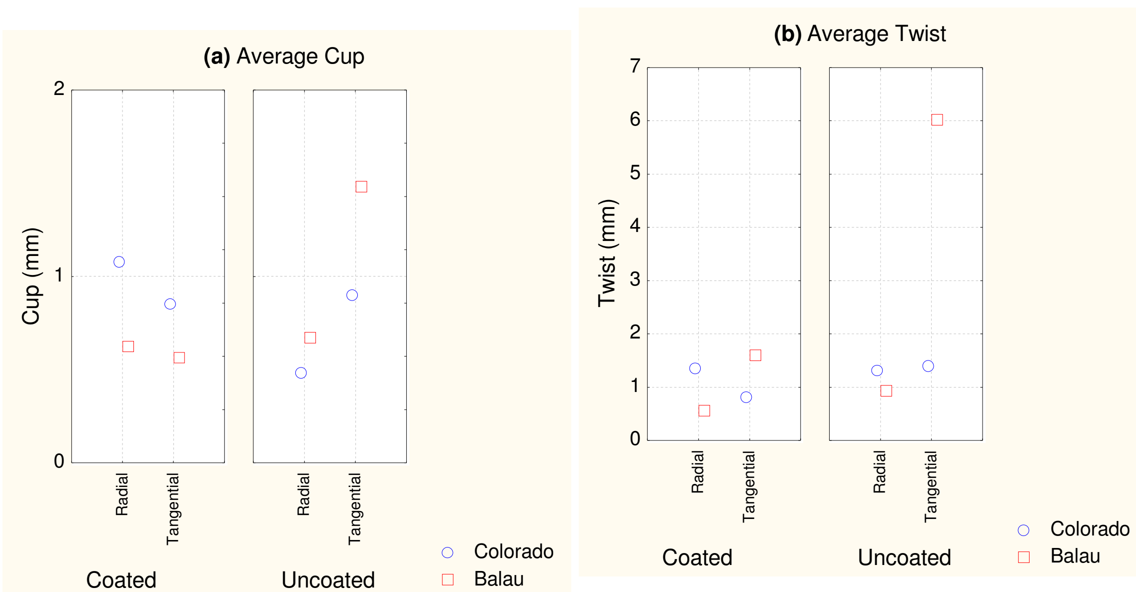


Figure 4.14: Average deformation of radially and tangentially cut, coated and uncoated Colorado and Balau samples after 912h of accelerated weathering: **(a)** cup and **(b)** twist

Cup: No statistically significant differences were found between the cupping values of radially cut, coated and uncoated as well as the two timbers (Figure 4.14a). Only tangentially cut uncoated Balau samples showed significantly higher amounts of cupping. When comparing the swelling coefficients of Colorado and Balau (Table 4.13), it can be seen that Balau has a larger difference between its radial and tangential swelling coefficients, which could explain the larger amount of cupping found in Balau. The coated samples showed less cupping than the uncoated samples which indicated that the coating was effective in controlling the moisture gradients in samples i.e. decreased the amount of deformation.

Twist: No statistically significant differences were found between the amount of twist observed for coated Colorado and Balau (Figure 4.14b). The only statistically significant difference observed was the amount of twisting between uncoated tangentially cut Colorado and Balau. Uncoated, tangentially cut Balau showed excessive amounts of twist relative to Colorado. The reason for this excessive twisting could also be attributed to the difference between Balau's radial and tangential swelling coefficients.

Cracks: The only cracks found in both Colorado and Balau were found in the tangentially cut samples. Balau showed a significantly higher amount of cracks when compared to Colorado. The coating prevented crack formation in the samples, except in the tangentially cut Balau samples. The excessive amount of crack formation in Balau could once again be attributed to stress formed in the samples because of Balau's large swelling anisotropy.

4.3.2.5 FT-IR surface analysis

The FT-IR spectra of coated and uncoated samples before and after weathering are shown in Figures 4.15 - 4.16. Additional spectra are given on the weathering rates and comparisons between species, these results are presented in Appendix 2.

Photodegradation of coated and uncoated wood causes mainly changes in the absorption intensities at 1720-1740, 1592, 1508, and 1230-1261 cm^{-1} (Temiz *et al*, 2007). The intensity and changes of these bands are related to changes in chemical composition of the functional groups and chemical structure of wood components of which lignin normally undergoes the biggest changes. The assignment of these characteristic IR absorption peaks in wood are listed in Table 4.14.

The absorption band at 1509 and 1600 cm^{-1} are characteristic peaks for lignin due to the C=C stretching vibrations of the aromatic rings present in lignin. This peak usually appears between 1515 -1500 cm^{-1} and at 1600 cm^{-1} depending on the ring substituents. In this investigation, the peak at 1509 cm^{-1}, for coated and uncoated Balau (Figure 4.15) and Colorado (Figure 4.16), had decreased significantly after 912h of exposure. No significant differences were found between the intensities of these peaks for Colorado and Balau.

Furthermore, no differences could be observed between coated and uncoated samples. The same results were found for the peaks at 1597 cm^{-1}. From these results it can be confirmed that lignin was degraded and that the coating was not effective in preventing the photo-degradation of the aromatic rings present in lignin.

Table 4.14: Assignment of IR absorption spectra bands in wood (Temiz et al, 2007).

Peak (cm^{-1})	Functional group	Contained in:
1720–40	• C=O in:	- unconjugated ketones - aldehydes - carboxyl groups
1645–60	• C=O in:	- para-OH substituted aryl ketones - quinones
1600/1510	• C=C in:	- aromatic ring in lignin
1462 / 1425	• C–H in:	- lignin - carbohydrates
1375	• C–H in:	- cellulose - hemicelluloses
1330 / 1320	• C–H in: • C–O in:	- cellulose - syringyl derivatives
1268	• Guaiacyl ring breathing • C–O in: • C–O linkage in guaiacyl aromatic methoxyl groups	-lignin - lignin
1226-44	• Syringyl ring breathing • C–O in:	- lignin - lignin - xylan
1162	• C–O–C in:	- cellulose

The 1461 cm^{-1} peak is characteristic of the C-H vibration found in lignin and carbohydrates. A significant decrease was found in this peak for both uncoated Colorado and Balau. After 912h of exposure no significant difference was observed between species. In contrast to uncoated samples, coated samples showed no significant decrease at these peaks. This result would indicate that the coating was effective in protecting substructures in the lignin molecules.

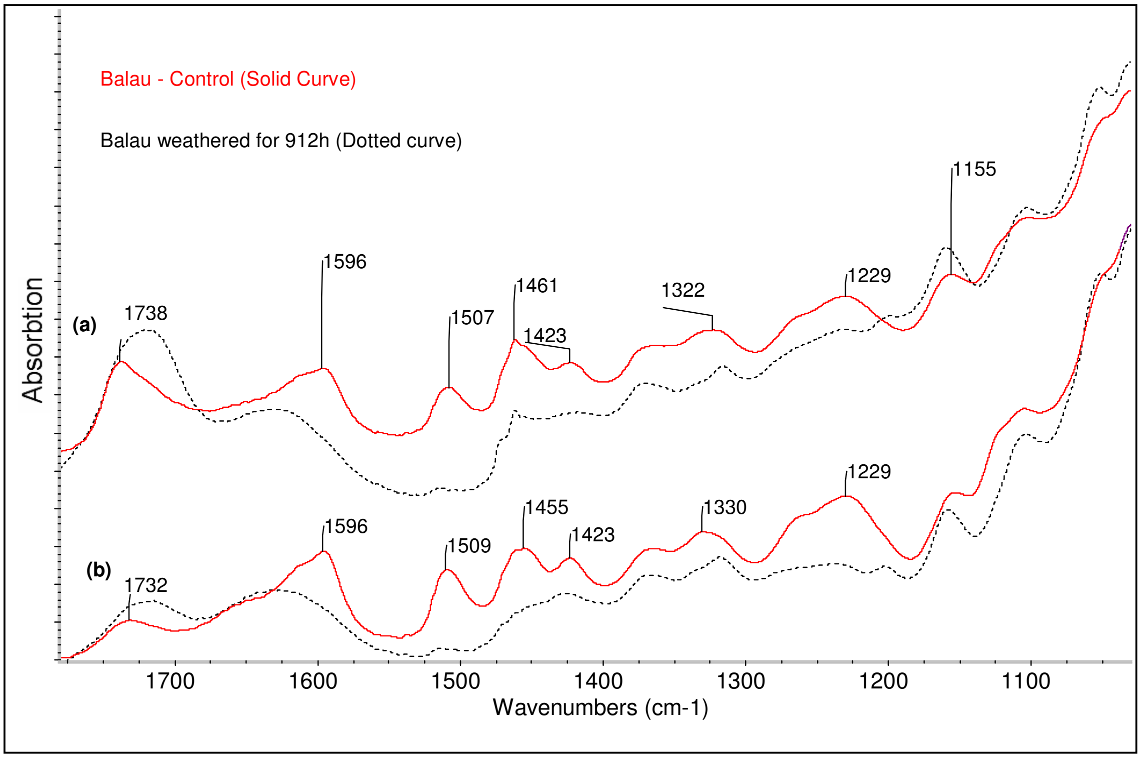


Figure 4.15: FT-IR spectra of Balau showing the effect of treatment: **(a)** Coated Balau weathered for 912h; **(b)** Uncoated Balau weathered for 912h.

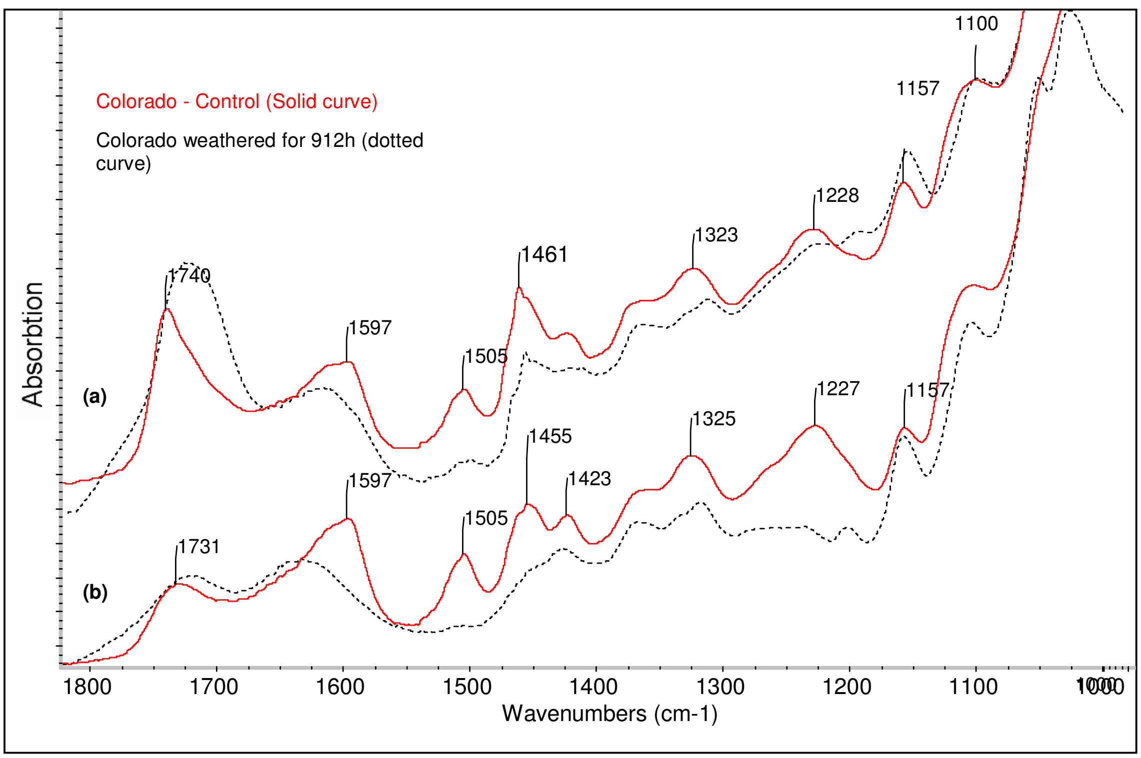


Figure 4.16: FT-IR spectra of Colorado showing the effect of treatment: **(a)** Coated Colorado weathered for 912h; **(b)** Uncoated Colorado weathered for 912h.

The absorption at 1229 cm^{-1} is a characteristic absorption of syringyl ring breathing in lignin, and C-O stretching vibration in lignin and xylan. These peaks were significantly decreased in the spectra of the uncoated samples after 912h of weathering. However, the absorption peaks at 1229 cm^{-1} of the coated samples did not change significantly; this is in agreement with results found by Temiz *et al.* (2007) on the weathering of oil treated wood. They found that oil treatments could partly prevent the degradation of hemicelluloses. Their explanation for this was that oil filled the lumen and cell walls of wood, thus providing a chemical-mechanical or physical protection of the hemicelluloses. It has also been reported that oils act as water repellents thus diminishing the consequences of the water's washing effect. Oils cannot prevent lignin and cellulose degradation, merely retard it.

In summary, no significant differences were found between the peak intensities of Colorado and Balau, and the coating was effective in retarding the rate and final amount of lignin degradation.

4.4 Conclusion

A. Comparison of the material (anatomical, physical and chemical) properties of Colorado and Balau:

- Colorado had smaller vessel lumina, fewer vessels/m^2 and smaller rays than Balau.
- Colorado had a higher density than Balau.
- Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's.
- The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado had a lower swelling anisotropy which can probably result in a lower tendency to twist in service.
- Colorado had a higher water soluble extractive content than Balau which lead to the rapid initial colour changes of uncoated wood.

Balau is a popular choice when considering a timber for exterior use because of its good weathering performance. From the many similarities found between the material properties of Balau and Colorado, one would expect little difference in the weathering behaviour between the two timbers.

B. Comparison of the accelerated weathering behaviour Colorado and Balau as determined by their material properties and processing (cutting pattern and surface treatment):

Colour: No significant differences were found for the overall colour change (ΔE^*) between the two timbers. The only significant difference observed regarding colour change between Colorado and Balau was the large increase of Colorado's a^* value. The reddening of Colorado could be attributed to its large quantity of water soluble extractives which leached to the surface when exposed to water and UV radiation. As weathering continued, these extractives were washed off the surface and the wood faded back to a greener colour.

The coating was effective in decreasing the amount of discolouration. The total amount of colour change (ΔE^*) of the coated samples was less than half the amount observed for the uncoated samples.

Surface roughness: Balau showed a significantly higher increase in roughness than Colorado. This could be explained by the lower density and higher swelling anisotropy of Balau. Radially cut samples showed a larger increase in roughness than tangentially cut samples. The increase in roughness observed for coated samples were not significantly different from uncoated samples, the coating was thus ineffective in retarding the roughening of surfaces.

Deformation: Balau showed larger amounts of twisting and crack formation than Colorado; this could also be attributed to the higher swelling anisotropy of Balau. Both these defects were only observed for the uncoated, tangentially cut samples.

Wettability: No significant differences were found between the hydrophobicity of the two timbers. The coating was effective in increasing the initial hydrophobicity of samples, and maintained a relatively hydrophobic surface during weathering. No differences were found concerning the effect of sample cut on sample surface wettability.

Surface chemistry: FT-IR studies showed that there were no significant differences between Colorado and Balau's surface chemistry after 912h of weathering. The coating was not effective in preventing the photo-degradation of the aromatic rings present in lignin (1509 cm^{-1} and 1597 cm^{-1}). However, the coating was effective in preserving the 1461 cm^{-1} peak which is characteristic of the C-H vibrations found in lignin, the 1229cm^{-1} which is characteristic of syringyl ring breathing in lignin, and C-O stretching vibration in lignin and xylan. The explanation for this could be that oil fills the lumen and cell walls of wood, thus providing a chemical-mechanical or physical protection of the hemicelluloses. It has also been reported that oils act as water repellents thus diminishing the consequences of the water's washing effect. Oils cannot prevent lignin and cellulose degradation, merely retard it.

C. Final comment

Although similar behaviour was observed, it should be noted that this artificial weathering study merely served as a screening test (number of samples, n = 12) and remains a simulation of natural conditions. Natural weathering of the material or when assembled in constructions might result in different outcomes. Based on the results of this exploratory, artificial weathering study, the properties and weathering performance of Colorado were comparable with Balau. Based on aesthetics considerations (colour change and crack formation), Colorado performed similar to Balau and but cupped and twisted less.

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Chapter 5: Conclusions

Weathering is a complex process and to measure the performance of a material during exposure to weathering factors is a complicated task. In this study there were many variables to consider and compare namely: Artificial weathering vs. Natural weathering, Balau vs. Colorado, Radial vs. Tangential grain orientation and Coated vs. Uncoated material. The conclusions of this study can be summarized as follows:

A. Comparison of the material (anatomical, physical and chemical) properties of Colorado and Balau:

- Colorado had smaller vessel lumen area, fewer vessels/m^2 and smaller rays than Balau.
- Colorado had a higher density than Balau.
- Although both timbers had a relatively low FSP, Colorado's FSP was 2.3 percentage points higher than Balau's.
- The swelling coefficients (radial and tangential) of Colorado were slightly higher than Balau's but Colorado had a lower swelling anisotropy resulting in a lower tendency to twist.
- Colorado had a higher water soluble extractive content than Balau which lead to the rapid initial colour changes of uncoated wood.

Balau is a popular choice when considering a timber for exterior use because of its good weathering performance. From the many similarities found between the material properties of Balau and Colorado, one would expect little difference in the weathering behaviour between the two timbers.

B. Comparison between the natural and accelerated weathering behaviour Colorado and Balau as determined by their change in material properties, environment and processing (cutting pattern and surface treatment):

<u>**Colour**</u>

Natural weathering: No initial differences were found for the overall colour change (ΔE^*) between Stellenbosch and Yzerfontein. After 30 weeks of weathering Colorado had undergone slightly more colour change than Balau. Coating had a significant effect on the amount on colour change; however, the difference between coated and uncoated was smaller than expected.

A significant difference was observed between Colorado and Balau's change in redness (a^*). Colorado experienced a larger overall decrease in redness (a^*) than Balau. This could be attributed to Colorado's large quantity of water soluble extractives which were leached out and washed of the surface during weathering. Coating had no significant effect in decreasing the amount of change in redness (a^*).

After 30 weeks of weathering Balau showed a greater decrease in b^* than Colorado at the Stellenbosch site, but the two timbers' b^* values decreased similarly at the Yzerfontein site.

No statistically significant differences were observed between the lightness values (L^*) samples at Stellenbosch and Yzerfontein. Both Colorado and Balau showed less change in lightness after weathering when coated compared to the uncoated samples. Uncoated Colorado ended slightly darker than Balau. However, this difference was so small, even though statistically significant, it could not be distinguished by the human eye.

Artificial weathering: Also, no significant differences were found for the overall colour change (ΔE^*) between the two timbers. The only significant difference observed regarding colour change between Colorado and Balau, was the large increase of Colorado's a^* value. The reddening of Colorado could be attributed to its large quantity of water soluble extractives which leached to the surface when exposed to water and UV radiation. As weathering continued, these extractives were washed of the surface and the wood faded back to a greener colour. The coating was effective in decreasing the amount of discolouration. The total amount of colour change (ΔE^*) of the coated samples was less than half the amount observed for the uncoated samples.

Accelerated weathering showed the same amount of overall colour change (ΔE^*) after 912h of weathering as the decking after 12 weeks of weathering. The rate of colour change was thus 3 times higher under accelerated weathering conditions than under natural weathering conditions. The overall colour change (ΔE^*) of coated samples under accelerated weathering conditions, however, showed far less change than under natural conditions. This meaning that accelerated weathering was not a reliable method of predicting colour change for the natural weathering of coated timber.

Surface roughness

No statistically significant differences were observed between the roughness values of decking samples at Stellenbosch and Yzerfontein. During natural and accelerated weathering Balau showed a significantly higher increase in roughness than Colorado. This could be explained by the lower density and higher swelling anisotropy of Balau. Radially cut samples showed a larger increase in roughness than tangentially cut samples. The increase in roughness observed for coated samples was lower than observed for uncoated samples. The coating was thus effective in retarding the roughening of surfaces under both types of weathering.

Substrate defects

These were mainly assessed during exposure of the timbers to natural weathering.

Decking samples at Yzerfontein exhibited more surface checking than at Stellenbosch. Balau showed larger amounts of surface checking than Colorado at Stellenbosch and Yzerfontein. Coating decreased the amount of surface checks on Colorado and Balau.

Crack formation was more severe at Stellenbosch than at Yzerfontein. Radially cut Colorado showed slightly higher amounts crack formation at Stellenbosch than Balau. Coating was not able to decrease the amount of cracks formed.

Deformation

During natural and accelerated weathering Colorado showed slightly more cup than Balau, however, Balau showed much larger amounts of twisting than Colorado. This could also be attributed to the higher swelling anisotropy of Balau. Both these defects were mostly only observed for the uncoated, tangentially cut samples.

Wettability

No statistically significant differences were found between the hydrophobicity of the two timbers. The coating was effective in increasing the initial hydrophobicity of samples and maintained a relatively hydrophobic surface during weathering. No differences were found concerning the effect of sample cut on sample surface wettability.

Surface chemistry

FT-IR studies conducted during and after artificial weathering indicated that there were no significant differences between Colorado and Balau's surface chemistry after 912h of weathering. The coating was not effective in preventing the photo-degradation of the aromatic rings present in lignin (1509 $cm^{-1}$and 1597 cm^{-1}). However, the coating was effective in preserving the 1461 cm^{-1} peak which is characteristic of the C-H vibrations found in lignin, and the 1229cm^{-1} which is characteristic of syringyl ring breathing in lignin, and C-O stretching vibration in lignin and xylan. The explanation for this could be that oil fills the lumen and cell walls of wood, thus providing a chemical-mechanical or physical protection of the hemicelluloses. It has also been reported that oils act as water repellents thus diminishing the consequences of the water's washing effect. Oils cannot prevent lignin and cellulose degradation, merely retard it.

C. Final comment

Artificial weathering was useful for studying the chemical changes that occurred during weathering but the physical changes did not correspond well with the results found during and after natural weathering. For this comparative study on Balau and Colorado, natural weathering is thus a more reliable method of studying timber weathering performance. From the results of the natural weathering study it can be concluded that both timbers performed better at Yzerfontein than at Stellenbosch; a result not anticipated as marine conditions are generally regarded as more harsh then inland conditions. This can be attributed to Stellenbosch's very low and continuously changing humidity in the summer time, causing excessive check and crack formation. Although longer exposure, a much larger number of samples and other exposure locations are required to confirm these findings, Colorado has shown to be comparable with Balau as a decking material. Based on aesthetics considerations (colour change and surface defects), Colorado performed similar to Balau but twisted less.

Appendix 1: EVALUATING THE WATER REGULATING PROPERTIES OF WOOD COATINGS

The Measurement of Liquid Water Permeability (LWP) and Water Vapour Permeability (WVP) of exterior) Finishes on Wood or Wood based substrates

method developed by
Tim Rypstra
Dept of Forest and Wood Science
Stellenbosch University

1. Principle of test methods

Determination of the amount of water (liquid or vapour), passing through a unit area of the coated wooden or wood-based substrate during a pre-selected period of time.

2. Test panels

- Defect free, smoothly planed, tangentially sawn SA pine or other selected timber species
- Sample dimensions: 300 mm (longitudinal length) x 100 mm (tangential width) x 15 mm radial thickness.
- Samples must be coated on five surfaces; 4 edges and 1 face according to manufacturer's specification
- Samples must be conditioned to a constant moisture content (e.g. at 20˚C / 65% RH) for at least three weeks
- Panel type, shape and dimensions are suitable for accelerated exterior weathering tests of coatings.

3. Apparatus and components

- Rectangular basin with 200 cm^2 rectangular area surrounded by rubber on edges
- 200 cm^2, rectangular shaped mould with O-ring embedded in edge
- Threaded studs and wing nuts
- Base plate

4. Permeability measurements

- Must be undertaken in the same room in which panels were conditioned.
- If both water vapour and liquid water permeability are determined on the same panel, the water vapour determination, being the least damaging, should be done first.
- After the water vapour determination, panels should be conditioned for at least four weeks before liquid water permeability tests can be conducted.
- Keep distilled water needed for tests in the same conditioning room
- The method is in principle suitable for other non-leaking substrates

5. Water Vapour Permeability (WVP) determination

- After conditioning, weigh panel to nearest second decimal in grams.
- Place rectangular basin on base of apparatus, and fill halfway with distilled water without wetting metal or rubber gasket surfaces that will come into contact with the wood panel. Place a custom-made polyethylene gasket on top of the rubber gasket to act as release agent for coated panels from the rubber gasket.

- Place coated wood panel with its coated face on the polyethylene gasket facing the water surface in the basin.
- Place rectangular mould on the back of the panel, positioning the O-ring in line with where the wood panel is making contact with the polyethylene and rubber gaskets.
- Tighten mould with wing nuts.
- After 7 days, remove panel and weigh.
- Calculate WVP of panel/coating composite as g water/1m^2/7d by multiplying the gain in mass (in g) by 50.

6. Liquid Water Permeability (LWP) determination

- After conditioning, weigh panel to nearest second decimal in grams.
- Turn rectangular basin upside down and place on base plate of apparatus.
- Place coated wood panel on the basin with its coated face upwards.
- Place rectangular mould with O-ring touching the face of the panel.
- Tighten mould with wing nuts.
- Pour distilled water in mould (75% full should be sufficient).
- After 24 h, pour out water without spilling on the panel, remove panel, blot off excess water with tissue paper and weigh panel.
- Calculate LWP of panel/coating composite as g water/1m^2/24h by multiplying the gain in mass (in g) by 50.

7. Enquiries

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Date: 31 March 2006

Appendix 2: FT-IR

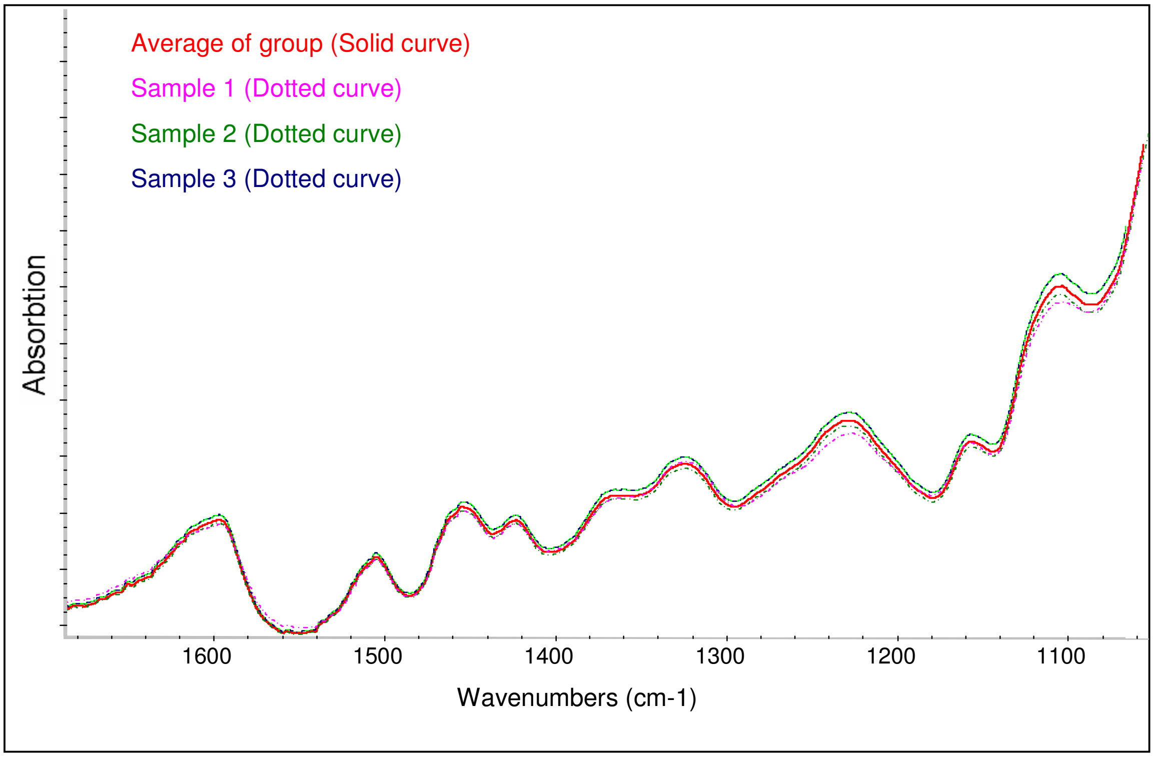

Figure A -1 Calculation of an average FT-IR spectrum, using FT-IR spectra obtained from three replicas.

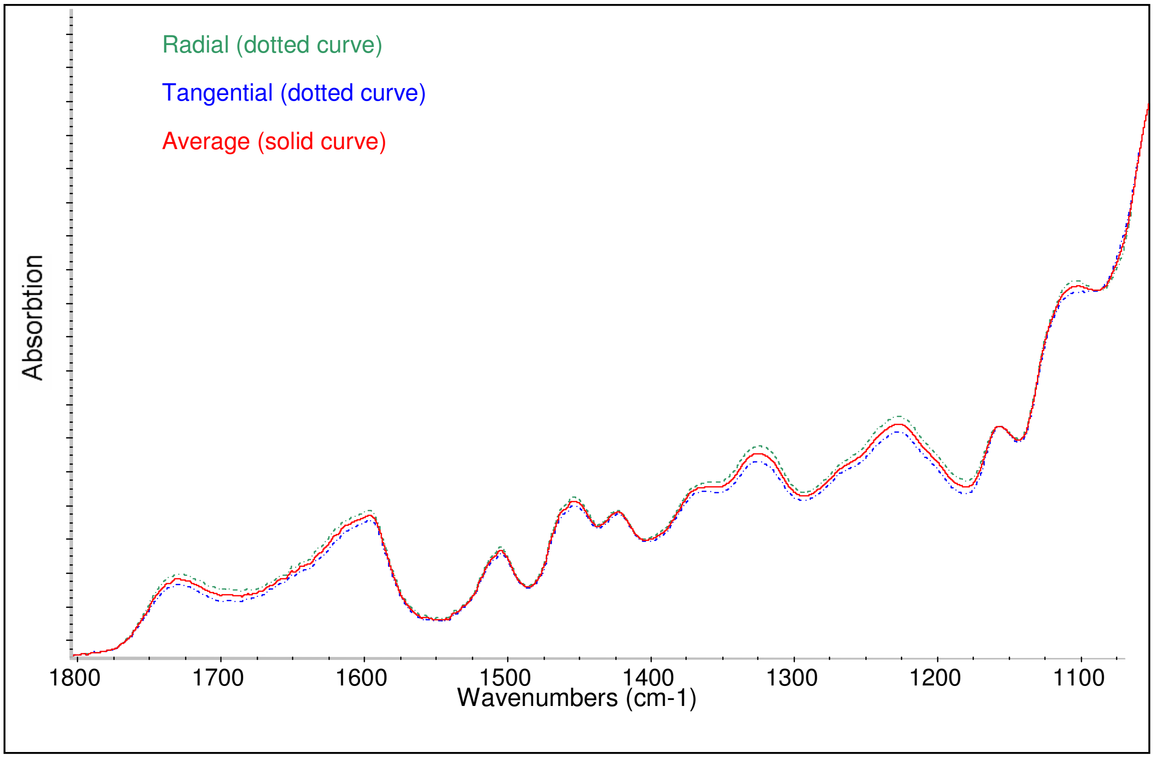

Figure A-2 Example of the test for differences between FT-IR spectra obtained from radially and tangentially cut samples, also indicating the average spectrum calculated from these.

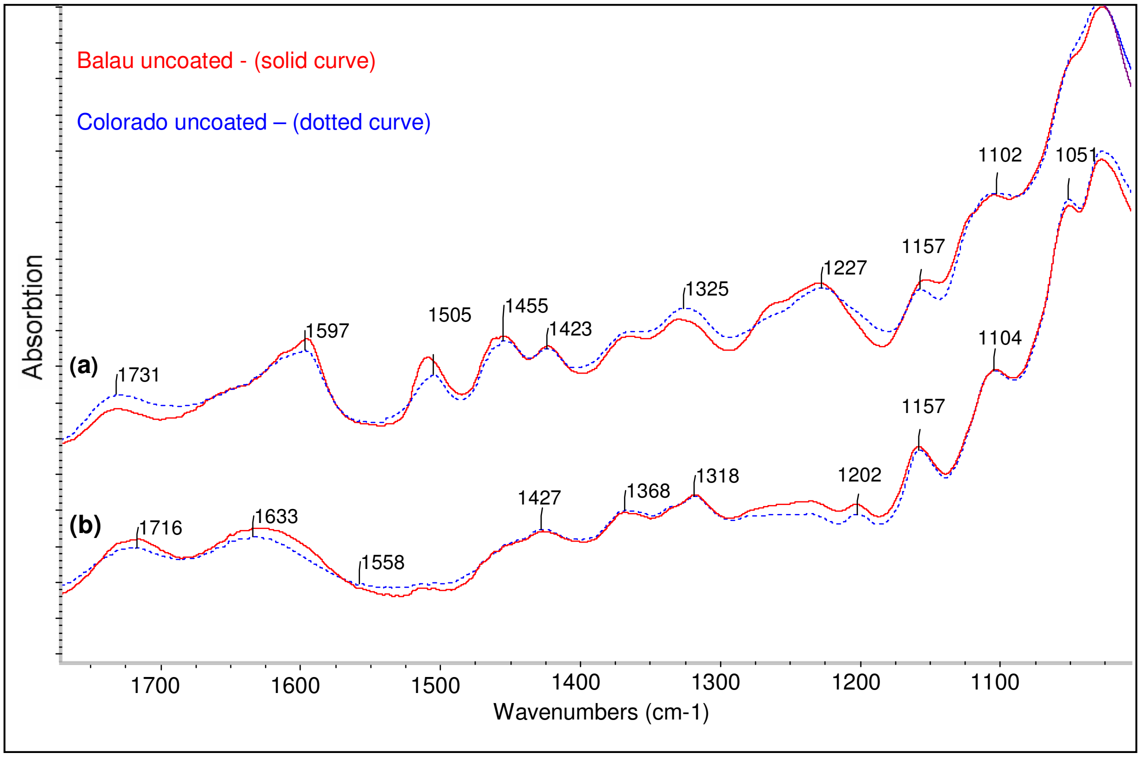

Figure A-3 FT-IR spectra of uncoated Balau and Colorado showing the difference between species before and after weathering: **(a)** Balau and Colorado unweathered; **(b)** Balau and Colorado weathered for 912h.

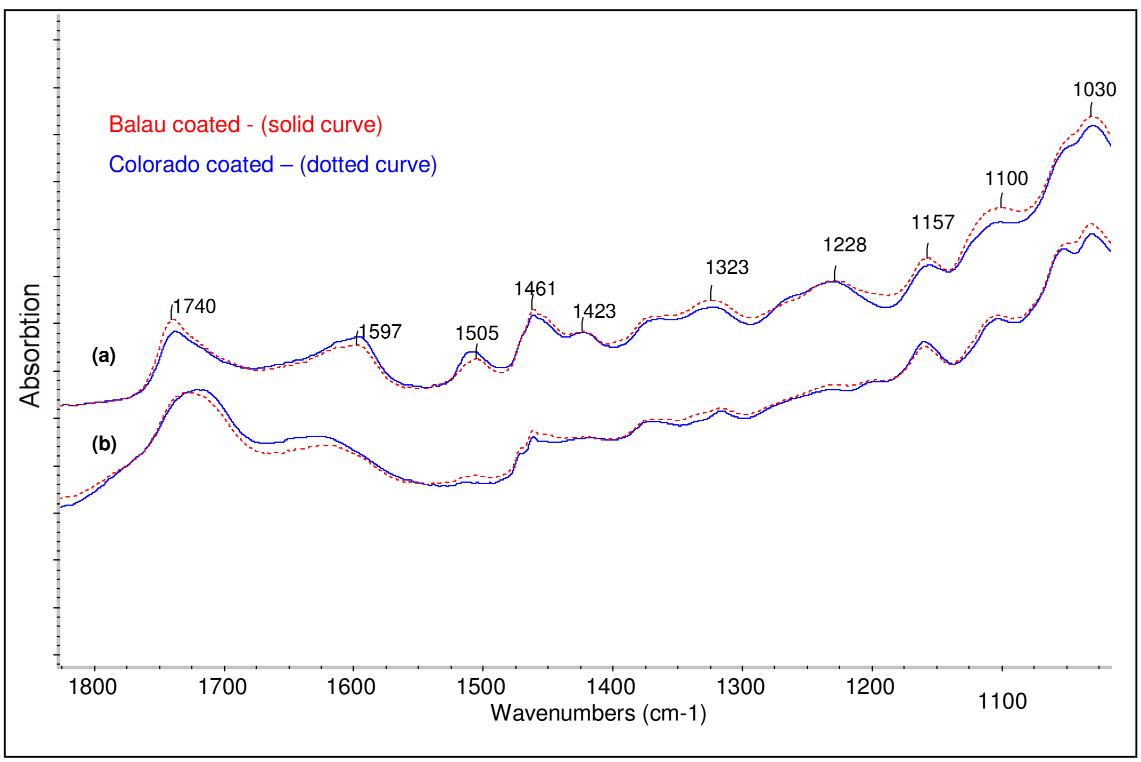

Figure A-4 FT-IR spectra of uncoated Balau and Colorado showing the difference between species before and after weathering: **(a)** Balau and Colorado unweathered; **(b)** Balau and Colorado weathered for 912h.

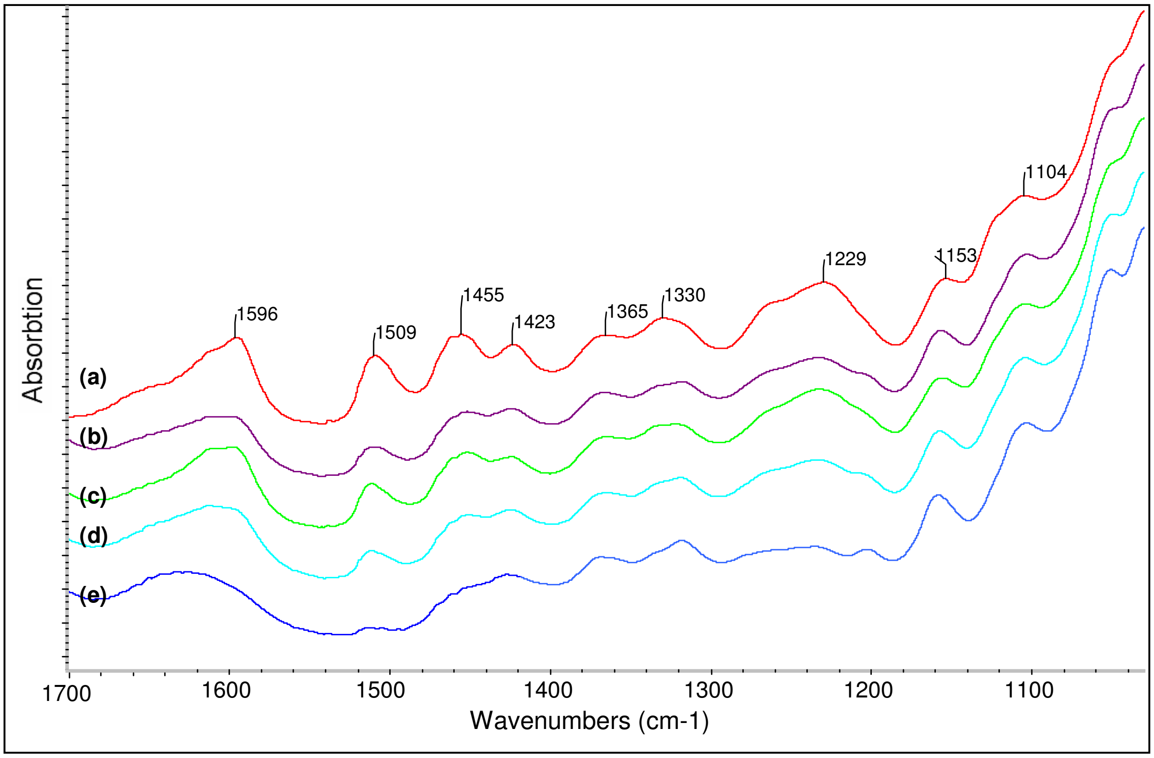

Figure A-5 FT-IR spectra of uncoated Balau: **(a)** unweathered; **(b)** weathered for 92h; **(c)** weathered for 200h; **(d)** weathered for 432h; **(e)** weathered for 912h.

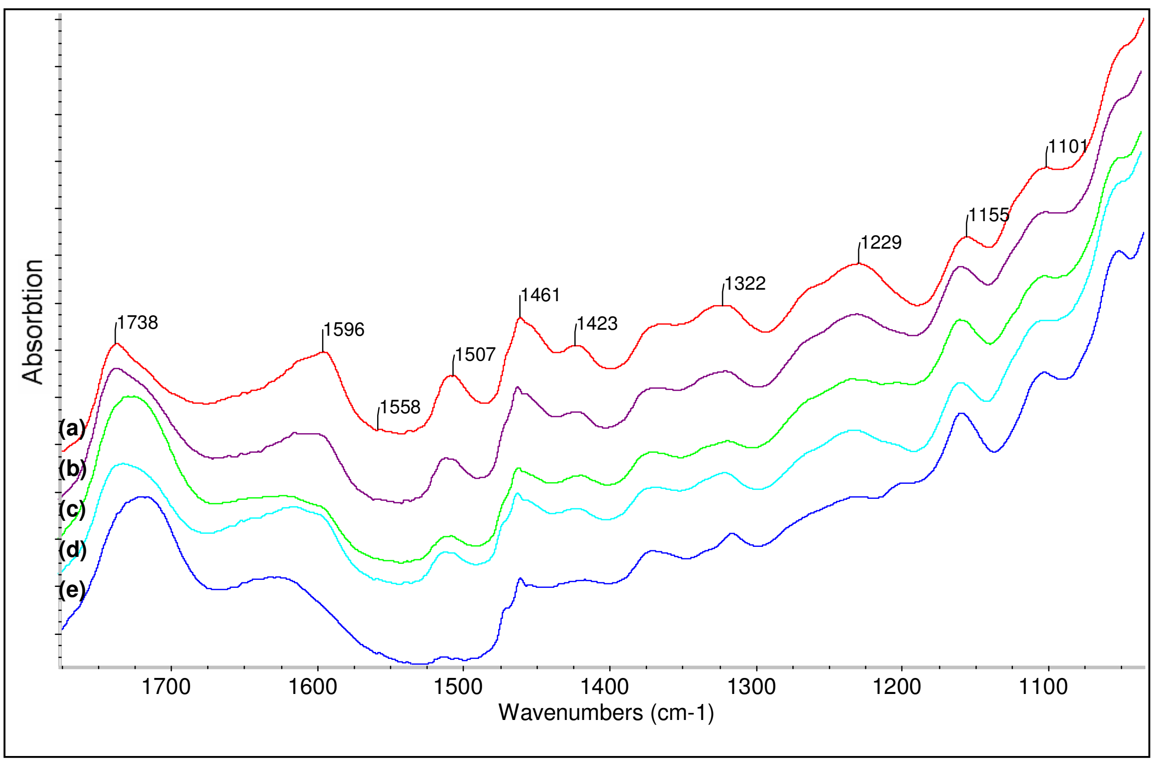

Figure A-6FT-IR spectra of coated Balau: **(a)** unweathered; **(b)** weathered for 92h; **(c)** weathered for 200h; **(d)** weathered for 432h; **(e)** weathered for 912h.

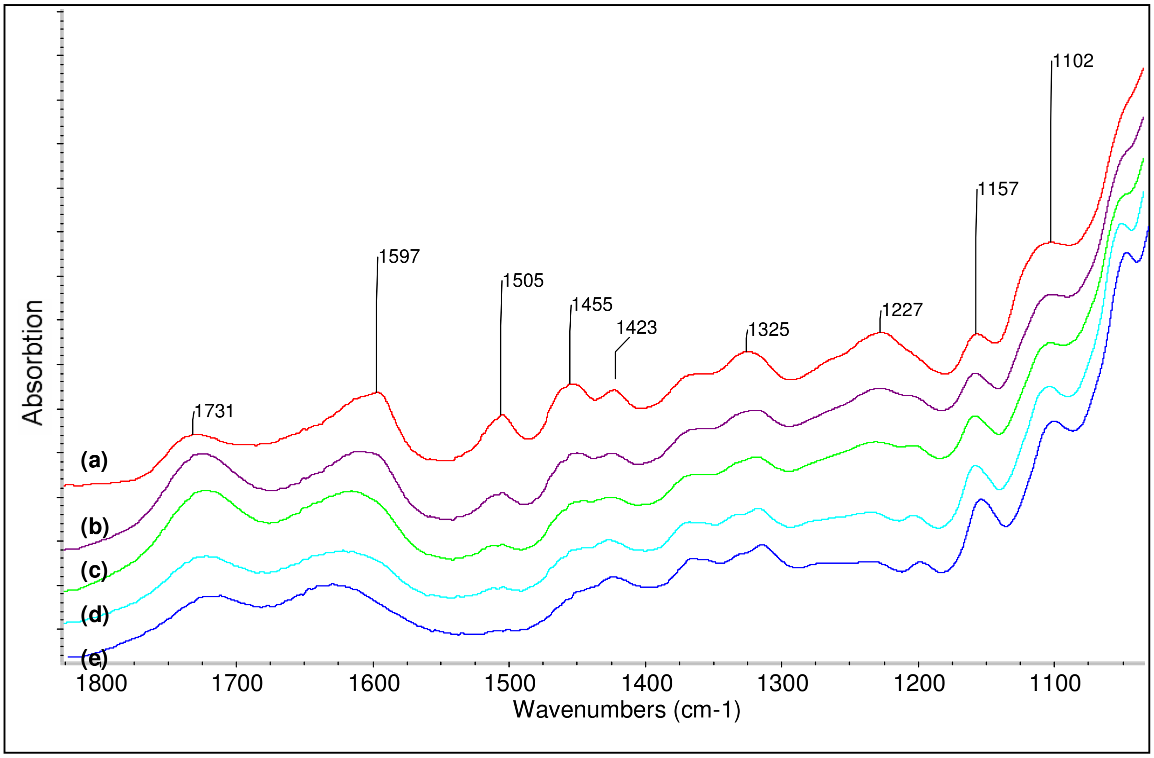

Figure A-7 FT-IR spectra of uncoated Colorado: **(a)** unweathered; **(b)** weathered for 92h; **(c)** weathered for 200h; **(d)** weathered for 432h; **(e)** weathered for 912h.

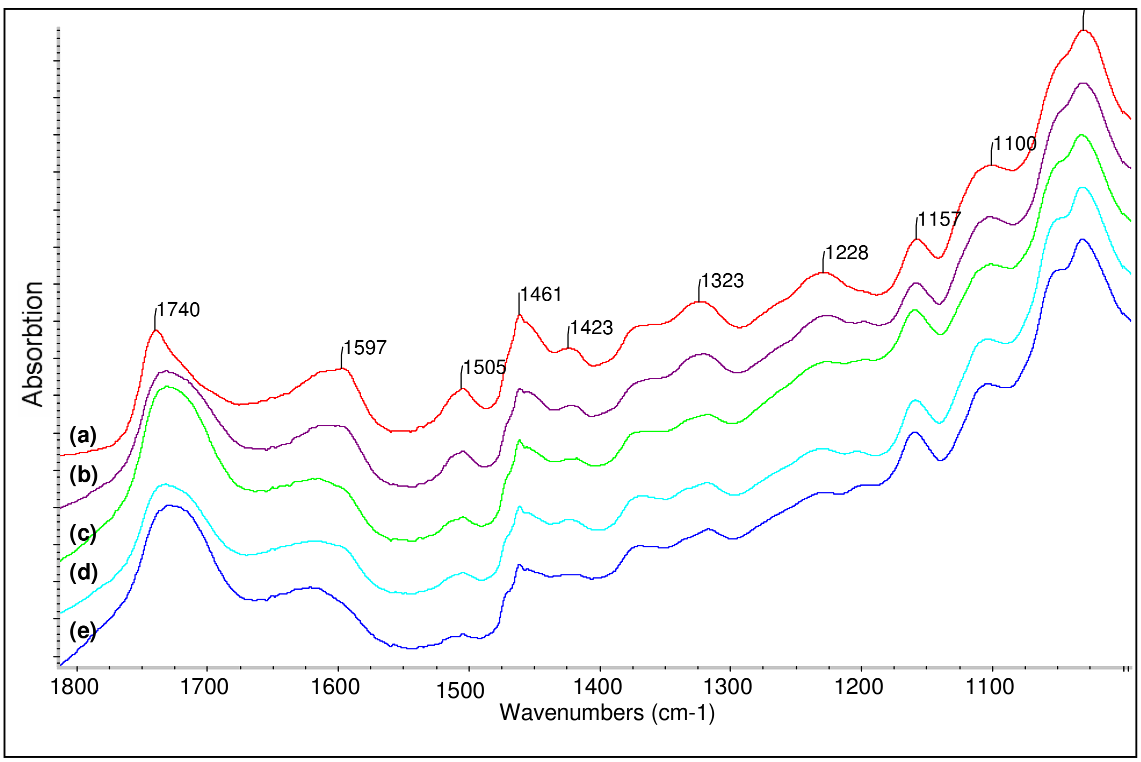

Figure A-8 FT-IR spectra of coated Colorado: **(a)** unweathered; **(b)** weathered for 92h; **(c)** weathered for 200h; **(d)** weathered for 432h; **(e)** weathered for 912h.