Maderas. Ciencia y Tecnología
ISSN: 0717-3644
ananias@ubiobio.cl
Universidad del Bío Bío
Chile

Keey, Roger B.

Colour development on drying

Maderas. Ciencia y Tecnología, vol. 7, núm. 1, 2005, pp. 3-16
Universidad del Bío Bío
Concepción, Chile

ISSN 0717-3644

maderas CIENCIA Y TECNOLOGIA, 7(1) 2005

ARTICULOS

COLOUR DEVELOPMENT ON DRYING♣

Roger B. Keey[1]

In memoriam of Dr. H. Peter STEINHAGEN

ABSTRACT

The drying of wet materials induces a number of physico-chemical changes in the product, often reflected in colour. For dried products sold on appearance, like certain grades of wood, the extent of colour development is highly significant in terms of the material's end-use. Until recently, colour was normally assessed by eye, but the availability of convenient spectrophotometers has provided industrial users with a means of quantitative description of colour. Examples from wood technology include assessing the impact of biological surface treatment, the impact of ultraviolet radiation, and screening of drying schedules by evaluating kiln brown-stain development. In other applications, the depth of colour might be used for the screening of drying schedules as an adjunct to other tests for stress development, or to pinpoint reaction and knotty wood in boards by an online scanner.

Keywords: colour, wood drying, kiln brownstain

NATURE OF COLOUR

Light and colour can mean different things to different people. While light and colour can be defined in terms of wavelengths of electromagnetic radiation, we respond to these properties in various ways. There are aesthetic and psychological dimensions. The psychology of colour was exploited, for example, by the late Polish filmmaker, Krysztof Krysztowski, who produced three films, Red, White and Blue, each colour reflecting the mood of the particular film.

We are taught from childhood that grass is green. But what do we see as "green"? Our individual perceptions may differ. While *green* in English may equate to *verde* in Portuguese, as far as the dictionary is concerned, one might speculate whether green fields of England evoke the same colour and feeling as the green of the Amazon jungle. The Welsh, who were there in Britain before the English arrived, have a word *glas*, which appears to cover a spectrum that are referred in English to green and brown; while perhaps the Roman invaders thought of *viridis* as the colour of the vernal grasses before they browned off. The indigenous language of New Zealand has a word *kakariki* for green; it is the same word as a parakeet whose plumage is certainly not grass-green.

♣ Paper invited. This paper was first presented at the IDS-2004, Sao Paulo. Received: 06.09.2004. Accepted: 04.10.2004. MADERAS: Ciencia y Tecnología 7(1):3-16.
[1] Wood Technology Research CentreUniversity of Canterbury, Christchurch, New Zealand. ✉: roger.keey@canterbury.ac.nz

Newton was an undergraduate student at Cambridge, when in 1665 the University was closed because of fear of the Great Plague spreading north from London. He was 22 at the time. He returned to his home at Woolsthorpe in eastern England, where he, in the space of two years, discovered the binomial theorem, worked out the elements of differential and integral calculus, described celestial mechanics and the theory of gravity, and produced the theory of colour in optics. Not a bad achievement for a young man. He might have been a brilliant scientist, but he was no draughtsman, as the rough sketch of his experimental set-up shows, depicting (in his own words) that "light is a heterogenous mixture of differently refrangible rays". In other words, sunlight could be split into the colours of the rainbow by passing it through a prism. Newton considered there were seven primary colours in the spectrum, perhaps influenced by his knowledge that there are seven distinct notes on the musical scale. Other scientists, such as Huynes disagreed: they claimed that the so-called seven, primary colours could be split into further colours.

Later, Young and Helmholz produced the three-colour theory of light: that light of any colour could be obtained by the mixing of appropriate amounts of only three colours that span the visible spectrum. Conventionally, these can be thought of the red, green and blue regions of the spectrum. By the late 1850's Maxwell worked out how to synthesise different colours using only red, green and blue light using a light-box. By varying the slit-widths for each of incident coloured beams, light of any colour could be obtained.

The human eye has three sets of cones sensitive to the red, green and blue light wavelengths, respectively. Sunlight has a flat intensity spectrum, being virtually the same as white light. Darker grey shades are produced by progressively reducing the intensity of white light. If the short, blue wavelengths are removed from white light, a yellow light is produced. By eliminating the long, red wavelengths one gets the colour cyan. We see magenta when the middle wavelengths are missing. Our optical systems are sensitive to both the *hue* or colour and the *brightness* or intensity. The eye is also sensitive to the colour *saturation* (the degree to which the light is viewed against a grey background).

COLOUR SPECIFICATION

In the 1930's the *Commission Internationale d'Éclairage* introduced a two-dimensional diagram, which could be used to quantify a particular colour or hue by its *chromacity*. The chromacity or colouredness of any light can be specified by a point within a region, which has an upper envelope of pure spectral colours (as viewed against white light) and a lower boundary representing colours produced by mixing pure red and blue light. The chromacity coordinates define the relative contribution of each primary, x being relative redness and y relative greenness. (The relative blueness z is found by difference as $z = 1 - x - y$.) The chromacity stems from the so-called tristimulus values, being standards that were taken from the averaged responses in three illuminants of a number of observers with normal colour vision. The dominant wavelength for the blue part was 465nm, the green part 545nm and the red 640nm.

The CIE chromacity diagram has some useful properties. A line from a point, which represents a given illuminant, drawn to the pure colour envelope through a point representing a particular colour gives the saturation C of the dominant wavelength of that hue. The mixture rule holds. If two monochromatic lights are mixed, the chromacity of the mixture lies on the straight line connecting the points representing the chromacities of the individual lights.

There are two colorimetric systems, which are derived from these chromacities, that define the colour of an object within a so-called *colour space*. In the CIE 1976 system, a colour solid is defined by three rectangular coordinates. The principal axis is the lightness level L^* on a 0-100 scale, 0 being total blackness and 100 pure white. Intermediate values give grey shades. The hue is specified by the other two chromic characters. One (a^*) defines the green-red axis, with negative values reflecting the dominance of greenness and positive ones redness. The second character (b^*) defines the blue-yellow axis, with negative values reflecting the dominance of blueness and positive ones yellowness. Alternatively, a cylindrical coordinate system may be used, with the a^* and b^* values being replaced by the saturation C and the hue angle h on the colour circle around the lightness axis.

The colour data for certain tropical species obtained by Goncalez (1993) and reported by Janin et al. (2001) are given in Table 1. The species are arranged in order of lightness. Ebony (*Diospyros crassiflora*) is normally regarded as a black wood, but it still has a significant reported lightness value of 26.2. It is perhaps better described as being dark grey, since the chromic characters a^* and b^* are almost zero. It is essentially hueless. The lightness values for Wenge (*Milletia laurentii*), which is a deep brown wood with a straight grain, depend upon the sawing pattern, whether flat or quarter-sawn. Presumably, this is a reflection of the appearance of the growth-rings. A wood such as Guariuba (*Claricia racemosa*) has relatively large L and b^* values, reflecting its light yellow appearance, particularly in the heartwood. By contrast, the decorative Amarante (*Peltogyne venosa*), also known in English as Purpleheart or Violetwood, has almost no yellow, as shown by its very small b^* value.

Table 1: CIE $L^*a^*b^*$ colour data for certain tropical woods. *After* Janin *et al.* (2001).

Common name	**Botanical name**	L^*	a^*	b^*
Ebony	*Diospyros crassiflora*	26.2	0.5	0.8
Wenge (quarter-sawn)	*Milletia laurtentii*	31.5	6.2	6.3
Wenge (flat-sawn)	*Milletia laurentii*	36.6	7.0	8.4
Amarante/ Purpleheart	*Peltogyne venosa*	38.1	17.9	3.7
Guariuba	*Claricia racemosa*	70.4	7.9	40.4

ORIGIN OF HEAT-DEVELOPED COLOUR IN BIOMATERIAL

Many biomaterials darken when heated or exposed to sunlight. Controlling this change in appearance is an important issue in maintaining the quality of dried products such a foodstuffs and wood. In this lecture, I will use the drying of wood to illustrate the changes that can take place, but the drying-control strategies are similar for all capillary-porous biomaterials containing both carbohydrates and proteinaceous substances.

Consider the drying of the sapwood of a softwood timber. In the initial stage of drying, sap and sap-soluble materials move to the evaporative zone close to the exposed surface of the wood under the action of capillary forces. These dissolved substances include sugars of low-molecular weight and nitrogenous compounds such as proteins. Essentially, these amino-acids catalyse the degradation of the sugars in the carbohydrate-enriched zone, with the formation of brownish compounds called *melanoidins* or *melanins*. (The word is derived from the Greek, meaning *black*).

Although the likelihood of so-called Maillard reactions has been a well-known feature of food processing besides kiln-drying of lumber, and has been the subject of numerous studies, the exact chemistry is still not well-understood. It appears that the rate at which the nitrogenous substances reach the surface is the limiting factor (Theander *et al.,* 1993; Dieste, 2002). The basic stoichiometric equation for the discolouration is then assumed to be

$$N + S \xrightarrow{k} C \qquad \textbf{(1)}$$

in which N is the molecular nitrogen present in the wood closest to the exposed surface, S are the molecular non-structural sugars there and C is some measure of colour. In Dieste's experiments on drying Radiata Pine under commercial kiln conditions, the presence of sugars was shown to be statistically insignificant. Therefore, it was assumed that the rate of discolouration could be given by an equation of the form

$$\frac{dC}{dt} = kN^m \qquad \textbf{(2)}$$

where k is the rate constant and m the order of reaction. Table 2 shows fitted values of the coefficient k and m for selected colour variables when time t is measured in hours.

Table 2: Empirical values of discolouration-rate parameters: rate constant k, order of reaction m and coefficient of determination R^2. *After* Dieste (2002).

Colour variable	***k***	***M***	***R*²**
Luminance R457	0.826	0.979	0.925
Lightness *L**	0.528	0.614	0.924
Blue-yellowness *b**	0.342	0.156	0.923

As kiln temperatures are raised, so the wood becomes more coloured. For softwoods grown in Northern Europe, such as Scots Pine (*P. sylvestris* L) and Norway Spruce (*Picea abies*), the wood becomes darker, redder and more saturated in colour (with a deeper hue) (Sundkvist, 2002). Similar changes are seen with broadleaf species such as Silver Birch (*Betula pendula* Roth) and European Beech (*Fagus sylvatica* L) (Stenudd, 2001).

The concentration of both sugars and nitrogenous compounds varies along the length of a tree's stem, but larger variations exist radially across the stem's cross-section than with height in the stem (Terziev *et al.,* 1997). Heartwood, as well as the innermost (and oldest) sapwood, contains a negligible amount of these compounds, but their concentration increases towards the cambium on the outside of the tree, which is the physiologically active zone when the tree is alive. There are also seasonal fluctuations. In northern Europe, it was found that the outer sapwood of Scots Pine (*P. sylvestris* L) contains a higher content of low-molecular-weight sugars during autumn and winter than during spring and summer (Tarvainen *et al.*, 2001). The starch content rises at the beginning of the growth period and then decreases in autumn as physiological activity wanes. Fructose and glucose are the dominant sugars. The seasonal variations of the nitrogenous compounds, however, are much less. Timber such as Scots Pine and Norway Spruce (Picea abies) that is felled in winter, however, discolours markedly more on kiln-drying than that felled at other times. This difference may be due to the enhanced sugar content in winter contrary to Dieste's finding, or some other factor.

Climate may affect the colour of wood in other ways. Apocryphal evidence indicates that Radiata pine from the southern part of New Zealand, which experiences cooler temperatures than the rest of the country, is more lightly coloured than wood from other regions. If this difference does exist, one possible reason may relate to the lesser formation of latewood during the cooler late summer and autumn in the south. Latewood is more coloured than earlywood, with more lignin, and the lesser accumulation of cell-wall mass in the south would lead to a brighter wood overall. A similar observation has been noted in a recent work on the variability of cell-wall mass with climate in Siberian larch (*Larix decidua*) (Silken and Kirdyanov, 2003).

Although the carbohydrate content of many commercial timber species differ little from each other, there can be significant variations between species. For example, the cellulose content for Japanese Thuya (*Thijopsis dilabrata*) is 38.4 %, while that for Yellow Pine (*P. strobus*) is 61.6% (Keey *et al.,* 2000). Yet even small changes of wood composition can show up. Sap from Scots Pine compared with that from Norway Spruce (*Pices abies* L) show noticeable differences in colour-change rate when heated when heated at temperatures in the range 60-95°C over a five-day period (Sehlstedt-Persson, 2003).

Drying of green sapwood causes a significant enrichment of the melanin precursors, In Scots Pine (*P. sylvestris* L.), the concentration of low-molecular sugars changes from 0.5-1% of the dry weight in the greenwood to 3-5% after drying, with nitrogenous compounds increasing from 0.03-0.06% to about 0.1% (Terziev, 1994). The concentration of these melanin precursors close to the surface in the initial stage of kiln-drying of permeable sapwood boards gives rise to the formation of brownstain, a thin brownish zone about 1-3mm below the exposed surfaces of the lumber. This colouration is temperature-dependent. The faster the drying schedule as the kiln's temperature is raised so higher is the enrichment of sugars at the surface (Terziev *et al.,* 1993). The formation of kiln brownstain in *Pinus radiata* is reported to become significant at temperatures above 60°C (Kreber and Haslett, 1997), and above 70°C for *P. sylvestris* (Sehlstedt-Persson, 2003). The stain degrades the wood as a finishing timber, requiring the surface layers to be planed off, with a loss of wood. (See Figure 1).

An additional factor in the enhancement of colour is the presence of resins. The flow of resins increases with temperature, especially around knots in pine. In kiln-dried lumber, the resin appears as crystalline dark-brownish spots on the exposed surfaces after drying. Any subsequent planing or dressing of the surfaces will remove these defects.

While surface brownstain is a problem with softwoods like Radiata Pine; sometimes, with a hardwood like Hard or Sugar Maple (*Acer saccharum* Marsh.), the interior of kiln-dried lumber can be relatively dark even if the outside has an acceptable colour (Yeo and Smith, 2003). This colour difference becomes a problem if the wood is subsequently resawn or machined. The Maillard-type reactions begin in the food-storage parenchyma cells, releasing melanins, which then occlude the cell lumens. The effect varies with the species. The critical temperature for the core-darkening of Hard Maple appears to be about 43°C when the moisture content is at or above fibre-saturation point. Thus, these workers suggest keeping the core temperature below this critical value until the wood has dried below fibre saturation as one way of ensuring that the final kiln-dried wood is acceptably bright and light in colour. This conclusion appears to be at variance with the results of other work on the inkiln darkening of European species such as Ash (*Fraxinus excelsior* L.) and Beech (*Fagus sylvatica*) (Straze *et al.*, 2003). In this case, the discolouring is ascribed to an enzymatic oxidative reaction that occurs in the parenchyma cells, with all the discoloured areas having a moisture content *below* fibre saturation. Both low temperatures and low relative humidities in the kiln are recommended to reduce the incidence of darkening.

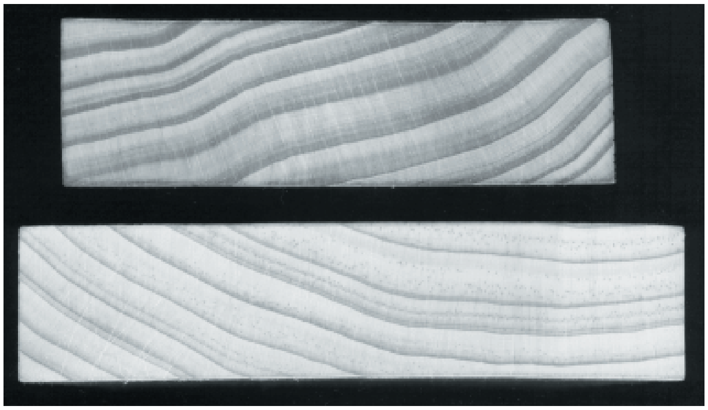

Fig. 1: Effect of high-temperature drying on the brightness or lightness of a softwood board. Kiln brownstain can be seen as thin zones just below the long faces of the board.

Weathering. Wood darkens naturally when exposed to the weather. Freshly-dried pine yellows on exposure to ultraviolet and visible light, which has sufficient energy to cleave most of the covalent bonds found in wood. Natural weathering of wood involves other factors such as temperature and moisture levels, microorganisms and atmospheric pollutants. However, the general darkening of wood is due mostly to a series of photochemically-induced reactions of lignin that do not require the presence of oxygen (Leary, 1967). Blocking of the phenolic hydroxy groups in lignin, by esterification for example, can achieve photostabilization and improve weatherability. Thus, it is considered that these hydroxyl groups are the reaction centres for yellowing (Leary, 1968). The change in colour has been attributed to the production of coloured demethoxyl compounds. Chemical treatments appear only to be a short-term palliative to hinder the discolouration. Acetylation, for example, has been found to be effective in providing a temporary retardation of colour change in Southern Yellow Pine (*P. palustris*) during 28 days of irradiation with a high-pressure, quartz mercury-vapour lamp (Hon, 1995).

In other tests of limited duration, when kiln-dried *Pinus radiata* boards were exposed to ultra-violet radiation from a sunbed lamp, most of the discolouration took place in the first 4 days of exposure, with an average increase in yellowness (expressed as the change in the chromacity b^*) of about 60% after 14 days (Boyce, 2003). The effect did not penetrate below 1mm from the surface and appeared independent of the drying conditions over the normal commercial working range. General observation of the performance of finished timbers suggests that this darkening slowly continues for years, and that varnishing of the wood does not hinder the process to any extent. A somewhat similar conclusion about the effect of drying conditions was reached by Terziev and Ekstedt (1997), who examined the weatherability of paint coatings on Scots Pine (*P. sylvestris* L.). Five different coatings faded with time, but different drying treatments did not induce significant differences in the discolouration of the wood. Neither did planing, and thus the removal of the layer where the concentration of melanin precursors would have been enhanced, influence the colour changes.

COLOUR AS AN INDICATOR OF WOOD QUALITY

Hardwoods such as European oak (*Quercus* spp.), which are used for decorative purposes, are chosen for their end use though various criteria, often empirical and traditional. Colour is one aspect that has aesthetic appeal. Several years ago, Mazet and Janin (1990) reported on a study involving 90 French and Italian assessors drawn from a number of woodworking industries. They were presented with a collection of industrial oak-veneer samples (200mm x 220mm), which were randomly grouped into 53 pairs. Each sample had been measured at 20 points for lightness L^* and hue angle h using a spectrophotometer. An opinion on whether there was any colour-related quality difference between the two samples in each pair was sought from all the professional assessors. Their evaluations were then compared with the measured absolute colour differences ΔE given by:

$$\Delta E = \left[(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2\right]^{1/2} \qquad (3)$$

where L^* is mean the lightness value and a^* and b^* are the mean chromacity co-ordinates of the two samples being compared over the 20 measurement points on each veneer. Over one-quarter (28%) of the assessors could not distinguish the difference when ΔE had a value of 2 units or less, but when the difference was much larger, in the range 6 to 11, the extent of non-choice had fallen by one-half to 14%. It appears that the natural colour-tone variability of the oak veneers influenced many individual selections, with Italian assessors placing more importance on uniformity, while the French assessors placed more weight on excessive yellow-red hues. (See Figure 2. The reason for this difference is doubtless a possible sociological research project!) However, differences in lightness were readily picked up, with just over half (56%) of the assessors being able to detect a difference ΔL^* of 1 unit or less, and 82% were able to detect differences in the range of 6 to 11 units of lightness. We have found a similar thing in our own tests on drying pine. Lightness variation is a more sensitive clue of colour change to the human eye that the accompanying change in chromic characters a^* and b^*.

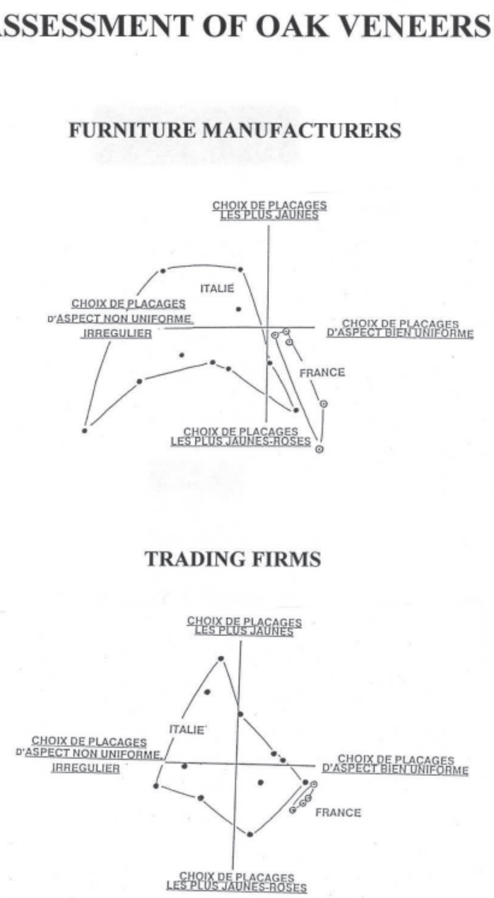

Fig. 2: Comparison of the assessments of 90 French and Italian timber specialists in comparing the appearance of 53 pairs of oak-veneer samples. The Italian assessors were more concerned with the uniformity of colour than their French counterparts, while the furniture manufactures detected more differences in reddish hues than those in the trade. *After* Mazet and Janin (1990).

Ledig and Seyfarth (2001) have carried further the idea of using colour as an indicator of product quality. Steaming of green hardwood boards is undertaken industrially to obtain a desired finishing colour without the use of additives. Colour is an important criterion in the appeal of furniture and parquet flooring. Steaming has the benefit of decreasing the contrast between heartwood- and sapwood, while enabling the operator to produce a timber that mimics a favoured species in colour. Normally the colour is assessed by eye, and the kiln-steaming schedule is set empirically. This procedure can pose problems in satisfying the requirements of new customers or when a specific change of colour is asked for. Earlier data (Kisseloff, 1991) for the steaming of beech at 80^{O}C and 100^{o}C suggested that the lightness L^* can be correlated with steaming time by a relationship of the kind

$$L^* = 78 + 0.4t - c\sqrt{t} \quad \textbf{(4)}$$

where c is a temperature-dependent coefficient and t is the steaming time in hours. Such a correlation implies that a less subjective method of assessment might be devised.

Spectrophotometric data on steaming beech show that, as the lightness *L** decreases, so the green-red *a** and the blue-yellow *b** chromatics increase. The band of data points in the *L**-*a** plane, for example, is relatively narrow. Thus, not all theoretical combination of colour variables can be achieved by steaming. So, for instance, it is impossible to specify the combination of very light and very red wood, and thus there are limitations on what species can be mimicked.

Ledig and Seyfarth (2001) have proposed a five-class system of colour levels to cover the whole range of colours produced by steaming. Each class has to be wide enough to encompass the natural variations in the wood, and only colour differences spanning two classes might be considered to be a colour defect. The average values of the colour variables for each class are set out in Table 3.

Table 3: Averaged values of colour variables for assessing colour levels in steam-treated beech. *After* Ledig and Seyfarth (2001).

Class	Lightness *L**	green-redness *a**	Blue-yellowness *b**
1	80.6	5.5	15.6
2	72.5	8.5	18.3
3	68.3	11.3	20.6
4	65.6	11.8	20.1
5	62.1	13.0	19.8

A set of seven rules was devised, using only the lightness and green-red chromacity, to allocate any given sample to its classification. This allowed a degree of fuzziness at class boundaries to compensate somewhat for natural variations over each sample. Further, a colour chart could be devised that was based on steamed samples allocated to the various classes, which then could be adopted elsewhere as a reference in those industries that did not have colour-measuring equipment to assess their products.

COLOUR AS A TRACER

Colour may be used as a tracer of other things. The extent of heat treatment is reflected in the depth of colour of the product. Kiln brownstain is a reflection of the accumulation of sap-borne materials. Some experiments undertaken over recent years in the Wood Technology Research Centre illustrate the possibilities.

Pit aspiration. Pit aspiration is believed to be the mechanism whereby sap can move to the exposed wood surface in the initial stages of drying the sapwood of a softwood (Keey *et al.,* 2000). The hollows of the wood fibres known as lumens are fully sap-filled, or almost so, except for a narrow zone next to each exposed surface of the sawn timber. The movement of sap to the surface has to overcome an adverse pressure gradient, since the lumens of the green wood must be under tension for nutrients in the living tree to pass from the roots to the crown. It is thought (Booker, 1996) that the sap exists under a metastable condition, and that the presence of isolated air bubbles or other factors (such as evaporation near the surface) triggers a sudden change in state, causing cavitation or vaporization with sufficient violence to force the remaining liquid out of the cavitating lumen through bordered pits connecting the lumen with its neighbour, which then close shut like one-way valves. (See Figure 3&4.) This is known as pit aspiration. As drying proceeds, the pits aspirate randomly, reducing the liquid permeability until the flow to the evaporative zone cannot match the evaporation rate. The wet core gradually shrinks as this zone then withdraws into the surface. Sap-borne chemicals therefore accumulate in the evaporative zone, where Maillard-type reactions can take place and the deposition of amorphous melanins can be observed. These deposits are not uniformly spread throughout the zone: some cells appear almost clear of coloured material, while others are clogged.

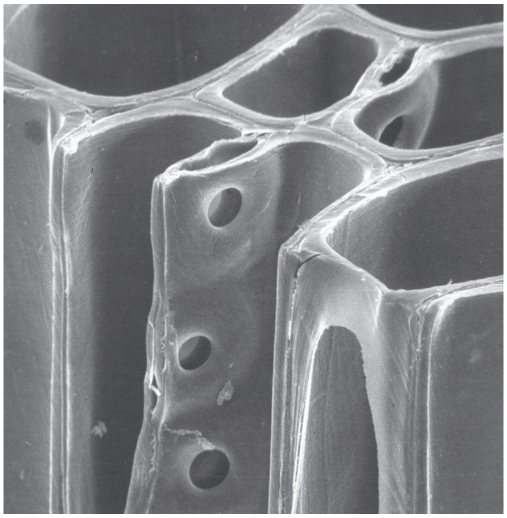

Fig.3: Bordered pits in the walls of a softwood tracheid (hollow fibre). *After* Butterfield (pers.comm.), in Keey *et al.* 2000.

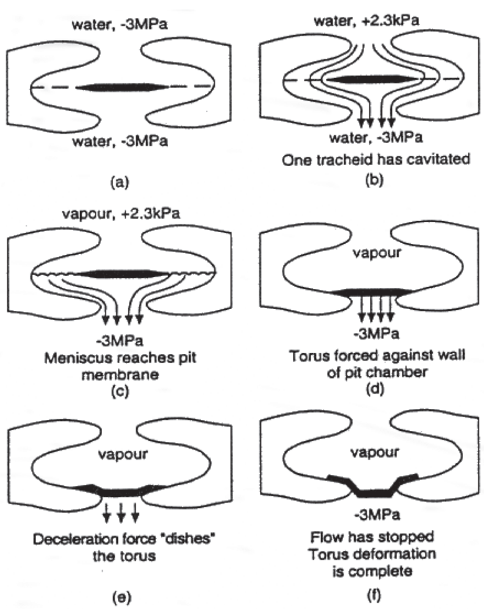

Fig. 4: Suggested mechanism of pit aspiration of softwood tracheids. *After* Booker (1996).

This is the phenomenon of kiln brown stain already referred to. As a means of inhibiting the formation of this stain, McCurdy *et al.* (2002), have suggested a bacterial pretreatment of the wood, whereby the bacteria reduce the levels of soluble carbohydrates in the sap (Powell *et al,* 2000) and enhance the permeability by eating the pit membranes (Archer, 1985). In tests to demonstrate this possibility, end-matched boards of *Pinus radiata* were sprinkled at 24^{o}C in a buffered solution containing wild wood bacteria in sawdust taken from a local timber mill. The boards were removed at various times up to 29 days, and then dried under high-temperature conditions. After about 20 hours drying, the boards were crosscut, examined for evidence of staining, and samples prepared for image analysis by surface sanding. Digital images (of low resolution by today's standards) were taken by camera using a diffuse light source to illuminate the samples. The images were then processed electronically into three separate 8-bit, grey-scale images to represent the colour variables *L*, a** and *b**. Only the lightness *L** was used as the tracing variable. In this way, lightness profiles at right-angles to the exposed surface could be constructed from these images.

The profiles of lightness normal to the board's surface show a minimum in the lightness about 0.4mm from the surface, which disappears after 8 days of bacterial treatment. After 29 days, the depth of colour throughout the wood was found to be virtually uniform at the initial core value, with a slight increase in lightness very close to the surface (<0.2mm). (See Figure 5). Clearly the treatment had virtually eliminated the deposition of melanins that are seen as a stain layer. Separate analysis by neutron radiography showed that the permeability of the wood had been enhanced by the treatment, and microscopy revealed the presence of bacteria with damaged (and porous) pit membranes (Nijdam *et al,* 2001). This damage prevented pit aspiration.

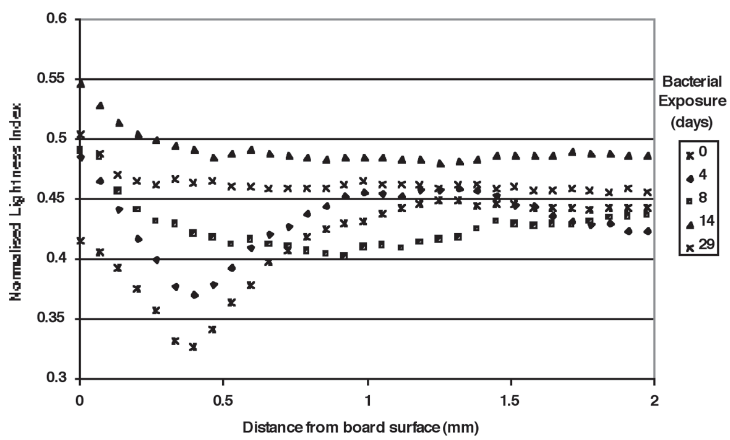

Fig. 5: Profiles of normalised lightness index (inverse greyness scale) through 50mm-thick *Pinus radiata* sample boards exposed to wild wood bacteria. *After* McCurdy *et al.* (2002).

Kiln schedules for bright wood. While it is known that excessive kiln temperatures lead to darker wood, the actual combination of kiln temperature and relative humidity to produce bright wood at the fastest possible rate is not. The use of lower temperatures might be compensated by the choice of lower relative humidities to maintain an acceptable drying rate. To search for an optimum combination of settings, tests were undertaken in drying edgematched- and end-matched boards in a closed-circuit drying tunnel under a range of commercial drying conditions that spanned dry-bulb temperatures from 50^{o}C to 120^{o}C and relative humidities from 14% to 67% (McCurdy *et al.,* 2003, 2004). For each schedule, a 50mm-thick board was cut into four smaller boards that were dried for 20%, 40%, 60% and 80% respectively, of the total drying time to determine how the moisture-content and lightness profiles varied as moisture was driven off. The boards were sampled, cut into blocks which themselves were sliced into 1mm-thick wafers. A surface-reflectance spectrophotometer was used to measure the colour of each slice, again in terms of *L*, a** and *b** values, but the lightness *L** was found to be the easiest variable to use as a tracer. (See Figure 6). From the lightness profiles, darkening of the wood appeared in the surface (0-1mm) slice after 40% of the drying span under high-temperature conditions, but after 20% of the total drying time under the lower-temperature, conventional drying conditions. Thus, the effect of the reduced kiln temperature is offset to some extent by the greater drying time needed at this lower temperature. The average lightness values for the fully-dried boards are given in Table 4. The fractional difference in lightness between the surface and the core, $\Delta l^* = (L^*_{surf} - L^*_{core})/L^*_{core}$, is a measure of the extent of darkening at the surface. The lowest-temperature schedule has the least change, while the schedule with an intermediate temperature in the range but high relative humidity (with a wet-bulb depression of 10°C) shows the greatest change in colour because of the prolonged drying time under small air-humidity gradients. Interestingly, there was very little colour change in the core over the range of conditions studied despite variations in the ultimate core temperatures. Possibly the progressive loss of sap-borne reactants reduces the concentration of melanins formed within the interior of the wood.

Table 4: Average lightness values *L** for fully-dried *Pinus radiata* boards at temperatures between 50°C and 120°C and relative humidities from 14% to 67%. *After* McCurdy *et al.* (2003).

Temperature	Relative humidity	L^*_{core}	L^*_{surf}	Δl^*
ACT	High	79	69	0.13
HT	Moderate	81	71	0.12
ACT	Moderate	81	75	0.07
ACT	Low	82	75	0.08
CT	High	81	77	0.05
CT	Moderate	80	76	0.05
CT	Low	81	79	0.02
LT	Moderate	82	81	0.01

Temperature ratings: ACT accelerated conventional; CT conventional; HT high, LT low.

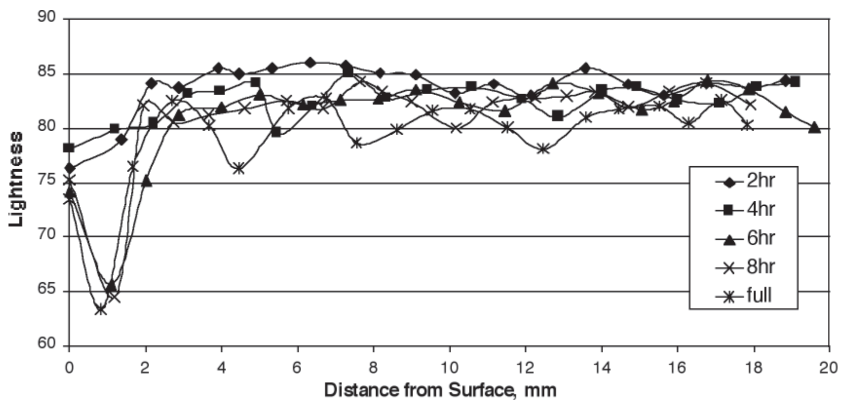

Fig. 6: Lightness *L**profiles for 50-mm thick *Pinus radiata* boards being dried at 5 m s^{-1} under dry and wet-bulb temperatures of 120°C and 70°C, respectively, *After* McCurdy *et al.* (2003).

Extensions to these tests are described in another paper (McCurdy *et al.,* 2004).

CONCLUDING REMARKS

Colour is a property which is important in assessing the fitness for purpose of much kiln-dried lumber alongside such properties as stiffness and moisture content. Since colour is a property both easily manipulated and changes with time, any quality criterion would need to be based on certified measurements taken at a set time after processing and before wrapping prior to dispatch to a customer.

In many cases, the lightness value *L** would be an adequate colour variable to use, requiring only a simple light-meter rather than a full spectral analyser. The use of colour charts is another low-cost possibility. On the other hand, large wood-processing enterprises might be able to justify expenditure on online spectrographic sensors. Such instruments might be able to distinguish between various kinds of darker wood, such as reaction and knotwood or the appearance of resin spots. This would enhance the ability to cut to advantage in preparing long lengths of clearwood for conversion to manufactured items such as mouldings.

Although my lecture has considered only application in wood drying, considerations of colour development are also important in the heat treatment and exposure of any biomaterial. In the baking of food products, for example, colour is an indicator of the end-point in processing. However, while the baker might look at colour in his plant, perhaps his customers are more interested in the amount of cream and jam in their buns. Colour is only one criterion of quality. In the case of freshly-cut fruits and vegetables, Maillard-type reactions occur rapidly under room conditions, posing problems for both the food manufacturer and the housewife, but that is another story!

LITERATURE

Archer, K.J. 1985. Bacterial modification of Douglas-fir for roundwood permeability. PhD thesis, University of Canterbury NZ.

Booker, R.E. 1996. New theories for liquid flow in wood. Proc. 5th Internat. IUFRO Wood Drying Conf., Québec Canada, pp.437-445.

Boyce, D. 2003. Colour development in UV-exposed *Pinus radiata* after kiln drying. BE Rep., CAPE, University of Canterbury NZ.

Dieste, A. 2002. Colour development in *Pinus radiata* D. Don under kiln-drying conditions. ME thesis, University of Canterbury NZ.

Goncalez, J. 1993. Caractérisation technologique de quatre espèces peu connues de la forêt Amazonienne: anatomie, chimie, couleur, propriéties physiques et mécaniques. Doct. thesis, ENGREF, Nancy, France.

Hon, D. N. S. 1995. Stabilization of wood color: is acetylation blocking effective?. *Wood & Fiber Sci*, 27: 360-367.

Janin, G.; Goncalez, J.; Ananías, R.A.; Charrier, B.; Fernándes da Silva, G.; Dilem, A. 2001. Aesthetics appreciation of wood colour and patterns by colorimetry. Part1. Colorimetry theory by the CIE Lab system. *Maderas: Ciencia y Tecnologia*. 3 (1&2):3-13.

Keey, R. B.; Langrish, T.A.G.; Walker, J.C.F. 2000. Kiln-Drying of Lumber. Springer, Berlin, 326pp.

Kisseloff, P. 1991. Trochnen und Dämpfen von Buchenschnittholz, *Vortrag Schweiz. Zeitschrift für Forstwesen* 142:407-414.

Kreber, B.; Haslett, A.N. 1997. A study of some factors promoting kiln brown stain formation in Radiata pine. *Holz als Roh- und Werkstoff*. 55:355-362.

Leary, G.J. 1967. The yellowing of wood by light. *TAPPI* 50(1):17-19.

Leary, G.J. 1968. The yellowing of wood by light. TAPPI. 51(6):257-260.

Ledig, S. F.; Seyfarth, R. 2001. Characterization of surface colour during wood processing. Proc. 7th Internat. IUFRO Wood Drying Conf., Tsukuba Japan, pp.288-293.

Mazet, J.F.; Janin, G. 1990. La qualité de l'aspect des placages de chênes: mesures de coleur et critères d'appréciation des professionnels français et italiens. *Ann. Sci. For*. 47:255-268.

McCurdy, M.C.; Nijdam, J.J.;Keey, R.B. 2002. Biological control of kiln brown stain in Radiata Pine. *Maderas: Ciencia y Tecnología* 4(2):140-147.

McCurdy, M.; Pang, S.; Keey, R. 2003. Measurement of colour development in *Pinus radiata* sapwood boards during drying at various schedules. Proc. 8th Internat. IUFRO Wood Drying Conf., Brasov Romania, pp.445-8.

McCurdy, M.; Shusheng, P.; Keey, R. 2004. Drying schedule optimisation for producing light-coloured softwood lumber. Proc. IDS 2004, São Paulo Brazil.

Nijdam, J.J.; Lehmann, E.; Keey, R.B. 2001. Bacterial treatment of *Pinus radiata* timber to improve permeability. Proc. 2nd IADC, Veracruz Mexico.

Powell, M.A.; Webber, J.F.; Eaton, R.A. 2000. Changes in moisture, soluble carbohydrate and bacterial numbers during water storage of pine. *For. Prod. J.* 50(3):74-80.

Sehlstedt-Persson, M. 2003. Colour responses to heat-treatment of extractives and sap from pine and spruce. Proc. 8th Internat. IUFRO Wood Drying Conf., Brasov Romania, pp.459-464.

Silkin, P.P.; Kirdyanov, A.V. 2003. The relationship between the variability of cell wall mass of earlywood and latewood tracheids in larch tree-rings, the rate of tree-ring growth and climatic changes. *Holzforschung* 57(1):1-7.

Stenudd, S. 2001. Colour changes in birch and beech during kiln drying. Proc. 7th Internat. IUFRO Wood Drying Conf., Tsukuba Japan, pp.300-5.

Straze, A.; Oven, P.; Zupanic, M.; Gorisek, Z. 2003. Colour changes of ash-wood (*Fraximus excelsior* L.) during conventional drying. Proc. 8th Internat. IUFRO Wood Drying Conf., Brasov Romania, pp.465-9.

Sundkvist, B. 2002. Wood color control during kiln drying. *For. Prod. J*. 52(2):30-37.

Tarvainen, V.; Saranpää, P.; Repola, J. 2001. Discoloration of Norway spruce and Scots pine timber during drying. Proc. 7th Internat. Wood Drying Conf., Tsukuba Japan, pp.294-9.

Terziev, N. 1993. Influence of kiln and air drying on redistribution of low-molecular sugars and nitrogenous compounds in Scots Pine (*Pinus sylvestris* L.) and consequences for mould susceptibility. Licent. thesis, Sveriges Landbruksuniversitet, Uppsala.

Terziev, N.; Boutelje, J.; Larsson, K. 1997. Seasonal fluctuations of low-molecular-weight sugars, starch and nitrogen in sapwood of *Pinus sylvestris* L.. *Scand. J. For. Res.* 12:216-224.

Terziev, N.; Boutelje, J.; Söderström, O. 1993. The influences of drying schedules on the redistribution of low-molecular sugars in *Pinus sylvestris* L. *Holzforschung*. 47:3-8.

Terziev, N.; Ekstedt, J. 1997. Discolouration of white coatings applied on kiln- and air-dried Scots Pine lumber. *Holz als Roh- und Werkstoff* 55: 71-81

Theander, O.; Bjurman, J.; Boutelje, J.B. 1993. Increase in the content of low-molecular carbohydrates at lumber surfaces during the drying and correlations with nitrogen content, yellowing and mould growth. *Wood Sci.Technol* 27:337-344.

Yeo, H.; Smith, W.B. 2003. Effect of temperature and moisture content on the discoloration of Hard Maple lumber. Proc. 8th Internat. IUFRO Wood Drying Conf., Brasov Romania, pp.455-8.