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Correlation between hue angle and lightness of light irradiated wood

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ABSTRACT

The objective of this study was to investigate irradiation characteristics of Beech (*Fagus crenata* Blume), black locust (*Robinia pseudoacacia* L.), Japanese cedar (*Cryptomeria japonica* D. Don) and spruce (*Picea abies* Karst.) wood samples by sunlight, xenon light and mercury vapour light. The colour change of the samples was evaluated by CIE L*a*b* and L*h*c* colour co-ordinate systems. It was found that the samples showed a rapid colour change at the initial period of treatment but the rate of change decreased with treatment time. It was determined that neither xenon nor mercury lamp light can accurately simulate sunlight. A wide range of colour changes were caused by the applied light sources. In spite of this wide colour range a good linear correlation was found between the lightness and the colour hue. The coefficients of determination (R^2) are between 0.7 and 0.96. Accordingly, this linear correlation gives the possibility of following the colour change during photodegradation by measuring only the lightness.

1. Introduction

The colour inhomogeneity of wood is one of its most beautiful natural characteristics, with the colour hue between red and yellow giving a warm, pleasing aesthetic effect. The cell structure of wood has a substantial amount of cell interfaces aligned parallel to the grain with reflection from these interfaces contributing to the appeal of wood as a material [1]. The incident angle of illumination affects this gloss and the colour of the wood [2]. The colouration of wood material is sensitive to both light and heat and the combination of light and heat treatment has more effect than when considering each as separate parameters [3–7].

The colour change of wood is the most sensitive indicator for the degradation caused by sunlight. The colour alteration of black locust wood can be seen by the naked eye after 2–3 h of irradiation. The objective colour monitoring of photodegradation has been applied in wood science only in the last twenty years [8–13] with the CIE L*a*b* colour co-ordinate system being used in most cases.

Tolvaj and Faix [9] examined three coniferous and two deciduous species irradiated by a mercury lamp for 200 h. A rapid change was found in colour difference in the first 50 h of irradiation process for all species, with half of the measured colour change taking place during the first 50 h of irradiation. Intensive and continuous yellowing of the samples was observed accompanied by moderate shift towards red. Similar changes were also reported in later works [10–17]. The visual observation of colour is represented perfectly by hue (h*, which represents a* and b* together), although the L*h*C* colour system is seldom used to monitor the colour change of wood [18,19].

It is a fact that the induced colour change depends highly on the type of light source [15]. The emission spectrum of the irradiator defines the emitted wavelength distribution. The UV component plays the main role causing photodegradation. Recently, lasers have been applied to determine the wavelength dependence of photodegradation [7,20–22]. Unfortunately, colour measurement was rarely applied in these studies [7].

Pandey [23] compared the photo-discoloration of natural and extractive-free wood samples. It was found that the extractive-free specimens exhibited a uniform increase in colour change with increasing irradiation time. Unextracted wood surfaces showed a rapid colour change during the initial period of exposure but a decrease upon prolonged exposure time. Analysis of colour changes and FTIR spectra measured from irradiated wood surfaces indicate that the presence of extractives increases the rate of photodiscoloration. The apparent increased rate of colour change in unextracted wood has been explained as being due to the photodegradation of polyphenolic extractives present in wood.

The objective of this study was to analyze colour changes measured on CIE L*, a*, b* and L*h*C* co-ordinate systems and use them to simplify the monitoring of the photodegradation of wood by colour change.

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2. Experimental

Samples from beech (*Fagus crenata* Blume), black locust (*Robinia pseudoacacia* L.) as the hardwood species and Japanese cedar (*Cryptomeria japonica* D. Don), spruce (*Picea abies* Karst.) for softwood species were used for the experiments. Samples having tangential surface dimensions of 50 × 10 × 2 mm (longitudinal; tangential; radial, respectively) were prepared. A set of samples were prepared from the same board to assure uniformity. The early wood of both sapwood and heartwood were irradiated from black locust, beech, Japanese cedar and spruce. Each species was represented by a series of two samples with five measuring points for each sample. Therefore the data presented in this work are the average of 10 measurements. The natural sunlight irradiation was carried out between 5th of May and 19th of August, 2003 when temperature varied from 16 to 41 °C, with a maximum relative humidity of. 80%. The daily average of total solar power density was between 436 and 459 W/m^2 in Takayama, Gifu Prefecture, Japan. Geographical data for Takayama are: 36° 9.3 min latitude with an altitude of 560 m. The samples were kept outside on sunny days only to determine the effect of the full sunlight only. After exposure the samples were stored in a dark room in the laboratory. The other series of specimens were irradiated with a xenon lamp at 180 W/m^2, ranging from 300 to 400 nm, for up to 200 h, at 63 °C (black panel) and 50% RH, in a commercial chamber (SX-75: Suga Test Instruments Co. Ltd., Tokyo). There was a quartz glass filter around the lamp. A strong UV light emitter, a mercury vapour lamp was also used to irradiate specimens (HAL 800NL, installed into a KBP.659 Nippon Denchi Co. Ltd. chamber.). The total light emission of the mercury lamp was 320 W. The samples were located 64 cm from the lamp. The air temperature in the chamber was 26 °C. Total irradiation time was 200 h for sunlight and xenon light, and 20 h for mercury light.

The colour of the wood specimens was measured before and after irradiation. The exposures were interrupted within the time period of 5, 10, 20, 30, 60 and 120 h (for the mercury lamp exposure times were one tenth of these times) to measure the colour data. The colour measurements were carried out with a colorimeter (SE-2000 Nippon Denshoku Industries Co. Ltd., Tokyo). The L*, a*, b* and L*, h*, C* colour co-ordinates were calculated based on the D_{65} light source.

3. Results and discussion

Colour stability is an important feature of products made from wood. The colour of wood is sensitive to light radiation. UV light in particular causes remarkable colour changes. Colour change is more pronounced initially during exposure than the other indicators (e.g. IR spectra). In some species this colour change is notable and visible even with the naked eye after a few hours of radiation as in the case of black locust. The colour change of the wood studied in these experiments was rapid, during the first 20 h of light irradiation by sun and xenon lamp, as illustrated in Figs. 1 and 2. Changes in lightness were particularly pronounced. Similar results have been presented in previous works [11,12,17,24]. The rapid period of lightness change caused by sunlight in the first 20 h accounted for 74% of the total change in black locust and 55% in beech and ca. 40% of those in softwoods. The extraordinary behaviour of black locust can be explained by its high extractive content. The UV light degrades the extractives followed by the rapid oxidation of the degradation products, resulting in a rapid decrease in lightness. The modified chromophores act as a form of energy trap which slows down the photodegradation of the main wood components [25]. That is why the lightness change of black locust is slower than that of the other examined species after 20 h of irradiation. This

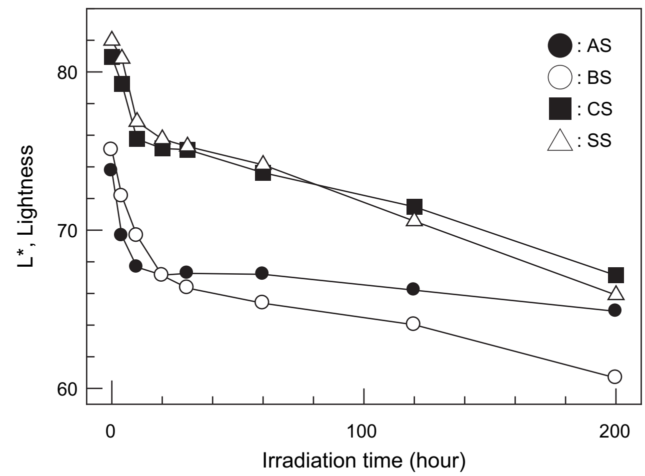

Fig. 1. Lightness change of black locust (A), beech (B), Japanese cedar (C) and spruce (S) samples caused by sunlight (S) irradiation.

protection by the chromophores provides black locust with properties that make it the most durable wood species for outdoor applications [26]. The xenon lamp caused greater changes in lightness than sunlight in the case of conifers but similar changes in hardwoods. Significant differences between the colour change caused by exposure to xenon lamp and sunlight was observed for spruce samples. After 50 h of irradiation the trend changed and the trend lines became parallel and linear to each other.

The effect of mercury lamp irradiation shows a difference among the four species compared to degradation caused by xenon and natural light exposure (Fig. 3). The mercury light irradiation was carried out for 20 h only which was 10 times shorter than the sunlight and xenon irradiations of 200 h. While the colour change tendencies were the same, the mercury light caused much greater colour changes than with the other sunlight and xenon light irradiation tests (Figs. 1–3). The emission spectrum of the mercury lamp (supplied by the producer of the lamp) is located mainly in the UV region (80%). It contains 31% UV-A (380–315 nm) radiation, 24% UV-B (315–280 nm) and 25% UV-C (>280 nm) radiation. The photons of UV-C range have sufficient energy to cause scission in almost all the chemical bonds in wood [27]. The sunlight reaching the surface of the Earth does not contain UV-C. Therefore using a mercury lamp can produce valuable results for understanding the nature of the UV photodegradation of wood, but it is unable to simulate sunlight.

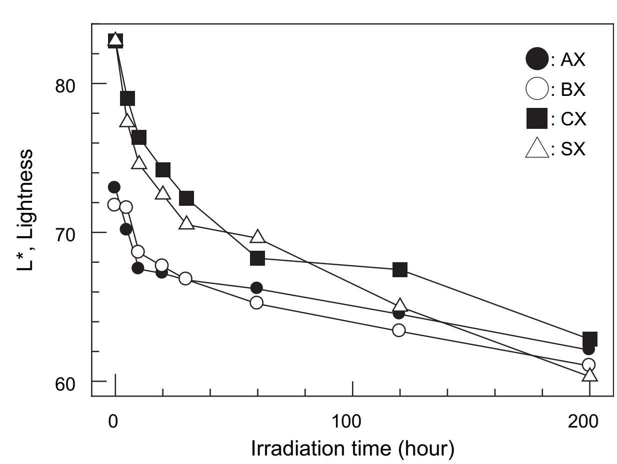

Fig. 2. Lightness change of black locust (A), beech (B), Japanese cedar (C) and spruce (S) samples caused by xenon lamp (X) irradiation.