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Techniques to Measure Moisture Content in Timber: A Review and Proposal for Inter-digital Sensing

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ABSTRACT

Timber is a commonly used building material which is porous in nature, continuously maintaining equality with relative humidity (RH) and temperature of the atmosphere in the immediate vicinity. Moisture content influences several performance parameters like timber durability, immunity to deterioration *etc*. Several procedures have been attempted which enables to measure the moisture contents in timber consistently and rather accurately. This review provides the technical details of the methodologies attempted so far to estimate moisture contents in timber specimens. The proposed inter-digital sensing was carried out at Department of Instrumentation, CUSAT during 2019-2020. Implementation of a method employing a spiral inter-digital capacitive sensor, which is low in cost and non-invasive in nature, is presented and discussed.

Key words: Capacitive sensing, Inter-digital transducers, Moisture measurement methods, Timber moisture.

Timber is a non-homogenous, hygroscopic substance, that absorbs water. Water absorption in timber is influenced by the temperature and relative humidity (RH) of the surroundings. During absorption of water by timber, initially water is retained in the walls of timber cells as bound water. Around 28-30% timber moisture content, varying based on timber species, is considered sufficient for full soaking of timber cell walls. This is termed as fiber saturation point (FSP). Up to FSP, the volume of timber also rises in proportion to the volume of water absorbed (Stamm, 1935). Beyond FSP, moisture is retained in cell cavities and intercellular voids as unbound water. For increased moisture contents above FSP, timber does not exhibit swelling. This is a reversible process with the timber shrinking as moisture content falls below FSP. Moisture affects timber in several ways as follows.

Physical deformation

As is well known, dimensional fluctuations in timber occur for moisture contents below FSP. In the tangential and radial directions, dimensional increase and decrease are considerably marked compared to the axial order, as indicated in Fig 1. In addition, as peripheral portions of timber primarily adapt to surroundings, a moisture gradient is developed within the timber cross-section that diminishes over time (Dietsch *et al*., 2015). Keeping low moisture gradient is a vital feature for checking uneven shrinkage and warping. Cycles of drying and rewetting also degrade the cell wall structure, resulting in escalations in the rate of swelling and magnitude of absorption (Rowell, 2012). This fluctuation is also subject to timber grain orientation, density and timber variety. Thus moisture content above FSP plays a significant role in the physical deformation of timber.

Timber deterioration

Fungi, bacteria, insects and exposure to severe ambient conditions can degrade the quality of timber. By restricting the moisture content below 20%, the deterioration in quality can be considerably reduced. Fungi require optimum conditions of temperature (10-32°C), oxygen, nutrients and moisture (above FSP) to grow. By regulating the exposure of timber to moisture, even in the presence of other factors, fungi become dormant. Destructive fungi such as soft rot, brown rot and white rot, each attack different chemical components of timber. Insect decay can be attributed to larvae, which feeds on timber. Larvae can survive in timber for up to 10 years. However, some attack dry timber and some moist timber. Insect attack can be controlled easily by reducing the moisture content of timber by removing sources of moisture and by providing proper ventilation in conjunction with chemical treatments (Shupe *et al*., 2008). Moisture also hampers the performance of coatings applied to timber surface and can cause superficial stain.

Micro structure of timber

At its biological level, timber can be categorized as soft and hard timber. Mature timber cells comprise of cell wall without

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any protoplast. The empty portion enclosed by the cell wall is called lumen. Pits are cell wall openings that facilitate delivery and contact among adjacent cells. They can be bordered pits, simple pits or half bordered pits. Hard timber (angiosperms) have special cell types called vessels along the longitudinal axis that convey nutrients and water to all parts of the plant. They are also referred as pores as they appear as large holes in the transverse direction. Depending on the distribution of these pores, hard timbers can be classified as diffuse porous, semi ring porous and ring porous. They are primarily useful in hard timber identification. Dense walled and thin lumen cell types called fibers are primarily responsible for the mechanical strength of timber. Fiber cell wall thickness governs the density and strength of hard timber. Other abundantly available cells are axial parenchyma, specific to each species. Structurally diverse ray parenchyma cells are also present that are predominantly involved in the synthesis, collection and passage of bio-chemicals. The elaborate cellular system forms a compact formation, thus being known as hard timbers. The cellular structure of soft timbers (gymnosperms) is less complex, comprising of elongated cells, hundred times longer than wider called tracheid. Tracheid facilitates conduction and mechanical support and comprises 90% of soft timber volume. Other cell types include brick-like ray parenchyma cells along the radial direction, functionally similar to those found in hard timbers and axial parenchyma in rare cases (Askeland and Wright, 2015; Rowell, 2012).

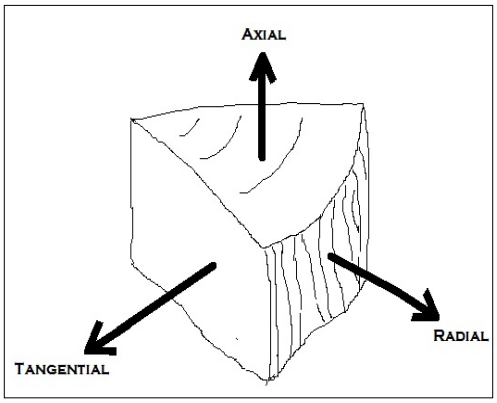

Fig 1: Timber anatomical direction.

In order to view detailed images in the micron range, Scanning Electron Microscopy can be employed. Targeting the electron beam onto the specimen, stationed in vacuum results in scattering of electrons, which are magnified by lenses to generate a micrograph. Secondary electrons resulting from scattering of electrons from the specimen surface are collected and processed to reproduce the surface image. These interactions and the consequent scattering present essential details about the superficial aspects of the specimen and assess timber damages, sample inhomogeneity *etc.,* making it a powerful tool to observe and analyze morphology of timber. Since timber is a non-conductive material, in order to observe the microstructure, samples must be sputter-coated with a very thin layer of a noble metal, like gold, to prevent charging artifacts during imaging (Collett, 2007; Hamed *et al*., 2012). Teak (*Tectona grandis*) were cut into strips of 5 mm × 5 mm with a thickness of 1 mm, dried and sputtered with gold (Au) with thickness below 10 nm using a JEOL Model-JFM 1600 Autofine Coater. Using the Scanning Electron Microscope (JEOL Model-JSM 6390) at accelerating voltage of 10 KV, the timber samples were examined. As shown in Fig 2, pits (a) and bordered pits (b) were observed at various magnifications.

Chemical composition of timber

Timber constitutes of carbon (50%), hydrogen (6%), oxygen (44%), nitrogen (<1%) and trace amounts of inorganic elements like magnesium, potassium, calcium, silicon and sodium (<1%). The major chemical components in timber comprises of cellulose (40-60%), hemicellulose (6-27%) and lignin (8-41%). Smaller quantities of organic components and inorganic minerals (ash) are found within 4 to 10% in timber (Pettersen, 1984).

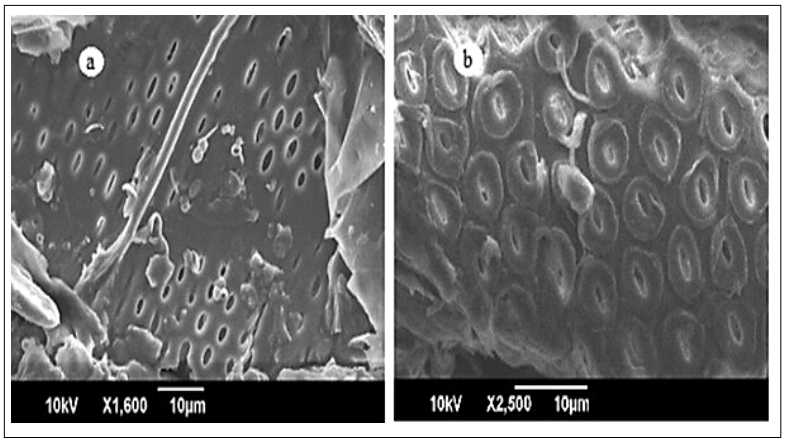

Fig 2: Scanning Electron Micrographs of (a) Pits in teak (b) Bordered pits in teak.

Parameters of interest for timber

Moisture content

Moisture content in percentage is one of the most important parameter that affects the quality of agricultural products and building materials (Badgujar *et al*., 2019; Anbukkarasi *et al*., 2013; Guha *et al*., 2012; Dash *et al*., 2022). Moisture content (MC) can be defined on a dry or wet basis. In order to define moisture content on wet basis, the weight of water content is divided by the weight of the specimen. On the dry basis, the weight of water content is divided by the dry weight of the specimen. Calculating moisture content on dry basis can produce MC level above 100%. For definition on dry basis, timber moisture content is defined as:

$$MC = \frac{\text{Weight of water content}}{\text{Dry weight of wood}} \times 100 \quad (1)$$

Timber density

This relates to specific gravity and moisture content (Simpson, 1993). This relationship can be estimated as:

$$D = \frac{G_b\,(1+ MC/100)}{1 - 0.265aG_b} \quad (2)$$

Where
D = Timber density (kg/m^3).
MC = Moisture content percentage.
G_b = Basic specific gravity.
a = (30-M / 30), assuming a linear interdependence of shrinkage and moisture content lower than 30%.

Permeability and porosity

When green timber is cut, the drying process depends on timber permeability and environmental conditions. Permeability quantifies liquid flow as a result of pressure difference. This is different from porosity which is the fractional void volume of timber. Timber is a highly porous material, but is not very permeable, as permeability depends on the void opening size and pit condition, which vary among different species. Furthermore, closed cells allow exchange of liquids and gases only through cell walls. Porosity is calculated as:

$$V_a = 1 - G(0.685 + 0.01\ MC/G_S) \quad (3)$$

Where
G = Timber specific gravity at specific moisture content.
G_s = Specific gravity of bound water at moisture content MC (Panigrahi *et al*., 2018).

As free water in cavities decrease, moisture content at surface reaches FSP. Intrinsic moisture flow includes liquid flow and diffusion of water vapor and water bound in the cell walls, whose diffusion is affected by the specific gravity of timber due to difference in moisture content between the interior portions and the surface and by the flow of heat from timber periphery to the center. The impact of internal resistance on the drying rate increases till equilibrium moisture content is attained. Dehydration of timber depends solely on its internal resistance when water in liquid state is nonexistent in timber (Jankowsky and Santos, 2005).

Differences between different varieties of timber

The variety of a timber specimen can be determined by examining sectioned timber with naked eye, using hand lens or light microscope to discern physical attributes by skilled persons. Macroscopic features like texture, color, luster, grain pattern *etc*. help to identify the timber species. Structural features like porosity, vessel layout and grouping, axial parenchyma pattern and abundance, ray dimensions and height, *etc*. are some of the microscopic features that form a framework in timber identification (Wheeler and Baas, 1998). As mentioned by Jiao (2020), DNA-based identification of timber is an emerging tool in species identification, but one drawback is that very inconsequential amount of timber tissue contains DNA.

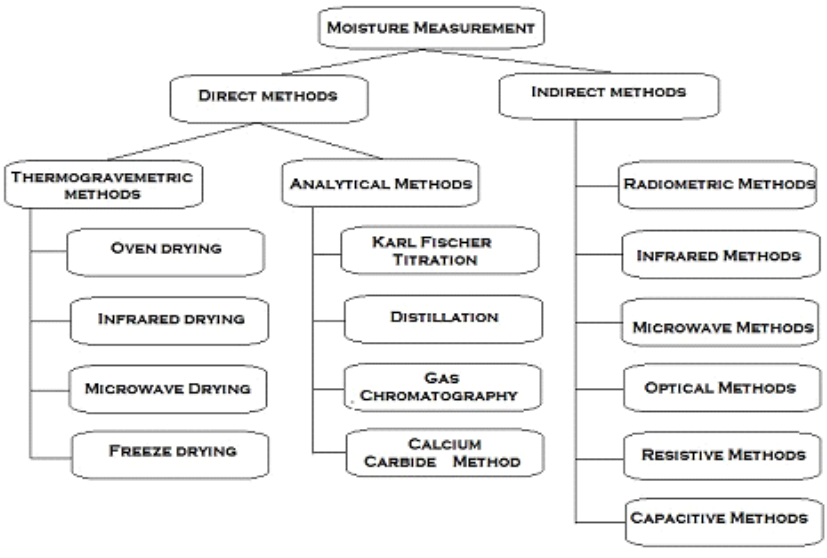

Fig 3: Various techniques to determine timber moisture contents.

Existing methods to determine timber moisture content

Various methods developed for timber moisture measurement are outlined in the following sub-sections, with the principle of each method briefly outlined along with the methodology adopted, including merits and demerits of each.

Methods used to determine moisture content in timber may be direct or indirect, as classified in Fig 3. Thermo-gravimetric methods and analytical methods come under direct methods. Thermo-gravimetric process is established on water loss following a drying procedure. Specimen weight is measured initially and on completing the drying procedure, which is realized when the loss in weight is minimal. The drying procedure can be realized using furnace, freeze drying, infrared drying or microwaves drying. Although accurate, these methods are destructive in nature and time consuming.

Analytical methods are direct chemical methods that differentiate between possible volatile compounds from moisture (Merlan, 2016). In distillation methods, water distills with solvents like Toluene or Xylene. Subsequent to condensation, the amount of separated water is measured. When compared with thermo-gravimetric methods, the deviation in the outcomes is attributed to volatile compounds discharged during heating in thermo-gravimetric methods (Samuelsson *et al*., 2006). Karl Fisher method is another moisture measurement technique, with dry methanol displacing water in the sample. Afterwards, the water is titrated following Karl Fisher method. These methods are suitable for samples with volatile compounds but not for timber with large moisture contents.

Direct methods

The standard oven drying method requires specimens initially weighed on a balance and then placed into a ventilated oven, with temperature preset to 103°C. As specified by ASTM International (2020), the specimens are assumed to be 'oven dry' when its loss in weight in a three-hour period falls below twice the weighing balance sensitivity for the primary method and when no appreciable change is observed in the mass readings in four hour intervals for the secondary method. This is taken as the oven-dry mass. This is a simple and inexpensive method. Accuracy is affected (absolute error of 5-10%) by volatile extractives evaporation in the course of drying procedure. Moreover, this is a time consuming and destructive procedure.

Microwave drying permits swift heating and drying compared to conventional oven heating method. This does not affect mechanical properties like timber strength compared to conventional drying (Hansson and Antti, 2003). Infrared drying is another complementary technique where infrared energy is used to dry the sample. The process of vacuum drying is as follows. Specimens are kept in impenetrable chambers below the atmospheric pressure *and* heated. Because of the overall pressure variation, the dominant moisture transfer is by bulk flow of water vapor, with significant movement of water in the longitudinal orientation. Conveniences of vacuum drying as reported by Espinoza and Bond (2016) include drying across specimens of large cross section, reduced drying temperatures and duration, improved specimen color retention, greater efficiency in energy and improved curbs on discharge of volatile extractives. Schindelholz *et al*. (2007) and Shaozhi *et al*. (2016) have shown that treating waterlogged archeological timber samples with polyethylene glycol (PEG) before freeze drying is superior to other drying methods like supercritical carbon dioxide drying or air drying.

So, though direct methods are accurate, in general, they are time consuming and destructive in nature. A replication of measurement for the same sample is not possible and so, are unsuitable for continuous moisture monitoring. The drying time can also differ for different species of timber.

IR optical methods

Infrared thermography (IRT) procedure permits viewing the whole specimen structure and locating internal defects. This non-invasive and non-destructive method can be applied in two modes: active and passive. Thermography in passive mode examines samples at a distinct temperature in comparison with the surrounding temperature. In contrast, an energy stimulant is applied resulting in internal heat flow in the sample (Avdelidis *et al*., 2011) in the active mode, suitable for damp timber with larger moisture content. Objects emit radiation in the electromagnetic spectrum above zero degrees Kelvin. Infrared thermal imaging detects infrared radiation emissions from the surface of the analyte, usually in the mid or far IR wavelength regions because of their low atmosphere absorption. In spite of lower sensitivities, IRT supports quick, non-destructive measurement of localized areas with varying moisture percentages. The thermographic experiment is carried out using a radiant heating system and an infrared camera. Thermographic images taken are analyzed using image processing software tools. In order to ensure that the emissivity value remains constant, the specimen is generally painted black. One disadvantage is that only the surface moisture content up to a few millimeters is measured (Ludwig *et al*., 2004; Pitarma *et al.,* 2019).

The near-infrared radiation (NIR) method permeates deeper into the specimen than Mid-IR. Santos *et al*. (2020) has investigated the influence of integrating sphere or fiber optic probe and the exterior specimen condition on the NIR spectra for moisture assessment in timber. Tsuchikawa *et al*. (2017) examined online NIR spectroscopic system for speedy moisture evaluation of veneer at 120 m/min and sufficient prediction accuracy. Tham *et al.* (2019) predicted moisture percentages of timber from green to air-dried condition, considering both capacitance and NIR spectra taken at two different wavelengths. The results have been highly accurate, quick, obtained from scaled down datasets. Here also only moisture content of timber surface could be measured.

Radiometric methods

Ray microscopy

When the sample is subject to divergence free X-ray beam, some photons get scattered. The residual quantity of photons passing through the sample is indicative of the sample type. The digital X-ray microscope consists of a X-ray source and a detector for X-ray densitometer. The samples with varying moisture content are placed in the digital X-ray microscope to determine the moisture content distribution. Watanabe *et al*. (2008) studied the progressing moisture contents and the moisture distribution in timber samples.

Dual-energy X-ray absorptiometry (DXA)

This technique adopts two distinct X-ray energies which get attenuated while passing through the specimen. This attenuation for both frequencies is recorded with a detector, which is correlated with the sample's effective atomic number that is subject to the moisture content. One distinct advantage of DXA is the ability to determine moisture content without knowing oven-dry density. The evidence that each substance has a unique absorption of X-ray energy is exploited in this method to measure the quantity of moisture in timber (Hultnas and Cano, 2012). Kim *et al*. (2015) determined the moisture content in the range of FSP and above, by interpreting the radiographs obtained using a polychromatic X-ray source and digital detector.

Nuclear magnetic resonance (NMR)

NMR method relies on the interaction between an applied magnetic field and the magnetic moment of an atomic nucleus. Atomic nuclei have magnetic moments because the protons comprising them possess spin. Nuclei are also charged and a moving electrical charge generates magnetism. Thus, the magnetic moment of the atomic nucleus arises, making the nucleus a dipole. Magnetic moment is an intrinsic property of every atomic nucleus. Hydrogen nuclei have the strongest magnetic moment and are utilized in NMR technique. A proton without influence from an external magnetic field spins and has its own magnetic moment in the direction of the spin axis. As an external field is applied, the protons will feel a torque forcing them to align either parallel or anti-parallel to the external field. Nuclei in the anti-parallel state have more energy than those in the parallel state. By applying a second external field, in the form of an electromagnetic signal in the radio frequency (R.F.) range, nuclei in the parallel state can be induced to ascend to the higher energy anti-parallel state. The frequency of the secondary field that will cause this is specific and when that state is achieved, the nucleus is said to be in resonance with the applied field. After the R.F. pulse, the nuclei return to their previous state emitting a signal in the frequency range they absorbed previously. The protons belonging to water molecules can be accurately determined. The set up in reference (Xu *et al*., 2017) consists of a permanent magnet in a region where the specimen is evaluated. A solenoid coil encases the sample tube *and* both the sample tube and the coil do not affect the NMR signal. This is conducted in a temperature controlled box, since temperature changes influences the field. The longitudinal relaxation times (T1) or transverse relaxation times (T2) are acquired from the NMR signal. The solid timber and the water within it, comprising of free and bound water are easily identified to the distinguishable T2 behavior. The smallest T2 value is of the cell wall (few microseconds), followed by bound water (few milliseconds) and free water (ten to hundreds of milliseconds). This method is extremely accurate and can distinguish between the contents of free and bound water (Guzenda *et al*., 2001). However, this is a high cost technology and R.F. coils need to be tuned regularly.

Radio frequency methods

R.F. attenuation and polarization

At frequencies lower than around 1GHz, electromagnetic waves interact strongly with water and penetrate deep enough into solid objects. Water molecules continuously attempt to reorient themselves according to the polarity of the applied electric field by absorbing energy from the electric field. This leads to energy loss or attenuation. The loss factor depends predominantly on the amount of water molecules. Besides, electromagnetic radiation slows down as it propagates through a solid material. As the wave slows down, its wavelength contracts. The loss in speed relies on the dielectric propagation constant of the sample in question. The propagation constant in turn depends on the timber density and moisture percentage. The retardation experienced by the wave can be measured as a change in phase as it is transmitted through the solid material. The third property that changes when an electromagnetic wave encounters when it is transmitted through a solid object is polarization. As described by Bucur (2003), timber is an anisotropic material and different directions have different dielectric characteristics. As the wave hits the material, its linear polarization shifts resolving into components in the direction of the minimum and maximum dielectric constant. So by measuring attenuation and change in polarization of RF waves through the material, the moisture content can be estimated.

Ground penetrating radar (GPR)

This non-destructive technique utilizes electromagnetic waves to realize three-dimensional representations employing direct or reflected wave approach. A GPR signal transmitted through the sample is influenced by timber density, moisture content, temperature and fiber orientation. The dielectric response of timber is superior when the applied electric field is parallel to the fiber direction compared to being perpendicular. GPR equipment comprises of an electromagnetic wave pulse generator and double coupled antenna made of dipolar elements (transmitter and receiver) (Abad *et al*., 2010). Mai *et al.* (2015) reported section wise linear/curvilinear dependence of permittivity on moisture content, with slope variation at FSP and good sensitivity for

microwave propagation components to timber moisture changes.

GPR radiograms can be recorded in two directions: longitudinal, where the electric field is perpendicularly polarized to timber fiber and transverse, where the electric field is parallel to the fibers. As direct waves travel along the specimen top layer, the measured values of the relative permittivity are seldom influenced by the field polarization. As the reflected waves traverse through the entire specimen, moisture content and relative permittivity are influenced by the material; with greater influence when the field is parallel to the timber fiber direction (Reci *et al*., 2016). One benefit of the GPR method is the capability to inspect a vast specimen area quickly.

Microwave methods

Microwaves measurements are similar to RF measurements, but have lower penetration depth. Assessment of phase-shift and attenuation provides density and moisture content utilizing multiple variable statistical methods. Moisture content is frequency independent and moderately dependent on temperature. The underlying principle exploited for moisture determination is that at higher frequencies, relaxation of molecules in water takes place. For industrial implementation, polarization-controllable dual-polarized antennas which can be used in place of rotating antennas and low noise amplifier can be used to dramatically reduce the noise level (Aichholzer *et al*., 2018).

The highest sensitivity is achieved by resonator sensors. Both planar and coaxial resonators have been utilized. A Vector Network Analyzer (VNA) has been used to excite and monitor the cylindrical cavity resonator operating in TM010 mode by Ozbey *et al*. (2020). After thoroughly soaking a timber specimen, it was positioned in a sensing channel and left to dry for 24 hours. The transmission spectrum of the cavity is observed by the VNA, registering regular information. One main advantage reported is non-destructive moisture determination with very high sensitivity of 6.2 MHz/MC%. Thus these sensing methods provide greater precision and speed *and* are radiation free. However, for industrial/commercial applications it can be too expensive.

Time domain reflectometry

Time-domain reflectometry (TDR) is widely used in cable fault detection. Here variations in velocity, signal impedance and time taken as signal traverses across cable length are computed. With increasing moisture content, travelling time increases. As electrical conductivity increases with moisture content, TDR sensitivity can be associated with moisture contents. TDR probes inserted into timber by Dahlen *et al*. (2020), along with automated data-logging capabilities, have been used to assess moisture in timber. In addition, moisture contents well above the FSP of timber have also been monitored for successive wet-dry cycles.

Resistive methods

Electrical resistance drops as moisture content increases, as water is more conductive than timber. Thus timber moisture can be deduced from measured resistance. Voltage is applied to two electrodes rammed into the timber and resistance can be measured across the electrodes. According to Stamm (1927), below FSP a direct relation exists between the logarithm of resistivity and timber moisture content. Thus measured resistance depends on internal factors like timber type, density, temperature, measuring direction, chemical additives and inner moisture gradients (Vermaas, 1975). External factors like electrode geometry and span, extent of measurement, electrode contact pressure, sample size and geometry, electrolytic effects, applied voltage *and* measurement delay can affect the measurement.

Direct current (DC) (Brischke and Lampen, 2014; Casans *et al*., 2018) or alternating current (AC) (Berga *et al*., 2019; Dai and Ahmet, 2001; Gao *et al*., 2018) has been supplied to the electrodes to obtain electrical resistance. A transient response in resistance is observed, because of polarization, when DC is applied. Alternating polarity of voltage can be supplied to the electrodes to reduce this consequence. Berga *et al*. (2019) developed an automatically tuning relaxation oscillator in conformance with equivalent timber resistance, allowing rapid and accurate estimation of timber moisture contents below 30% MC.

The resistance technique is suitable for MC below FSP, but at levels beyond FSP, the electrical conductance becomes poorly related to the MC. In addition, since electrodes can pierce only a few millimeters of timber, the moisture content of only the immediate area of the sample is revealed.

Capacitive methods

Dielectric constant, which can be determined by measuring the capacitance, rises as moisture content increases, but decreases with increasing frequencies. Other variables that mildly influence the measurement are temperature, structural direction and density (James, 1975). James (1986) carried out a detailed experimental study using stacks of veneers with different MC distributions: uniform MC, gradual moisture gradients and steep moisture gradients and with diverse electrode configurations generating parallel and non-parallel electric fields. As the frequency is decreased, the sensitivity of the dielectric properties to changes in MC increases, but also the sensitivity to moisture gradients increases. As the field strength varies significantly with position for non-parallel fields, position of the sample is a very significant factor. In general, capacitance method achieves sufficient reliability from 2% up to moisture percentage at FSP. Surface contact electrodes are greatly influenced by moisture gradients in the specimen. These are quick and easy to apply to the specimen. The method is wholly non-destructive in comparison to resistance-type pin electrodes that are inserted into the sample. They reflect the surface or near surface MC of the specimen.

Kandala *et al*. (2016) have evaluated fuel timber chips with MC ranging from 6% to 50% using a parallel-plate capacitor glued to the inner walls of the cylindrical container holding the timber samples. The standard error of prediction

was ± 2% with better prediction accuracies below 25% MC. Parallel rectangular electrodes adjustable to timber dimensions have been used by Moron *et al*. (2016) to determine moisture in timber samples taken from a building under restoration and from fresh samples. A parabolic behavior has been observed between sensor capacitance and MC% with very high coefficients of correlation. Fresh timber has slightly lower coefficients of correlation, possibly due to higher resin content in fresh timber. Both parallel and planar electrode topologies have been employed to monitor drying process of timber pellets online by Fuchs *et al*. (2009) and to measure the moisture content of palm timber in real time by Korkua and Sakphrom (2020). Rectangular inter-digital sensors have been used on rubber timber by Chetpattananondha *et al*. (2017) to determine moisture contents in the range 6-70% with 0.98% precision error. To overcome the limitation of average moisture content measurement over a predetermined extent, concentric planar electrodes of four different radii, about a central, circular ground electrode were designed by Laleicke and Kamke (2018) to incorporate multiple penetration depths in one sensor. The sensor could measure positive moisture content gradients instead of averages, with a restriction in negative moisture gradient determination.

Moisture monitoring using planar spiral interdigital capacitive sensors

The interdigital capacitive method has been adopted by us as it is completely non-destructive, low cost and non-radiative. Planar interdigital sensors require only one sided access to the test sample and it offers good accuracy even below 2% MC (Chetpattananondha *et al*., 2017). Oommen and Philip (2020) reported that a spiral inter-digital electrode topology exhibited a percentage increase in sensitivity by 21.7-28.4% over the corresponding rectangular inter-digital topology for the same sensor area. Subsequently this design has been adopted by Oommen and Philip (2021) to measure moisture contents of five varieties of timber.

The timber samples were sliced into cubes of size 20 × 20 × 20 mm^3 and dried to their anhydrous state by placing them in a heating chamber at 70°C for 30 days, weighing daily till the variation in weight between consecutive days was less than 0.1%. Once the oven dry weight is obtained, the samples were drenched in water in a controlled manner till their FSPs were exceeded for two days continuously. After exceeding FSP, the samples were weighed to record their wet timber weight, so that the weight of water can be calculated following equation (1). Thus the MC% for each sample could be calculated. The timber specimens were then placed over the surface of the electrode structure. Capacitance values were measured using an Impedance meter (HIOKI, Model IM 3570). The measurements were conducted at constant temperature to avoid any influence of temperature on the measurement or on the samples. For every sample of timber and for every value of moisture contents, six measurements were conducted, so as to estimate uncertainty in the measured values. The uncertainties in the measured values of capacitance were estimated to be below ± 0.05 pF.

The capacitance at different MC values for five different timber samples were measured, broadly spanning from 0 to 82% at room temperature (27°C) and plotted in Fig 4. Among the various samples, a maximum MC at 82% was obtained for rubber timber sample. The teak timber sample showed the least absorption of water with a maximum MC of 26%, as expected. Upon performing curve fitting, capacitance is found to follow an exponential growth as given by equation 4.

$$Y = a + be^{x/c} \quad (4)$$

Excellent correlation coefficients are obtained for all the curves and the fitting coefficients are charted in Table 1.

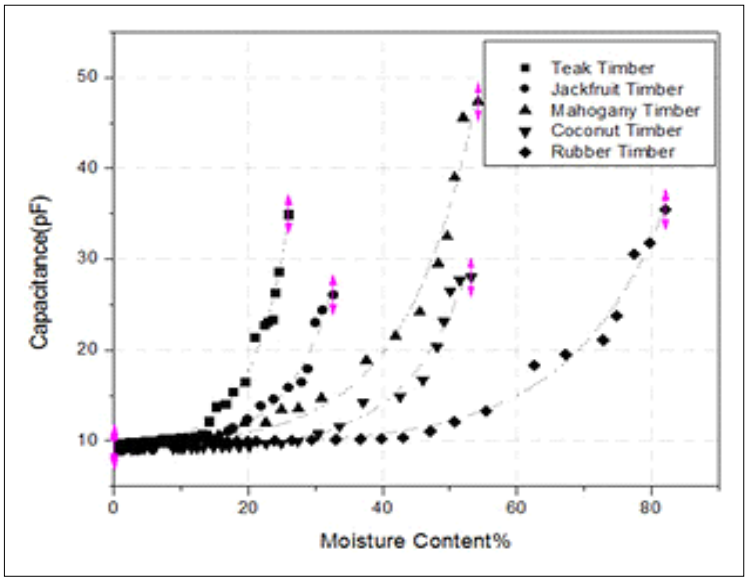

Fig 4: Measured capacitance values correlated to the MC% of 5 different timber species.

Table 1: Fitting parameters.

Timber variety	Correlation coefficient	a	b	c
Coconut	0.98	8.93	0.08	9.47
Jackfruit	0.98	9.32	0.15	6.86
Mahogany	0.99	9.4	0.24	10.63
Rubber	0.99	9.42	0.08	14.27
Teak	0.99	9.39	0.22	5.46

Table 2: Overall sensitivity in pF per MC.

Timber variety	Sensitivity (pF / MC)
Coconut	0.36
Jackfruit	0.51
Mahogany	0.7
Rubber	0.32
Teak	0.98

Similar behavior is reported by Korkua and Sakphrom (2020) and Moron *et al*. (2016). It is clear from Fig 4 that different species of timber have different sensitivities for capacitance with change in moisture contents and is tabulated in Table 2. This aspect should be taken in to account while designing a system for moisture measurements in timber samples. Thus Fig 4 shows an increasing trend of capacitance for increasing MC. For MC below FSP, bound water within the cells is not easily released, however greater increase is observed at higher MC above FSP.

CONCLUSION

This review presents the work done so far on various direct and indirect techniques for the measurement of timber moisture contents. The specific advantages and limitations of each of the techniques reported in literature are also presented. In addition, a new capacitance measurement method employing planar spiral electrode topology, designed to determine the total moisture contents in timber samples, is presented. As expected, the capacitance is found to vary exponentially with water contents in timber. From the measured capacitance data, curve fitting has been carried out to identify the relation between the variables involved. The fitting parameters have been estimated and reported. Following this technique, a sensor set up is developed to measure timber moisture contents in samples of different species with moisture contents up to 82%. We have seen that the technique is very promising for this measurement in terms of accuracy, speed, cost, dynamic range and simplicity. The capacitance technique offers many advantages like low cost, one sided access to the measurand, non-destructive and non-invasive in nature *etc.* Limitations of the technique are that only the near surface average MC of the specimen is revealed, sensitivity is dependent on the species of timber *etc*. So an auto-calibration of these effects is required while developing a commercial gadget for this measurement.

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Conflict of interest

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